Musculoskeletal Modeling with the Jaw Motion Data from TMD Patient

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Abstract. Temporomandibular disorder (TMD) is a prevalent dental disease in common with dental caries and periodontitis. The major symptoms of TMD are masticatory muscle pain, temporomandibular joint (TMJ) pain and impairment of jaw movement due to the pain and pathologic derangement of TMJs. However, there are few studies using TMD patient-specific motion data to drive the musculoskeletal model that can elucidate kinematic and biomechanical characteristics of the patient. The purpose of this study is to develop the workflow of musculoskeletal modeling of the mandible with jaw motion data obtained from a TMD patient. This involves establishment of patient-specific boundary conditions representing the characteristics of the TMJ. The jaw motion of a TMD patient was recorded and used as an input for driving the model.

Keywords. Musculoskeletal modeling, Jaw motion, Temporomandibular disorder, Inversed dynamics

1. Introduction

Along with dental caries and periodontitis, temporomandibular disorder (TMD) is one of the prevalent dental diseases. The major symptoms of TMD are pain/dysfunction of the masticatory muscles and temporomandibular joints (TMJs), and impairment of jaw movement including restricted range-of-motion of the jaw, clicking and crepitation of TMJs [1]. In clinical situations, it is typically observed that both limited jaw movement and pain could be improved after adequate TMD management by specialists. Tracking record of jaw motion can be used for effective functional assessment for TMD patients, because it is important to record and interpret the changes of jaw movement during a treatment sequence. Additionally, the jaw motion capture data can be input data for reverse engineering of the patients' condition and outcomes of treatment. Although the etiology of TMD is considered as multi factorial, kinematic factors in the etiology and phenomenology of TMD are poorly understood, thus their relative importance is still controversial [2].

On the other hand, inverse dynamics simulation is an effective computational method to determine the internal forces which are difficult to measure *in vivo*. Inverse dynamics-based software has been used for simulating muscle activations, muscle forces and TMJ

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reaction forces in various types of tasks [3-4], but there are few studies using TMD patient-specific motion data to drive the musculoskeletal model.

The purpose of our project was, therefore, to develop a patient-specific musculoskeletal model of a patient who has dysfunction in her masticatory system. As the first step, we implemented identification of the patient-specific boundary condition representing the bony surface characteristics of TMJ from motion capture data.

2. Method

2.1. Recording of jaw motion in patient

Figure 1. The inter-oral view of the patient

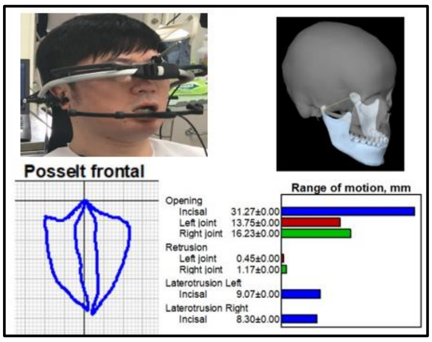


Figure 2. Measurement of jaw motion using orthodontic motion capture system

A 25-year old female patient was selected as the subject of this study. Informed consent relating to the purpose of study and management of personal information was obtained. As having imitated jaw movement and pain on the masticatory muscles at the first examination, the occlusal splint therapy (OST) and cognitive behavioral therapy were prescribed by a TMD specialist to improve the symptoms [5] (Figure 1). An orthodontic motion capture system (ARCUS Digma, Kavo dental excellence, Germany) was used to record and analyze the jaw motion during jaw opening (Figure 2). The bite fork was fixed to her lower dental arch for recording jaw motion at three virtual markers indicating the incisor point and left and right condyles. After recording, the data of marker's tracking were exported in text format files. The recording was conducted at three times during her treatment sequence: before treatment, *i.e.* starting OST, three months and six months after treatment, for assessing the treatment outcome and clinical course. In this study, we used the jaw motion data at before treatment, when the patient showed limitation of range-of-motion caused by TMJ pain. The measured motion data were digitally filtered with a low-pass filter (LPF) and a third order Butterworth filter. Particular noise problems existed at the maximal opening point, and the filter parameters had to be calibrated iteratively to retain the characteristics of the motion (Figure 7). The filtered jaw motion data were used as input driver data for musculoskeletal simulations in the AnyBody Modeling System (AMS) ver. 7.2 (AnyBody Technology, Aalborg, Denmark).

2.2. Description of the model with patient-specific constraint

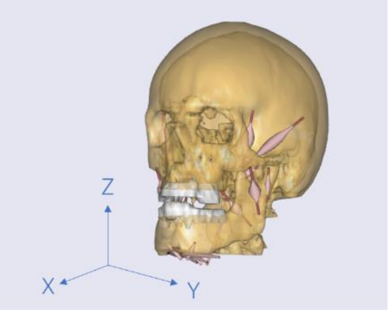


Figure 3. The musculoskeletal model of the human mandible.

The model of the skull and mandible in AMS were based on CT-scans of a 30-year old male (Figure 3) [4]. The entire skull and mandible were segmented in AMS and used for defining the muscle insertions and visualization. To represent the actual patient anatomy, the right and left TMJ fossa, *i.e.* the contact surfaces to the TMJ condyles, were modeled with parametric biphasic constraining planes (Figure 4). The two planes meet at a patient-specific origin and form patient-specific angles, α and β, with the skull reference frame. These parameters in turn constrain the movement of the condyle in the patient. This movement is detected by the motion capture system from where it can be reverse-engineered into patient-specific fossa parameters for the model. Each condyle has the possibility to rotate in all three dimensions and to translate along the specified constraining planes which means both condyles move with five degrees-of freedom. The model was equipped with 24 jaw muscles; 16 masticatory muscles and 8 suprahyoid muscles, actuating the movement of mandible. Each muscle was modelled as a Hill-type muscle consisting of contractile, parallel elastic and serial elastic elements, with the stiffness contribution of the tendon included in the serial elastic element. The details of model parameters were implemented from the study done by M. de Zee et al. [3]. The kinetic analysis was conducted after defining the constraint.

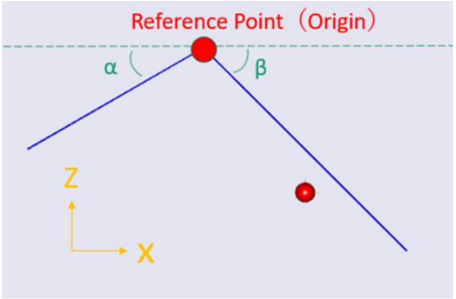


Figure 4. The schema of biphasic behavior

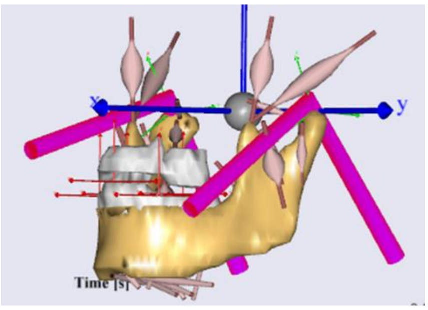


Figure5. Patient-specific constraining plane

3. Results and Discussion

3.1. Results

Figure 6 shows the trajectory of the three markers in sagittal, horizontal, and frontal planes (Figure 7). In the sagittal plane, the motions of both condyles show biphasic behavior during the opening-closing movement. Regarding the incisor point in frontal plane, the maximum unassisted jaw opening was 22 mm from which the subject has limitation of mandibular movement caused by the pain.

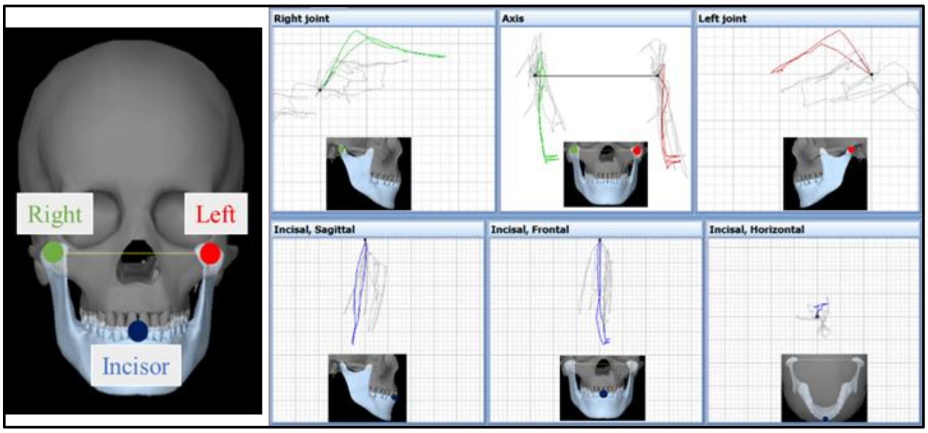


Figure 6. The trajectory of 3 marker positions in each plane

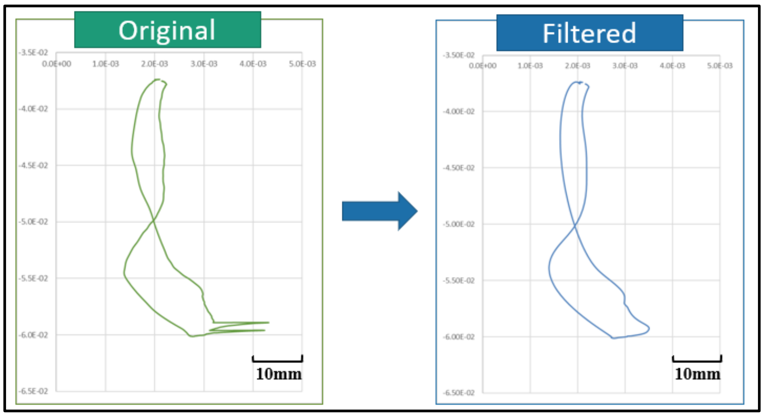
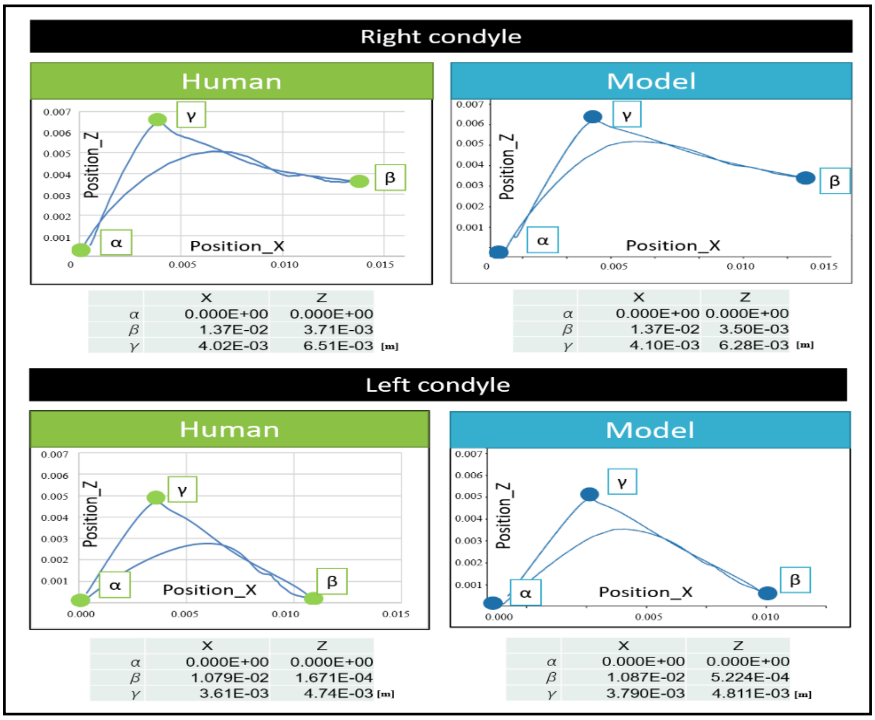


Figure 7. Filtered data of incisor point in frontal plane

Figure 8 shows the trajectory of both condyles in the subject and patient-specific model. Although the slight difference of each condyle position could be observed between the model and subject during opening, the ranges of motion and angle between 2 constraining planes in the model were consistent with the input data from which it can be concluded the characteristics of the motion were properly represented in the model.



Right condyle – Human

	X	Z
α	0.000E+00	0.000E+00
β	1.37E-02	3.71E-03
γ	4.02E-03	6.51E-03

[m]

Right condyle – Model

	X	Z
α	0.000E+00	0.000E+00
β	1.37E-02	3.50E-03
γ	4.10E-03	6.28E-03

[m]

Left condyle – Human

	X	Z
α	0.000E+00	0.000E+00
β	1.079E-02	1.671E-04
γ	3.61E-03	4.74E-03

[m]

Left condyle – Model

	X	Z
α	0.000E+00	0.000E+00
β	1.087E-02	5.224E-04
γ	3.790E-03	4.811E-03

[m]

Figure 8. The trajectory of condyle in the subject and patient-specific model

Figure 9 shows the results of kinetic analysis of condyle motions in the simple demo model prepared in AMS and patient specific model constructed in the present study. The characteristics of the condyle's curved motions are successfully represented in the patient-specific model.

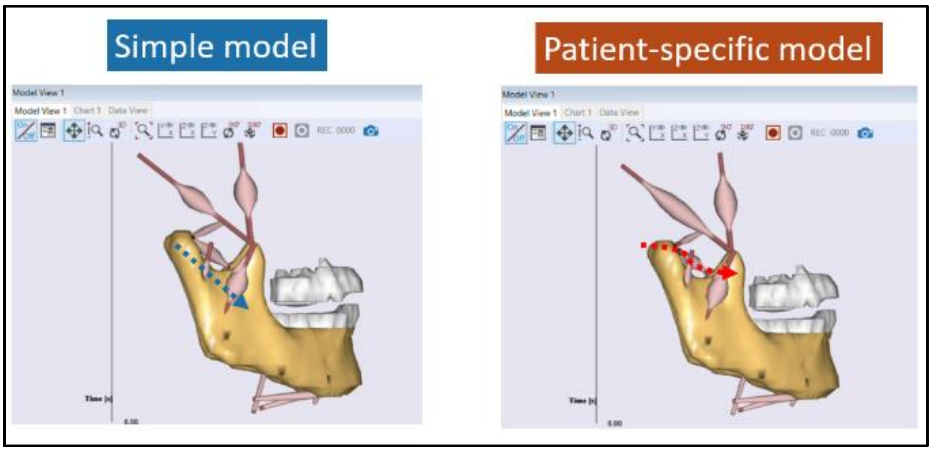


Figure 9. The motion of condyle in simple model and patient-specific model

3.2. Discussion

The TMD is a comprehensive diagnostic label of syndrome including various signs and symptom with different pathology, hence the exact etiology is still controversial [2, 6-7]. The methodology developed in this paper is the first step of a process, in which biomechanics can contribute to the knowledge of the problem. The orthodontic motion capture employed in this study is a relatively simple and accessible procedure, and the developed model shows possibility to extract patient-specific features from motion capture data and to implement them into a biphasic and patient-specific model with the TMJ fossa constraints. This will facilitate the use of musculoskeletal modelling for an investigation of larger cohorts of patients and might enable clinical use of digital human modelling in orthodontic and prosthodontic treatment.

Although the noise of recorded data can be minimized by experimental procedures using an accurate measuring device, it can never be completely removed. It turned out that the measured jaw motion data needed to be filtered with the settings obtained in an iterative process before using the data for kinetic analysis. An automated procedure for processing of the motion capture data will probably be necessary for use of the modelling technique on a larger, clinical scale.

In the present musculoskeletal model, the motion of each condyle was properly consistent with the motion-captured jaw motion data. The temporomandibular joints are hinging and sliding joints, so that their correct, patient-specific representation is important for the credibility of the kinetic model. In this study, small displacements between the measured motions and model's motions were observed, which is considered to be the consequence of using soft drivers in the musculoskeletal model to compromise between redundant positional information from the motion capture markers. Since the skull and mandible used in this study were based on a demo model representing a different patient, incompatibility between measured jaw motions from the patient in question and bony geometries from the template model might influence the result. Future work must include patient-specific scaling of the template model [8].

The model neglects the influence of ligaments, which are also constraining the motion during jaw opening. Future work will attempt to also identify ligament properties based on the relevant part of the motion capture data using parameter identification [9], thus extending the patient-specific adaptation of the model from motion capture data.

Although only jaw motion data at before treatment were included in this study, the jaw motion was improved with the progress of the treatment. Future comparative studies based on patients' jaw motions as treatment progresses could be clarify the interaction between the clinical symptoms and musculoskeletal systems such as muscle activations, muscle forces and TMJ reaction forces. This will be helpful to elucidate the TMD etiology and phenomenology from a biomechanical point-of-view. Additionally, the musculoskeletal simulation could provide boundary conditions for a patient-specific finite element analysis [10]. These types of digital human simulation could pave the way for simulation-based diagnostics and assessment systems [11] and would link well with future CAD/CAM systems in dentistry.

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