Human-Machine Coupled Modeling of Mandibular Musculoskeletal Multibody System and Its Applications in Quantitative Rehabilitation

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Introduction

About 44.1% of the patients suffering from oral and maxillary tumors had trismus syndrome (restricted mouth opening) six months after mandibulectomy [4]. Patients with restricted mouth opening can use mandibular movement function trainer (MMFT) for jaw-opening training. However, existing MMFT cannot consider individual mandibular movement characteristics. Mandibular musculoskeletal modeling can reveal the patient-specific muscle recruitment patterns and temporomandibular joint (TMJ) impedance during jaw opening [1]. In this paper, a human-machine coupling model was established based on flexible multibody dynamics, and it was further utilized to design the MMFT auxiliary forces of each patient.

Methods

A total of 8 patients with oral and maxillary tumors (4 males and 4 females, aged 22-62 years) were recruited. Each patient underwent CBCT scans before and six months after mandibular reconstruction. The patient's jaw opening-closing movement data was collected by the WINJAW ultrasound system. During jaw movement tests, electromyography (EMG) data of jaw-closing muscles (e.g., anterior temporalis and masseter) was simultaneously recorded with the WINJAW EMG device.

A patient-specific musculoskeletal multibody modeling was then established by combining obtained CT imaging, mandibular kinematics, and EMG data; see Figure 1(a). Based on the personalized CBCT data, the geometry of the skull, mandible, and hyoid bone was reconstructed using Mimics software. The mandibular muscles were discretized by a flexible muscle element considering distributed inertia and a Hill-type model. The TMJ was simplified as the soft tissue contact between the TMJ condyle and fossa. To obtain the activations during jaw opening-closing movements, a forward-inverse dynamic coupling framework [2] was then performed using an EMG-driven controller and feedback control loops.

The MMFT prototype consisted of two bladders within the mouth and a cable-driven system outside the mouth. In the human-machine model, the intraoral trainer was modeled as a single force acting on the mandibular bone, the extraoral trainer was modeled as a backward force, shown in Figure 1(b). To design the combination of MMFT assisted force, a hybrid optimization problem was proposed by combining the jaw opening degree and the assisted forces generated by the trainer. Here, we assumed that the jaw opening degree should be as large as possible, and the MMFT assisted forces as small as possible. Therefore, the optimization objective function J can be selected as:

$$J = w_1 \cdot \frac{\left| y_{\text{open}} - y_{\text{width}} \right|}{y_{\text{width}}} + w_2 \cdot \left\| \mathbf{F}_{\text{in}} \right\| + w_3 \cdot \left\| \mathbf{F}_{\text{out}} \right\| \tag{1}$$

where y_{open} denotes the actual jaw opening degree, $\mathbf{F}_{\text{in}}$ is the intraoral opening force, and $\mathbf{F}_{\text{out}}$ is the extraoral opening force. The weight factors w_1, w_2, w_3 should satisfy $w_1 + w_2 + w_3 = 1$.

For simplification, we assumed that only the intraoral trainer was used as a functional trainer. If the threshold jaw opening magnitude cannot be achieved, the cable-driven extraoral trainer should be also used as a guidance for jaw opening movements. The optimized jaw opening-closing kinematics were used as the model inputs, and the extraoral trainer was inversely calculated by the flexible cable element with arbitrary Lagrangian-Eulerian (ALE) description [3].

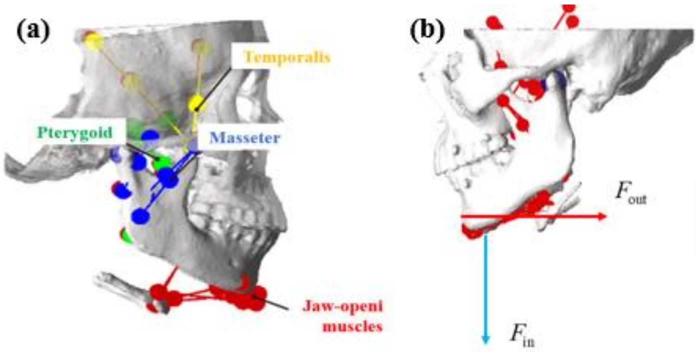

Figure 1: MMFT-musculoskeletal coupling multibody model. (a) Subject-specific mandibular musculoskeletal model; (b) Human-machine coupling model

Results and Conclusion

Numerical predictions for eight trismus patients demonstrated the feasibility of designing a personalized rehabilitation framework. Comparing the predicted jaw-opening functions with experimental measurements, the average root-mean-square error (RMSE) of the mandibular opening angle is -0.7 ± 0.7 deg, and the RMSE of the mandibular opening distance is -1.4 ± 1.1 mm. Moreover, we analyzed the influence of patient-specific characteristics on the optimized assisted forces exerted by intraoral and extraoral trainers; see Table 1. Patients #2 and #7 need intraoral and extraoral trainers because their opening magnitude was less than the threshold value (35mm) when the intraoral force was increased to its maximum. These patients might need a backward force for successful jaw-opening movement. Other patients only need an intraoral trainer if we choose 35mm of jaw opening magnitude as the threshold value of trismus. A subject-specific musculoskeletal multibody modeling method for patients with oral-maxillary was established, and an optimization design method to determine the assisted forces provided by the MMFT was proposed based on human-machine coupling analysis, providing an effective quantitative way for postoperative rehabilitation.

Table 1: Optimized assisted force and the corresponding jaw opening angle of each subject

Subject	Assisted force (N)		Maximal jaw opening (mm)	
(#)	Intraoral	Extraoral(N)	original	with MMFT
1	166.2	0	32.0	34.6
2	187.0	62.9	17.9	29.4
3	190.4	0	34.3	38.5
4	133.3	0	28.4	30.6
5	183.5	0	28.5	34.9
6	163.9	0	34.6	40.2
7	182.1	100.0	24.3	27.9
8	119.4	0	22.2	36.0
Average	165.7	20.4	27.8	34.0

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