

An Integrated, Dynamic Jaw and Laryngeal Model Constructed From CT Data

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Abstract. Computational modeling is an important tool for studying the structure and function of human anatomy in biomedicine. In this paper, a dynamic, anatomically accurate model of the human mandibular and laryngeal structures is presented along with a set of forward dynamic simulations that show consistency with previously published jaw modeling literature. Laryngeal motion during swallowing was also simulated and shows plausible upward displacement consistent with published recordings. A novel open source modeling platform, ArtiSynth, is described in the context of its use in the construction and simulation of the biomechanical jaw and larynx model.

1 Introduction

We have developed a high fidelity, dynamic, biomechanical model of the human jaw and laryngeal structures utilizing high resolution CT data for creating the model geometry and fast computational techniques for realtime simulation.

The jaw subsystem of our model is based upon previously published literature [1], in which a commercial mechanical simulation package, ADAMS, was used to construct a model of the human jaw. We have extended this work by incorporating the hyoid bone, cricothyroid complex, and associated muscles, which enables analysis of interactions between the jaw and laryngeal systems and other physiological tasks, such as swallowing [2] and vocal chord stretching [3]. Our model has been created using ArtiSynth [4], an open-source biomechanical modeling system which we have developed specifically for creating models of the human head and upper airway. ArtiSynth enables a modular approach to model construction, allows flexible incorporation of medical image data to inform model geometry, and provides significant improvements to usability and efficiency in creating forward dynamic simulations of the complex human mandibular system. It provides an extensible framework for connecting anatomical models, and we are integrating the jaw model with a 3D deformable tongue model in an effort to realize a complete, dynamic model of the human upper airway.

Computational modeling is an important tool for medical and scientific analysis of the human body. In particular, dynamic modeling allows for the study of the relationship between structure and function in physiological actions. The applications of craniomandibular modeling in biomedicine are significant and include the analysis of morphological and functional pathology, surgical planning and prediction, and the role of jaw posture during obstructive sleep apnea.

2 The Model

Our three-dimensional, dynamic jaw model (Figure 1) is rooted in published literature on biomechanics models of the human jaw. As such, it shares a number of commonalities with previously published models; however, we have made innovations in both modeling and simulation techniques that further the state of the art.

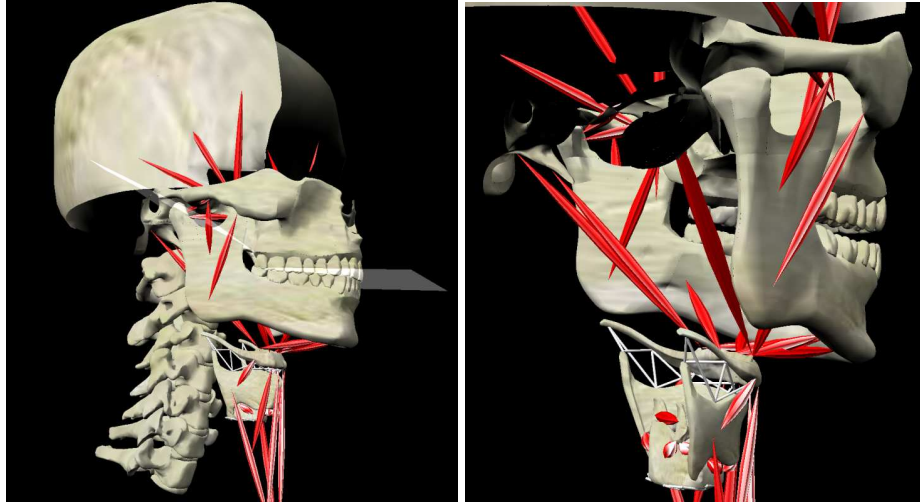


Fig. 1. The jaw model showing maxilla, mandible, laryngeal structures, and vertebrae, along with straight-line muscles and connective tissue.

2.1 Related Work

Mathematical models have been used extensively to study the biomechanics of the human musculoskeletal system (see [5] for review).

Computational models of the human jaw have been used primarily to study jaw function in speech and mastication. Various aspects of human mastication have been analyzed with biomechanical models including joint dynamics [6], bite forces [7], muscle dynamics [8], and passive muscle forces [9] [10]. Jaw motion in speech utterances have also been extensively studied with models [11].

Physics-based models represent the mandible bone as a rigid body, the temporomandibular joint as a mechanical joint or contact surface, and the jaw muscles as tension-producing straight-line actuators. The Peck jaw model [1] was developed with a commercial computer aided engineering (CAE) package ADAMS, and the Koolstra jaw models have been developed both with FORTRAN libraries [8] [12] and a commercial CAE package Madymo [6].

2.2 Model Construction

Our jaw and laryngeal model was constructed within ArtiSynth, a platform for three-dimensional biomechanical physics-based modeling and simulation targeted specifically at modeling orofacial and upper airway anatomy.

ArtiSynth provides a Java API that includes a set of base components (rigid bodies, particles, muscles, and finite element meshes) that can be extended and assembled to create complex biomechanical models. The jaw model was constructed with these model components given the appropriate geometric and dynamic properties described below.

Model Structure. The jaw substructure (Fig. 1) consists of a fixed rigid skull and a floating rigid mandible that are connected by two temporomandibular joints. These joints are modeled presently as rigid bilateral planar constraints, angled downward and forward, restricting the translation of the mandible to the planar surface, which approximates the curvilinear condylar path.

Bite contact is achieved by an additional rigid unilateral planar constraint located at the upper mid-incisor point and angled to the occlusal plane that generates reaction forces at bite points normal to this dental plane. Our rigid body constraint formulation does allow for general mesh-on-mesh multi-point contact between the maxilla and mandible teeth. This would be potentially useful for detailed studies of three-dimensional bite forces using high resolution surface scans of dental casts. It also is computationally feasible, since it has recently been shown that contact simulation has an expected complexity of $O(n)$, in the number of contacts, for systems with a fixed number of degrees of freedom [13].

The laryngeal substructure includes rigid structures for the hyoid bone and laryngeal cartilages, as well as a fixed sternum to anchor hyoid and thyroid depressor muscles and a fixed vertebrae column as a landmark for anatomy registration. Stiff spring meshes are used to connect the hyoid and thyroid, representing the thyrohyoid membrane, as well as to anchor the cricothyroid complex, representing longitudinal compliance of the trachea (see Fig. 5).

The jaw and laryngeal model is actuated by a set of 45 straight-line Hill-type [14] muscles. Muscle properties for jaw muscles, including maximum force magnitude, fibre-to-tendon length ratios, and passive tension characteristics, are based on published values (see Table 1 in [1]). Laryngeal muscle parameters have been scaled from mandibular muscle properties based on approximate muscle cross-sectional area. Muscle attachment sites have been taken from medical image data (see below). ArtiSynth allows for modular exchange of model components, therefore simpler (linear spring) or more complex (multipennate muscle model) muscle components can be easily interchanged with the standard Hill-type model.

We have used a mass of 200 g for the mandible as reported in [9], and have chosen masses 10, 24, and 23 g for the hyoid, thyroid, and cricoid respectively. Center of mass and inertia properties have been derived from the body mass and mesh geometry.

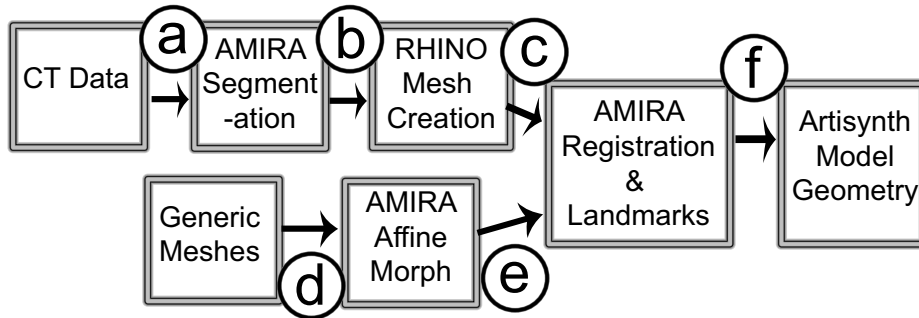


Fig. 2. Process diagram showing the creation of ArtiSynth Geometry from CT data: (a) raw voxel data, (b) segmented voxel mesh, (c) clean NURBS mesh, (d) generic mesh, (e) mesh shaped to specific anatomy, (f) registered meshes and muscle attachment location geometry.

Geometry Extraction From CT Data. Several previous models have used published average values to create their model geometry. We used high-resolution (0.4 mm cubic voxel), cone-beam CT scans of a 35 year-old male with normal craniofacial and dental anatomy as an anatomical template.

The process of creating ArtiSynth geometry from the CT data is diagrammed in Fig. 2 and involved the use of two additional software applications: Amira [15], which was used to segment the raw CT data, and Rhino [16], which was used to fit NURBS surfaces to the segmented data. The created structures include a mandible, maxilla, tooth crowns, palate, pterygoid fossae, zygomatic arches, articular eminentia and fossae, infratemporal fossa, postglenoid region, and hyoid bone. Generic meshes for tooth crowns, temporal bones, thyroid cartilage, cricoid bone, arytenoids and cervical vertebrae were morphed and registered using Amira to complete the full set of craniomandibular and laryngeal structures.

We used conventional descriptors to set bilateral landmarks for each muscle attachment [17] [18]. These muscles included the anterior, middle and posterior temporalis, deep and superficial masseter, superior and inferior lateral pterygoid, medial pterygoid, anterior and posterior digastric, posterior mylohyoid, stylohyoid, geniohyoid, thyrohyoid, and cricothyroid muscles. Arbitrary locations were chosen for the inferior sternal attachments of the sternohyoid and sternothyroid, and the intermediate tendon of the omohyoid.

With the file interface support built into ArtiSynth, we were able to directly import the anatomical meshes and muscle attachment data into our model.

3 Model Validation: Forward Simulation

The complexities of the human mastication system, including both kinematic and actuator redundancy [19], are such that forward-dynamics simulation is the most common type of analysis used to study jaw motion with computer models. The

trial and error process of tuning 18 muscle drive signals to achieve desired output motion was found to be tedious by previous authors because the input editing, simulation control, and output visualization tools were in separate programs [9]. In an attempt to create a more effective system for synthesizing jaw motion, ArtiSynth integrates both knobs and graphs into the simulation environment so that an experimenter can quickly tune inputs to achieve desired outcomes using a highly interactive direct manipulation interface.

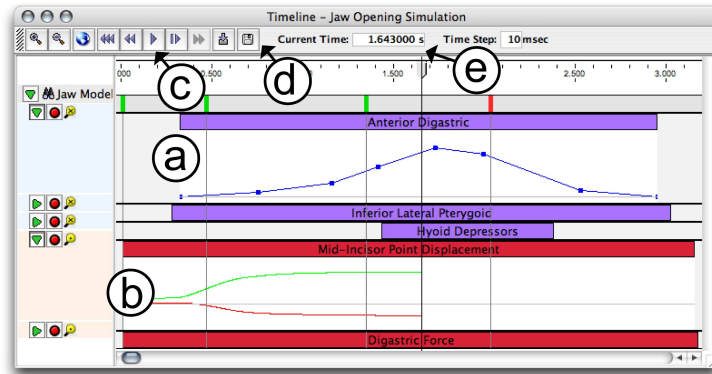


Fig. 3. The ArtiSynth Timeline controlling a jaw motion simulation: (a) input probe (i.e. muscle activation), (b) output probe (i.e. incisor position), (c) play controls, (d) save / load buttons, (e) current time cursor. Input probe data can be modified globally by stretching and translating probes or locally by directly dragging knot points.

ArtiSynth Simulation Timeline. The ArtiSynth Timeline integrates input data manipulation (*input probes*), simulation control, and output data extraction (*output probe*) in an intuitive interface that is designed on the metaphor of a timeline used in video editing (Fig. 3).

For jaw motion simulation, input probes provided piece-wise linear muscle drive trajectories to individual muscles and functional muscle groups. Output probes recorded position, velocity, and force data from the model. Simulations were created by scaling and translating input probes along the timeline to coordinate the timing of muscle excitation consistent with putative muscle drive. Appropriate output probes are activated to record output data for the duration of the simulation.

3.1 Results

To validate our model, we activated it with muscle excitations to create a series of motions and verified that the resulting jaw trajectories and postures corresponded to those reported in the literature for similar sets of muscle excitation.

The motions we chose to simulate include jaw rest posture, close, midline protrusion, and symmetrical opening. Predicted mid-incisor point position in the mid-sagittal plane for the jaw motion trials is shown in Fig. 4.

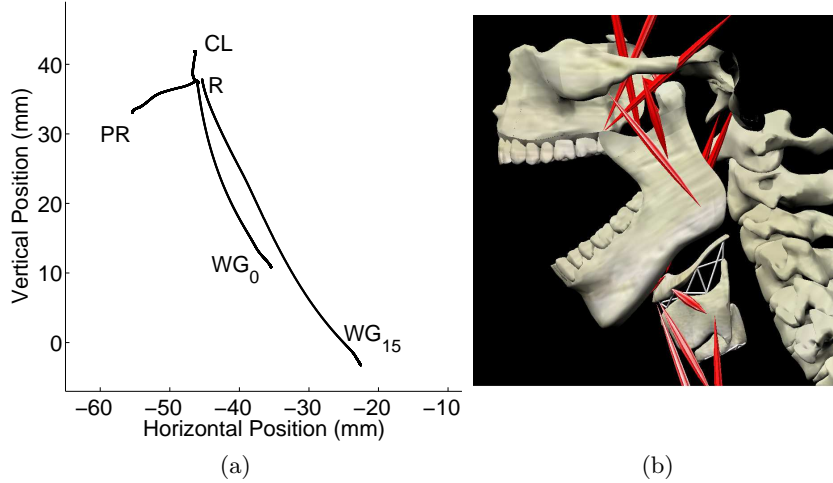


Fig. 4. (a) Plot of Mid-incisor point in mid-sagittal plane for four jaw postural tasks: rest position (R), close (CL), maximum protrusion (PR), opening to 35 mm wide gape with no head rotation (WG_0), opening to maximum gape (51 mm) with 15° backward head rotation (WG_{15}). (b) Graphic image of jaw at maximum gape, showing alignment of hyoid bone with lower edge of mandible during head rotation.

Postural Rest Position. In order to achieve a plausible interincisal separation of 3-5 mm at rest under gravity, our model required a steady-state activity of 0.04% maximum activation in the closer muscles (temporalis, masseter, and medial pterygoid). This agrees closely with similar findings in [9]. Increased activation of the closer muscles moved the mandible upward until it stopped rigidly at dental intercusp contact.

Wide Jaw Opening. Our model was driven to maximum jaw opening by full activation of the jaw opening muscles (anterior digastric, mylohyoid, and inferior lateral pterygoid) in two separate simulations. For comparison to [1] we used reduced passive muscle tension characteristics for the closers and achieved a maximum gape of 38 mm. For comparison to [20] we applied a 15° rotation to the head, and the model achieved a full wide gape opening of 50 mm. At wide gape, with a backward rotated head, the anterior tip of the hyoid body was aligned with the lower edge of the mandible, which is consistent with cephalometric measurements published in [21]. In both wide opening actions, the hyoid depressor muscles were activated to stabilize and slightly lower (1 mm) the laryngeal complex.

Protrusion. We simulated forward midline protrusion of the mandible by activating the inferior lateral pterygoid alone. The model achieved a self-limited forward protrusion consistent with normal behaviour.

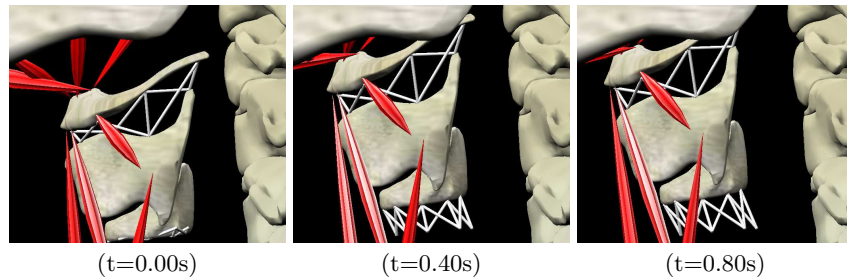


Fig. 5. Time-lapsed graphics of laryngeal complex elevation during simulated swallow.

Swallowing. We initiated swallowing by activating the temporalis, masseter, and medial pterygoid muscles to elevate and stabilize the mandible. Upward motion of the larynx occurred following excitation of the digastric, mylohyoid, geniohyoid, and stylohyoid muscles. Predicted magnitude and duration of upward and forward translation of the laryngeal complex (see Fig. 5) is consistent with previous literature on laryngeal elevation [2].

4 Future Directions

Inverse Dynamics Muscle Prediction. As stated in [19], the prediction of muscle recruitment patterns for the human mastication system is the dominant challenge in jaw movement analysis. We are working on an inverse-dynamics scheme to automatically drive the jaw model to follow a desired motion trajectory for speech and mastication tasks. Parameters of muscle force magnitude, jaw stiffness, and task speed are being studied to solve the actuator redundancy problem.

Connection with Deformable 3D Tongue Model. We are also working on developing a dynamically interconnected, muscle driven, rigid body jaw-larynx and finite-element tongue model. Our preliminary model integration has a rudimentary implementation of this connection. We suggest this is an extremely rich direction for biomechanics modeling as the tongue body and extrinsic muscles have a major effect on laryngeal positioning, and the jaw-tongue-larynx system captures the predominant contributors to the fundamental human functions of feeding, breathing, and speaking.

5 Conclusion

We have presented our jaw and laryngeal modeling efforts within the context of our innovative biomechanical simulation software platform, ArtiSynth. We have

presented preliminary results of jaw motion simulations that agree with the validation studies performed in previously published literature. Our model extends previous work in physics-based, muscle-driven jaw modeling through advancements in computational techniques and an increased anatomical complexity due to the addition of dynamic laryngeal structures. The medical applications of this computational model are numerous and we are currently working on integrating this model with soft tissue models of the tongue and larynx.

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