

A 3D DYNAMIC BIOMECHANICAL SWALLOWING MODEL FOR TRAINING AND DIAGNOSIS OF DYSPHAGIA

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ABSTRACT

We present a three dimensional (3D) biomechanical swallowing model of the oral, pharyngeal and laryngeal (OPAL) muscles and structures. Such modeling may aid in predicting functional outcomes in swallowing disorder (i.e. dysphagia) treatment and could significantly reduce therapy time. Our physics-based model captures the OPAL anatomical geometries and kinematics from 2D animations constructed from video-fluoroscopic (VF) evaluations of real patient swallowing events using the Modified Barium Swallow Impairment Profile (MBSImP™©) protocol. We investigate the upper airway dynamics with these clinically accurate kinematics and geometries. We use smoothed particle hydrodynamics (SPH) modeling of water-like and nectar-like fluid boluses, simulated within an airway-skin mesh that encompasses our modeled 3D structures and follows the model's dynamics. We demonstrate that our model can simulate a bolus in a manner consistent with clinical data, and can robustly handle fluid with different viscosity incorporating a wide range of moving boundary conditions.

Index Terms— biomechanical modeling, dysphagia, swallowing, smoothed particle hydrodynamics.

1. INTRODUCTION

Swallowing is a complex physiological process during which liquid and food boluses are propelled from the mouth to the stomach through positive pressures applied to the bolus tail through the oral cavity, pharynx and esophagus. Airway closure must be coordinated with bolus transport to protect the airway and prevent aspiration. Swallowing is commonly described as occurring in phases (oral, pharyngeal, esophageal) though, such characterization does not sufficiently capture the overlap and interdependence of structural movements relative to bolus flow that are essential for normal bolus clearance and airway protection [1]. A healthy swallow involves an intricate neuromotor function that requires coordinated motion of the oral, pharyngeal and laryngeal (OPAL) muscles and structures. Swallowing difficulties, clinically termed as dysphagia, result from

abnormalities in the nervous system or any disruption to structure(s) involved in the swallowing process. Serious adverse consequences of dysphagia include malnutrition, dehydration and aspiration pneumonia, a leading cause of death in the elderly [1]. Dysphagia patients' suffering also extends to reduced social and psychological function [2] as eating and drinking are important aspects of quality of life. Proper diagnosis, management and treatment of dysphagia are thus critical for optimizing patient health and wellbeing.

Dysphagia treatments are normally tailored to patient-specific impairments identified through a standardized swallowing assessment process, for which modified barium swallow (MBS) studies are currently the standard clinical practice [3]. In an MBS study, the patient is asked to swallow a standardized set of barium liquid and food bolus consistencies since the properties of the bolus have been shown to affect the swallowing dynamics [3][4]. An MBS study provides real-time visualization of bolus flow relative to anatomical movements of the oral, pharyngeal and laryngeal regions. Such visualization allows clinicians to evaluate the nature and severity of underlying swallowing impairments, and the presence and timing of aspiration. Martin-Harris et al. [3] proposed a standardized Modified Barium Swallow Impairment Profile (MBSImP™©) protocol to quantify different swallowing impairments, and to establish favourable inter- and intra-rater variability between trained clinicians. MBSImP™© reliability training includes video-fluoroscopic (VF) data and clinically validated animations of 17 physiologic swallowing impairments.

The mechanism leading to the propagation of the bolus through the pharynx is quite complex. Some studies used simplified geometries to study the bolus flow and swallowing dynamics [5], but a sufficiently realistic and detailed geometrical model is crucial to obtain clinically meaningful results from a biomechanical simulation. In this paper, we propose a 3D biomechanical model of the OPAL complex capable of simulating swallowing. Our model is based on the geometric and kinematic information derived from the swallowing animations used to train clinicians on using the MBSImP™© protocol and these animations are validated for clinician training. Our 3D model allows for a prospective view of the swallowing events compared to the current 2D

sagittal and anterior-posterior images captured by VF. Our physics-based model is also capable of simulating the bolus in a manner that is consistent with the 2D animations used in MBSImP™ training. Such physics-driven simulation would enable clinicians to alter the timing and nature of swallowing movements and to visualize the effects of these simulated interventions on bolus clearance and airway protection, further enhancing the MBSImP™ utility.

2. MATERIALS AND METHODS

The proposed modeling framework is summarized in Fig. 1. In section 2.1 we describe the model’s geometry and derive the kinematics from input data, i.e. the 2D animations and corresponding VF images. In Section 2.2 we describe how we used the derived kinematics to drive our 3D biomechanical model. In section 2.3 we describe the embedding of a watertight airway-skin mesh that deforms with the model dynamics that we use to simulate a fluid bolus based on an SPH formulation described in section 2.4.

2.1. Geometry and Kinematics

The inputs to our modeling framework are the 2D MBSImP™ animations created from VF images capturing real swallowing events. The animations were created using an underlying 2.5D geometric model (i.e. only a lateral side model is used) with shape changes specified over time for the animation. The swallowing components in the 2D animation video, as illustrated in Fig. 1(a) and Fig. 3(b), are shown using only the mid-sagittal cut plane as the VF is performed in that plane. Therefore, to create full 3D geometries of the

oropharyngeal structures in our model (tongue, hard and soft palate, teeth, arytenoid, hyoid, jaw, thyroid, cricoid, epiglottis and trachea), we mirror the components around the mid sagittal plane. We repeat this for each of the time frames of normal swallowing animation to generate a sequence of surface meshes for all the swallowing components.

2.2. Kinematically-Driven Biomechanical Model

We build our 3D biomechanical model using the ArtiSynth (www.artisynth.org), a simulation toolkit that supports combined multi-body and finite element simulation [6]. We simulate our model as a mixture of rigid bodies with 6-degrees of freedom (DOF) frames and finite element models (FEMs) with 3-DOF for each node within the volumetric body. We model the bony structures (jaw and teeth) as rigid bodies and simulate the soft structures (tongue and soft palate), which exhibit large deformations during swallowing, as FEMs with tetrahedral elements. Furthermore, we scale our model by matching the tongue dimensions to the average human tongue measurements reported in [7]. This is important since morphometrically realistic models are necessary to produce meaningful results from a physics based model. Fig. 2 shows the different components of our biomechanical model. To drive our model with the clinically accurate kinematics extracted from our input data, we update the positions of the FEM surface nodes at each time frame with the vertices of the corresponding surface mesh sequence extracted earlier from the animation (discussed in Section 2.1). By doing so, we propagate the kinematics and accurate timings of the swallow events into our coupled biomechanical model.

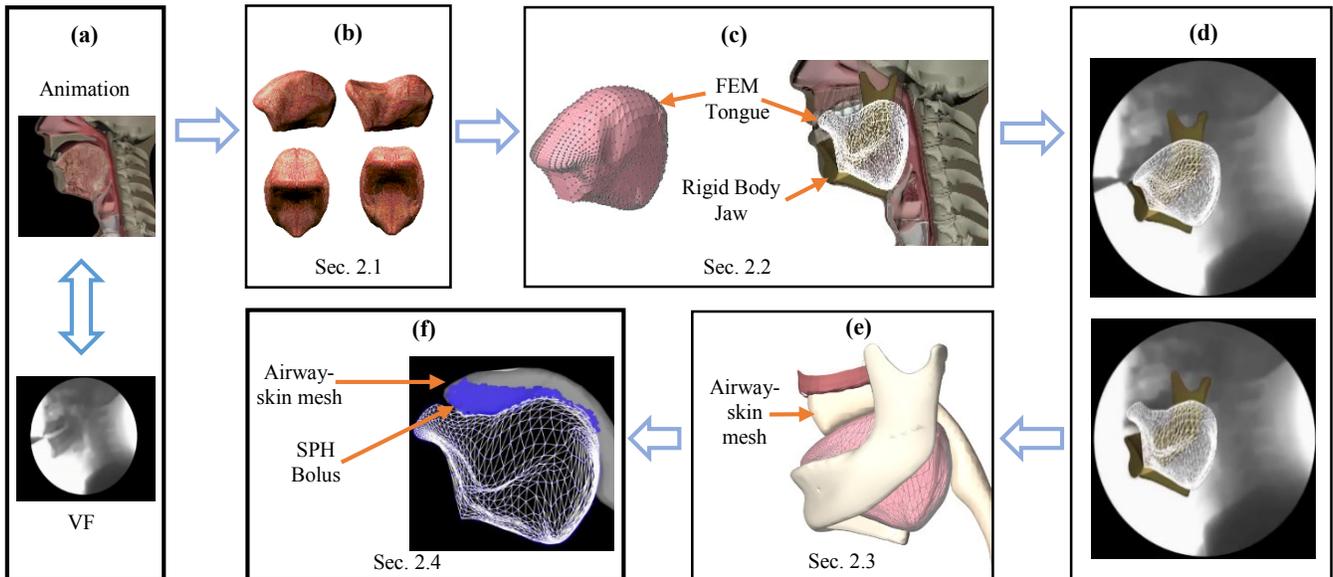


Fig. 1. Overview of our proposed model generation framework: (a) Input to our model: swallowing animation (top) and corresponding VF (bottom). (b) Surface geometry and kinematics extracted from animations (illustrated only for tongue). (c) Volumetric geometries generated from surface geometries in (b) superimposed on the 2D animation video. (d) Our model superimposed on the VF of a normal swallow. (e) Airway-skin mesh attached to the coupled model. (f) Output of our model: simulated SPH fluid bolus inside the airway-skin mesh.

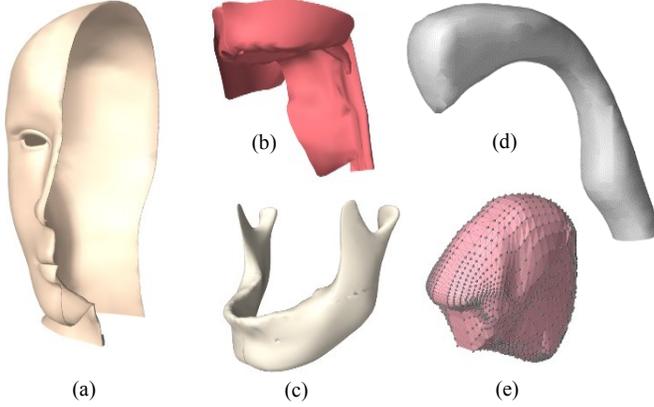


Fig. 2. Components of our biomechanical swallowing model. (a) Face, (b) hard and soft palate, (c) jaw, simulated as rigid body frames with 6-DOF. (d) Airway-skin mesh representing the mucosa lining of the mouth and throat. (e) Tongue simulated as an FEM with 3-DOF for each node.

2.3. Deformable Airway Geometry

We define our airway as the empty space starting from the lip closure through the oral cavity ending at the inferior pharynx. The size, shape and volume of the airway are greatly influenced by surrounding structures, and thus change significantly during the swallowing process. Our airway model is: 1) influenced by all dynamic components, e.g. FEMs, and rigid bodies, 2) deforms with the underlying model dynamics, and 3) binds and holds the bolus throughout the swallowing motion.

We manually create an airway model using a watertight surface mesh that represents the ‘airway-skin’ to fit the model at the initiation of a swallow ($t = 0$). We use the unified skinning approach proposed in [8] to couple the airway-skin mesh with the model’s dynamics. In ArtiSynth, different components, like rigid bodies and FEMs, can be attached by making the position q_a of an attached component to be a function of a master component position q_m , where there may be more than one master component that influences q_a . The collective state of the attached component is given by $q_a = f(q_m)$. The position of each vertex of the airway-skin mesh q_{as} is dependent on q_m , namely the dynamic components in the model, and is given by:

$$q_{as} = q_{as0} + \sum_{i=1}^M w_i f_i(q_m, q_{m0}, q_{as0}) \quad (1)$$

where q_{as0} is the initial position of the airway-skin point, q_{m0} is the collective rest state of the q_m , w_i is the skinning weight associated with the i^{th} master component, and f_i is the corresponding bending function. The resulting airway-skin provides a two-way coupling that allows forces to be transmitted back and forth between the skin mesh and underlying dynamic components. This bi-directional

coupling is the main motivation behind the use of FEMs in our model. Although we are kinematically driving our model, the bi-directional coupling of FEMs, provided by the airway-skin, supports further development of our model into an integrated muscle-driven biomechanical model, in which muscle fibers are embedded in the FEMs and activated to allow for a desired swallowing movement.

2.4. SPH Simulation

SPH is a Lagrangian fluid domain representation where a fluid is represented as a large number of discrete particles. This surface-free representation can incorporate irregular moving boundaries for the simulated fluid and allows for splitting and merging of the fluid model without re-meshing. These advantages make SPH convenient for our swallowing simulation. We use the SPH formulation described in [9] that solves the incompressible Navier-Stokes equations for a Lagrangian system. Using this formulation, the fluid bolus model is simulated inside the airway-mesh (derived in Section 2.3). This airway skin-mesh acts as the deforming boundary for SPH formulation. As the airway-mesh deforms due to the change in the OPAL geometry during a swallow, it creates forces on the fluid particles. These particles then move to represent the bolus movement. The simulation is advanced using small time steps to maintain simulation stability. While the airway-mesh supports bi-directional coupling, we only propagate forces from the 3D model to the fluid particles, as we are modeling the kinematic trajectories of the 3D surfaces as they move rather than the influence the fluid has on the dynamic structures.

3. RESULTS

We simulated the oral dynamics of swallowing, where the bolus is propelled from the oral cavity into the pharynx, with a kinematically-driven rigid-body jaw model, a stationary rigid-body hard palate model, and a kinematically-driven FEM of the tongue. The initial inter-particle spacing between the SPH particles was 2 mm with a total of 2594 particles simulating 20.75 mL of fluid. Two simulations were performed with different viscosities: one with a thinner liquid (water-like, 8×10^{-3} Pa) and the other with a thicker liquid (nectar-like, 1×10^{-2} Pa). The density ρ for both of the simulations was initialized at 1000 kg/m^3 and a no slip condition was applied to simulate solid walls. Gravitational force was applied from a superior to inferior direction, equivalent to someone swallowing in an upright position.

For both thin and thick fluids, the airway-skin was able to contain the bolus and allowed it to flow from the oral cavity towards the pharynx. Qualitative observations indicate that the water-like bolus escapes the oral cavity with greater velocity than the nectar-like bolus, for the same set of kinematics. This result is intuitive since we expect our model to simulate significantly different positions and track the mass of the bolus, when the viscosity of the fluid is changed.

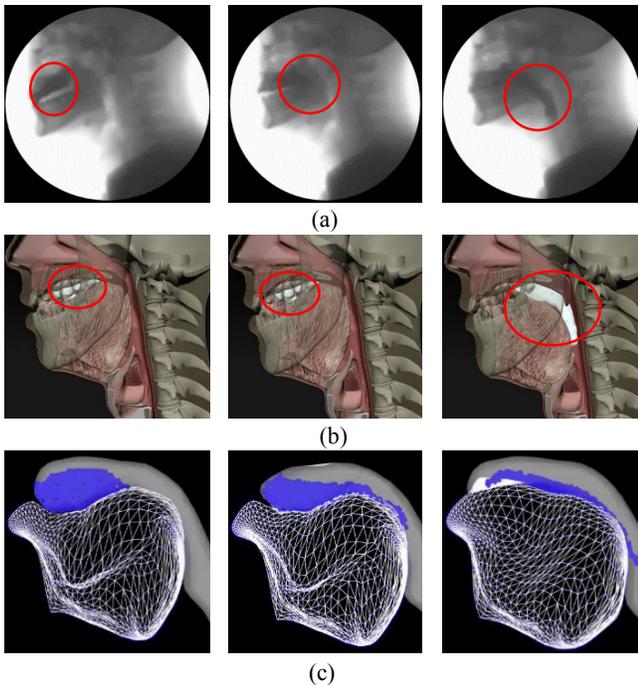


Fig. 3. Comparing simulation results: (a) VF frames of a normal swallow (bolus indicated by the red circles appears dark), (b) 2D swallowing animation frames (bolus shown in white), and (c) our simulated SPH fluid bolus (in blue). Our 3D model is able to track and emulate the bolus from the VF and animation input data.

4. CONCLUSIONS

We presented a 3D biomechanical swallowing model of the oral, pharyngeal and laryngeal (OPAL) muscles and structures. Our contributions is three-fold: 1) Establishing a platform to propagate the geometry and swallowing kinematics from MBSImP™ training animations to a physics-based biomechanical model; 2) Driving the physics-based biomechanical model with clinically-validated timings of swallowing events, acquired using the kinematics from the animations; 3) Simulating a fluid bolus using SPH providing visualizations of structural movements and changes in the bolus flow with different bolus consistencies.

We show that the movement of our simulated bolus, which allows for 3D visualization of swallow motion during oral transport, is qualitatively similar to that of the clinical data (Fig. 3). The 3D perspective visualization would provide a trainee clinician better insight into swallowing dynamics. We believe that, our model can potentially become a 3D interactive platform for MBSImP™ training. In this paper, we built our model by enforcing symmetry, as the aim was to investigate the feasibility of using SPH to simulate a fluid bolus in a physics-based 3D model driven by kinematics derived from clinical data. Our model can however be extended to allow for subject-specific geometry which could lead to improved identification of physiologic treatment

targets and enable testing of intervention strategies on the model rather in-vivo trial and error. Furthermore, ArtiSynth supports a muscle driven FE model where the muscle fibres embedded in the model can be activated to follow a desired movement. For the scope of this work, we drive our FE models kinematically. It is possible to use the inverse modeling capability of ArtiSynth to estimate the virtual muscle activation from the kinematics of our implemented FE tongue for a normal and impaired swallow. This can give a deeper comprehension of the swallowing physiology from a neurological perspective and aid dysphagia diagnosis.

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