Development of a 3D Biomechanical Swallowing Model for Dysphagia Training
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Introduction
Dysphagia (swallowing abnormalities) is a clinical symptom commonly associated with stroke, multiple sclerosis, cancer and other diseases that impede normal function of oropharyngeal nerves and muscles. Modified Barium Swallow (MBS) studies provide a 2D visualization of the bolus transport mechanisms which is crucial for treatment and diagnosis of dysphagia. We present a 3D biomechanical model of the oral, pharyngeal and laryngeal (OPAL) complex built from standardized clinical training data used in the MBSImP™© protocol [1]. We show that our model can simulate a bolus using Smoothed Particle Hydrodynamics (SPH) [2] technique in a manner consistent with the MBSImP™© training data while providing 3D perspective visualization into the swallowing dynamics and bolus transport mechanism. Furthermore, our model offers the additional flexibility of simulating boluses of different consistencies to explore ‘what-if’ scenarios that may prove useful for planning dysphagia treatment.

Methods
We create our model geometries from the 2D animations that were used to produce the MBSImP™© training set. We mirror the swallowing components around the mid-sagittal plane to get full 3D geometries and repeat this for all time frames to capture the kinematics. We build our biomechanical model using ArtiSynth (www.artisynth.org) [3] and model the softer oropharyngeal structures (e.g. tongue, uvula, pharyngeal wall, arytenoid) undergoing non-rigid deformation during a swallowing motion as finite element models (FEM). We model bony structures (e.g. hard palate, jaw) as rigid bodies with limited degree of freedom. We use the derived kinematics to drive our model. We fit a watertight airway mesh to the model at the initiation of a swallow and deform the airway mesh with the model dynamics using a unified skinning approach [4]. To simulate the bolus inside the airway-skin mesh we use smoothed particle hydrodynamics (SPH) by solving incompressible, viscous, iso-thermal Navier-Stokes equations. Our deforming airway-skin applies force on the SPH particles that, as a result, move to represent the bolus movement.

Results
We simulated 5mL of bolus with density $\rho$ initialized at 1000 kg/m$^3$. Furthermore, we simulated fluids with 4 different dynamic viscosities each representing a standard category of liquid defined by the National Dysphagia Diet Task (NDD) force; thin (1-50cP), nectar-like (51-350cP), honey-like (351-1750cP), and spoon-thick (>1750cP). Qualitative observations indicate that the thinnest (water-like) bolus escapes the oral cavity faster than the thickest (spoon-thick) one as expected during a real swallow.

Comparing same instances of a swallowing event: VF (top row), swallowing animation (middle row) and simulated (honey-thick) bolus with viscosity of 1000cP (bottom row).

Conclusions
We proposed a 3D biomechanical model consisting of oropharyngeal structures and simulated a bolus qualitatively similar to the clinical training data used in the MBSImP™© protocol. We also simulated boluses of different consistencies to investigate that our model can simulate significantly different bolus positions and track the mass of the bolus as the viscosity is changed. By interactively changing views and altering bolus consistencies, we anticipate that clinicians may be able to gain deeper understanding of the complex dynamics involved in swallowing to facilitate training and treatment planning.

References