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Numerical simulation of interaction between organs and food bolus during swallowing and aspiration

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ABSTRACT

The mechanism of swallowing is still not fully understood, because the process of swallowing is a rapid and complex interaction among several involved organs and the food bolus. In this work, with the aim of studying swallowing and aspiration processes noninvasively and systematically, a computer simulation method for analyzing the involved organs and water (considered as the food bolus) is proposed. The shape and motion of the organs involved in swallowing are modeled in the same way as in our previous study, by using the Hamiltonian moving particle simulation (MPS) method and forced displacements on the basis of motion in a healthy volunteer. The bolus flow is simulated using the explicit MPS method for fluid analysis. The interaction between the organs and the bolus is analyzed using a fluid-structure coupling scheme. To validate the proposed method, the behavior of the simulated bolus flow is compared qualitatively and quantitatively with corresponding medical images. In addition to the healthy motion model, disorder motion models are constructed for reproducing the aspiration phenomenon by computer simulation. The behaviors of the organs and the bolus considered as the food bolus in the healthy and disorder motion models are compared for evaluating the mechanism of aspiration.

1. Introduction

Swallowing of meals is one of the greatest pleasures for humans as well as a requisite for sustaining human life. In developed nations, an increase in cases of aspiration pneumonia, which is caused by swallowing disorder, has become a serious problem [7,11]. However, the biomechanics of swallowing and aspiration is still not fully understood because the process of swallowing is a rapid and complex interaction between the food bolus and the involved organs, i.e., the tongue, palate, pharynx, esophagus, and larynx. Recently, 320-row area detected computed tomography (ADCT) and real-time magnetic resonance imaging (MRI) were applied to the swallowing process [12,22,23], and the three-dimensional dynamic morphologies of the organs and the food bolus that had never been observed by ordinary videofluorography (VF) were obtained. However, the temporal and spatial resolutions of these techniques are insufficient to clearly explain the detailed biomechanics of the swallowing and aspiration. In addition, practical swallowing examinations conducted on patients with swallowing disorders cause several physical loads and pose a risk of aspiration to the patients.

Simulation of swallowing enables quantitative and systematic virtual examinations of swallowing under detailed control of the organ motions and the physical properties of the food bolus. Simulations have previously been conducted with focus on a particular organ by using simplified shape and motion models with the aim of thoroughly investigating some of the swallowing mechanisms [4,8,20,21]. For elucidating the differences between healthy swallowing and aspiration, realistic simulation models representing the entire swallowing process [9,10,13,14] are also necessary. Kikuchi et al. [14] presented a model for simulating the behavior of all organs involved in swallowing on the basis of CT and VF images. However, in their study, they did not analyze food bolus flow. Comparison of food bolus flows between VF images and simulation results is necessary to confirm the validity of the simulation results.

In the present study, a computer simulation model of the food bolus and the organs is proposed for investigating the swallowing and aspiration processes noninvasively and systematically. The shape and motion of the tongue, palate, pharynx, esophagus, and larynx were modeled based on the CT and VF images acquired from a healthy volunteer, as was done in our previous study [14]. The behavior of the organs was analyzed using the Hamiltonian moving particle simulation (MPS) method [29] as this method is suitable for analyzing a

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hyperelastic material under a large deformation. The food bolus is analyzed as a fluid flow using the explicit MPS method [24] because this method is suitable for representing the food bolus flow including free surfaces. The interaction between the organs and the food bolus is analyzed using a coupling scheme [28]. This coupling scheme was designed to retain the interaction forces of structure and fluid symmetry; it was verified via simulations of dam-break flow on elastic walls. For the validation of the simulation model proposed in this study, the food bolus flow during a healthy swallowing process is compared between the simulation results and the VF images. The velocity profile of the food bolus in the simulation results is investigated to elaborate the behavior of the food bolus more thoroughly in comparison to the VF images.

In addition, to reproduce the aspiration phenomena, disorder motion models are constructed by impairing some laryngeal movements from the healthy motion model. Such a systematic case study with a single subject is impossible if simulation methods are not employed. The simulation results for the behaviors of the food bolus and the organs in the healthy and disorder motion models are compared carefully to investigate the mechanism of aspiration.

2. Numerical methods

2.1. Structural analysis

As done in our previous study [14], an organ is modeled as a hyperelastic body by using the following equations:

$$\rho\frac{\partial \mathbf{v}}{\partial t} = \mathbf{f}_{\text{elastic}} + \mathbf{f}_{\text{artificial}} + \mathbf{f}_{\text{viscous}} + \mathbf{f}_{\text{contact}} + \mathbf{f}_{\text{interaction}}, \tag{1}$$

where ρ [kg/m^3] and $\mathbf{v}$ [m/s] denote the density and velocity, respectively; and the right-hand-side terms (from the left) denote the elastic, artificial potential, viscous, contact, and fluid interaction forces, respectively, applied per unit volume [N/m^3]. The organ is discretized into particles with initial diameter l_0 [m].

2.1.1. Hamiltonian MPS method for analysis of elastic force

The governing equation of elastodynamics is expressed as follows:

$$\rho\frac{\partial \mathbf{v}}{\partial t} = -\frac{\partial W}{\partial \mathbf{r}}, \tag{2}$$

where W [J/m^3] denotes the strain energy density function, and $\mathbf{r}$ [m] denotes the relative position.

Let $\mathbf{r}_{ij} = \mathbf{x}_j - \mathbf{x}_i$ and $\mathbf{r}_{ij}^0 = \mathbf{x}_j^0 - \mathbf{x}_i^0$ be the present and initial positions, respectively, of particle j relative to particle i. The weight function w_{ij}^0 [-] is defined as follows:

$$w_{ij}^0\left(|\mathbf{r}_{ij}^0|\right) = \begin{Bmatrix} \dfrac{r_{\text{e,elastic}}}{|\mathbf{r}_{ij}^0|} - 1, & \left(0 < |\mathbf{r}_{ij}^0| < r_{\text{e,elastic}}\right) \\ 0, & \left(r_{\text{e,elastic}} \le |\mathbf{r}_{ij}^0|\right) \end{Bmatrix}, \tag{3}$$

where $r_{e,\text{elastic}} = 1.5 l_0$ [m] is the effective radius. In the Hamiltonian MPS method [29], the elastic force [N/m^3] is derived from Eq. (2) as follows:

$$\mathbf{f}_{i,\text{elastic}} = \sum_j \left(\mathbf{F}_i \mathbf{S}_i \mathbf{A}_i^{-1} \mathbf{r}_{ij}^0 + \mathbf{F}_j \mathbf{S}_j \mathbf{A}_j^{-1} \mathbf{r}_{ij}^0\right) w_{ij}^0, \tag{4}$$

$$\mathbf{A}_i = \sum_j \mathbf{r}_{ij}^0 \otimes \mathbf{r}_{ij}^0\, w_{ij}^0, \tag{5}$$

where $\otimes$ denotes the tensor product, $\mathbf{F}_i$ [-] denotes the deformation gradient tensor, $\mathbf{S}_i$ [Pa] denotes the second Piola–Kirchhoff stress tensor, and $\mathbf{A}_i$ [m^2] denotes the normalized tensor.

2.1.2. Constitutive law

In this study, the following Mooney–Rivlin model is applied:

$$W = C_1^{\text{MR}}(\tilde{I}_1 - 3) + C_2^{\text{MR}}(\tilde{I}_2 - 3) + D_1(J - 1)^2, \tag{6}$$

where C_1^{MR} [Pa], C_2^{MR} [Pa], and D_1 [Pa] are the material constants mentioned in detail at Section 4; J [-] is the third invariant of $\mathbf{F}$; and $\tilde{I}_1$ [-] and $\tilde{I}_2$ [-] are, respectively, the first and second reduced invariants of the right Cauchy–Green deformation tensor. Further, the zero-strain Young's modulus [Pa] is derived as follows:

$$E = 6(C_1^{\text{MR}} + C_2^{\text{MR}}). \tag{7}$$

2.1.3. Artificial potential, viscous, and contact forces

To suppress the spurious singular modes caused by application of the Hamiltonian MPS method, an artificial potential force $\mathbf{f}_{i,\text{artificial}}$ [N/m^3] is employed [17]. Moreover, to stabilize the calculation of the dynamic analysis, the particle velocity is attenuated using a viscous force $\mathbf{f}_{i,\text{viscous}}$ [N/m^3] in the standard MPS method [18]. The contact force $\mathbf{f}_{i,\text{contact}}$ [N/m^3] was calculated using a penalty method that uses metaballs [15]. In this method, the penetration of a particle into the wall and the unit normal vector of the wall are calculated using the metaball function.

The verification and validation of this structural analysis method have been performed in our previous studies by analyzing the uniaxial compression [15].

2.2. Fluid analysis

The food bolus is also discretized into particles with initial diameter l_0 [m] and simulated using the explicit MPS method [24]. The governing equations are the continuity equation and the Navier–Stokes equation:

$$\frac{D\rho}{Dt} + \rho\, \text{div}\, \mathbf{v} = 0 \tag{8}$$

and

$$\frac{D\mathbf{v}}{Dt} = -\frac{1}{\rho}\nabla P + \nu\nabla^2\mathbf{v} + \mathbf{g} + \frac{1}{\rho}\mathbf{f}_{\text{surface tension}}, \tag{9}$$

where P [Pa], ν [m^2/s], $\mathbf{g}$ [m/s^2], and $\mathbf{f}_{i,\text{surface tension}}$ [N/m^3] denote the pressure, dynamic viscosity, gravity acceleration, and the force acting owing to surface tension per unit volume, respectively.

The explicit MPS method assumes minute compressibility. In the method, the pressure is evaluated using the following function corresponding to the equation of state:

$$P_i = \begin{Bmatrix} c^2\rho\dfrac{n_i - n^0}{n^0}, & (n_i > n^0) \\ 0, & (n_i \le n^0) \end{Bmatrix}, \tag{10}$$

where n_i and n^0 are the present and initial particle number density. The speed of sound c [m/s] is determined to maintain the Mach number less than 0.2 to conserve the volume of fluid. The leading edge position of collapse of a water column shows good agreement with that obtained using the semi-implicit MPS and VOF methods, thus verifying the explicit MPS method [24].

The following weight function is utilized in this study:

$$w_{ij}\left(|\mathbf{r}_{ij}|\right) = \begin{cases} \dfrac{r_{\text{e,fluid}}}{|\mathbf{r}_{ij}|} + \dfrac{|\mathbf{r}_{ij}|}{r_{\text{e,fluid}}} - 2\,, & \left(0 < |\mathbf{r}_{ij}| < r_{\text{e,fluid}}\right) \\ 0\,, & \left(r_{\text{e,fluid}} < |\mathbf{r}_{ij}|\right) \end{cases}, \tag{11}$$

with the effective radius $r_{e,\text{fluid}} = 2.5 l_0$ [m]. The pressure gradient is discretized as follows [30]:

$$\nabla P_i = \left[\sum_j \left(\frac{\mathbf{r}_{ij}}{|\mathbf{r}_{ij}|} \otimes \frac{\mathbf{r}_{ij}}{|\mathbf{r}_{ij}|} w_{ij}\right)\right]^{-1} \cdot \left[\sum_j \frac{\mathbf{r}_{ij}}{|\mathbf{r}_{ij}|} \otimes \frac{P_i + P_j}{|\mathbf{r}_{ij}|} w_{ij}\right]. \tag{12}$$

The surface tension of the food bolus and the contact angles between the food bolus and the organ surface are modeled as interparticle potential forces [16] as follows: