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Development of a numerical simulator of human swallowing using a particle method

(Part 1. Preliminary evaluation of the possibility of numerical simulation using the MPS method)

KAMIYA Tetsu, PhD, TOYAMA Yoshio, MICHIWAKI Yukihiro, DDS, PhD, KIKUCHI Takahiro

Abstract—**The aim of the present study was to evaluate the possibility of numerical simulation of the swallowing process using a moving particle simulation (MPS) method, which defined the food bolus as a number of particles in a fluid, a solid, and an elastic body. In order to verify the accuracy of the simulation results, a simple water bolus falling model was solved using the three-dimensional (3D) MPS method. We also examined the simplified swallowing simulation using a two-dimensional (2D) MPS method to confirm the interactions between the liquid, solid, elastic bolus, and organ structure. In a comparison of the 3D MPS simulation and experiments, the falling time of the water bolus and the configuration of the interface between the liquid and air corresponded exactly to the experimental measurements and the visualization images. The results showed that the accuracy of the 3D MPS simulation was qualitatively high for the simple falling model. Based on the results of the simplified swallowing simulation using the 2D MPS method, each bolus, defined as a liquid, solid, and elastic body, exhibited different behavior when the organs were transformed forcedly. This confirmed that the MPS method could be used for coupled simulations of the fluid, the solid, the elastic body, and the organ structures. The results suggested that the MPS method could be used to develop a numerical simulator of the swallowing process.**

I. INTRODUCTION

Nowadays, aging advances in many developed countries. The cause of unexpected death of elderly people is mainly aspiration-related pneumonia [1]. Thus, the emergence of swallowing difficulties is part of the aging process. To improve the quality of life for elderly people, there is an emphatic need for research and development on the safety of food and the mechanisms of swallowing disorders.

Previously, the determination of the safety food for people with swallowing disorders or patients with swallowing difficulty involved the testing of food, considered to be appropriate, by trial and error. This method risked choking on food bolus or aspiration pneumonia in elderly people and patients. In this study, we conducted a preliminary examination to simulate the swallowing action, which involves interaction among organs and foods. In particular, we focused on the moving particle simulation (MPS) method, which treats a food bolus as particles.

Several studies of the swallowing action have been carried out. In a medical-image-based simulation, researchers estimated the forces from organs and the movement of the food bolus using VF images [2]. The accurate 3D finite element method (FEM) models have considered the forced transformations in a coupled simulation of the organs, the liquid bolus, and splashes of the liquid during calculations [3]. The mainstream numerical simulations of the swallowing action are FEM, the MPS method, which can calculate the fluid splashes and large transformations have been used recently. The MPS method was proposed to simulate the swallowing action [4], but the validity of the simulation was not evaluated. In another case study, the 2D MPS method was used based on a consideration of the movements of organs in VF images of the swallowing action [5]. As previously suggested, 3D MPS method and a coupled simulation of the organs and the food bolus would be preferable to describe the flow configuration around the epiglottis.

It is not clear whether the MPS method used to simulate the swallowing action describes a 3D flow pattern with liquid splashes around the epiglottis or whether it considers the coupled simulation of organ movements and the liquid bolus.

The aim of this study is to evaluate the possibility of using the MPS method to define a fluid as particles during the simulation of the swallowing action. The MPS method could then simulate large transformations of the liquid surface and the coupled calculation of liquids and organs using the solid and elastic components. The MPS method could then be used as a swallowing simulation to estimate the swallowing action and to determine better food properties for people with swallowing disorders or patients with swallowing difficulty.

II. THEORY

A. Governing equations

The MPS method developed by Koshizuka *et al.* [6] is a well-known method for studying a free surface or large transformations of a fluid. The governing equations are expressed using the conservation laws of mass and momentum:

T. Kamiya is with Meiji Co., Ltd., Odawara, Japan (corresponding author; phone: +81 465-37-3697; fax: +81 465-37-3594; e-mail: tetsu.kamiya@meiji.com).

Y. Toyama is with Meiji Co., Ltd., Odawara, Japan (e-mail: yoshio.toyama@meiji.com).

Y. Michiwaki is with Musashino Red Cross Hospital, Musashino, Japan (e-mail: yukirom@musashino.jrc.or.jp).

T. Kikuchi is with Musashino Red Cross Hospital, Musashino, Japan (e-mail: oralsurg@musashino.jrc.or.jp)..

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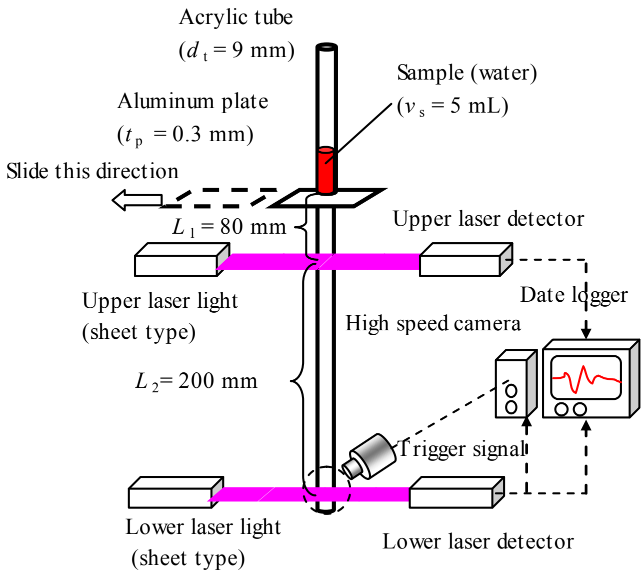


Figure 1. Schematic diagram of water falling experiment

$$\frac{\partial \rho}{\partial t} = 0 \tag{1}$$

$$\frac{D\mathrm{u}}{Dt} = -\frac{1}{\rho}\nabla P + \mathrm{f} \tag{2}$$

where ρ denotes the density [kg/m^3], P is the pressure [Pa], **u** is the velocity [m/s], and **f** is the external force. The governing equations are discretized as particle interaction models [6].

B. *Particle interaction models*

A particle interacts with a neighboring particle via a weight function w (r), which is defined as

$$w(r) = \begin{cases} \frac{r_e}{r} - 1 & 0 \le r \le r_e \\ 0 & r_e \le r \end{cases} \tag{3}$$

where r is the distance between two particles and r_e is the finite distance. The interactions are restricted to r_e [6].

III. EXPERIMENTAL

A. *Experimental apparatus for measuring the falling time and the front surface of a water bolus*

To confirm the accuracy of the 3D MPS method, a simple water falling experiment was carried out. The experimental apparatus is shown in Fig. 1. The test sample (water, 5 mL) was held on an aluminum slide plate (thickness = 0.3 mm) and injected into a vertical acrylic tube (inner diameter of the tube = 9 mm). Laser sensors (Keyence Corp., LV-NH100**)** were installed at the upper and lower positions of the acrylic tube (distance between sensors = 200 mm). Both laser sensors could detect the water bolus arrival based on laser light interruption. To measure the water bolus arrival and the bolus front surface simultaneously, a high-speed camera (Keyence Corp., CV-3500) was triggered by the interrupted signal of the lower laser detector, which was installed in the same area as the lower laser sensor. The falling period was calculated as the difference between the interruption times of both sensors.

Table 1. Properties of sample water

Density	ρ	[kg/m^3]	1000
Kinematic viscosity	ν	[m^2/s]	1×10^{-6}
Surface tension	σ	[N/m]	0.072
Contact angle between water and acryl plate	θ_{fs}	[°]	78

Table 2. Input data and method used for simulation

Initial distance of particle	d_{in}	[m]	0.001
Number of particles	N_p	[-]	4966
Radius of interaction	r_e	[-]	3.1
Kinetic viscosity between fluid and wall	ν_{fs}	[m^2/s]	5×10^{-6}
Slip condition of wall surface			Non slip
Method of pressure calculation			Implicit
Method of viscosity calculation			Implicit
Method of surface tension calculation			Potential model

The properties of the sample used in the experiment and the simulation are shown in Table 1. The contact angle between the sample water and the acrylic plate was based on an average of 10 measurements.

B. *3D MPS method*

Particleworks 4.0 (Prometech software Inc.) was used as a solver to simulate the water falling experiment with the 3D MPS method. The input data, setting values, and methods used are shown in Table 2.

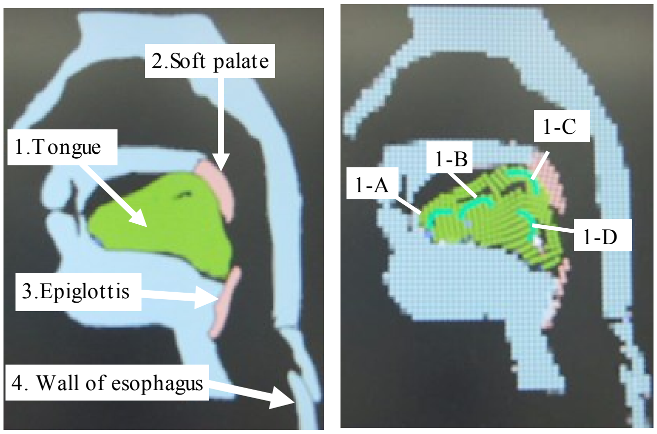
The normalized particle density, which is equivalent to the signals detected in the experiments, was defined for a comparison of the experimental falling time as

$$N_d = \frac{N_{\max} - N}{N_{\max}} \tag{4}$$

where $N_{\max}$ is the maximum particle density at the measurement point and N is the particle density at the measurement time.

C. *Method for the 2D coupled simulation of organ movements and a food bolus*

The 2D MPS method was applied using Physicafe (Prometech Software Inc.) to evaluate the possibility of the coupled simulation of movement and the food bolus. Details of the simple 2D MPS swallowing model are shown in Fig. 2. Note that the aim of this research was to determine the potential of the 2D MPS method for the simulation of the



a. Moving parts of 2D swallowing model

b. Moving walls of tongue defined as elastic body

Figure 2. Details of simple 2D MPS swallowing model

Table 3 Settings of moving parts

Moving part		Moving Direction		Rotation
		X	Y	
1. Tongue	1-A	$-\sin(t) - 0.5$	$2\sin(t - 1)$	-
	1-B	$-3\sin(t)$	$-3\sin(t) - 1$	-
	1-C	$-\sin(t-1) - 1$	$-4\sin(t-1)$	-
	1-D	$-2\sin(t) - 2$	$-2\sin(t-3) + 2$	-
2. Soft palate		$-2\sin(t)$	-	$0.5\sin(t-3)$
3.Epiglottis		$\sin(t+1.2) - 0.8$	$-\sin(t+1.2) + 1$	$0.8\sin(t+1.2) - 0.6$
4.Wall of esophagus		$2\sin(t+1.2)$	$-2\sin(t+1.2)$	-

swallowing action, so the simulation model was produced from schematic pictures and it is not medically correct. The moving parts of the 2D swallowing model defined four parts (1, tongue; 2, soft palate; 3, epiglottis; 4, wall of the esophagus), as shown in Fig. 2a. There were four moving solid parts in the elastic tongue body shown in Fig. 2b. The movement of each part was defined by the combinations of time-dependent periodic functions shown in Table 3.

Due to the limitations of the commercial 2D MPS software used, the elapsed time and other physical properties were defined as normalized and relative values. The normalized elapsed time t_{en} [s] was defined as

$$t_{en} = t_{es} / t_s \tag{5}$$

where t_{es} is the real elapsed time [s] and t_s is the standard simulation time [s]. The viscosity, density, modulus of elasticity, and adhesiveness were defined as values relative to (relatively low or relatively high) a standard material.

IV. RESULTS AND DISCUSSION

A. Comparison of the liquid bolus arrival time and falling time

The measured signals indicating the liquid bolus arrival are shown in Fig. 3. Rapid changes in the signal indicated the time when the liquid bolus arrived. It is clear that the arrival times were almost equal for the upper and lower measuring points. The falling times from the upper to the lower sensor were 131 ms in the experiment and 134 ms in the simulation. These results show that the 3D MPS method could simulate the liquid bolus arrival time and the falling time at the measurement points with high accuracy.

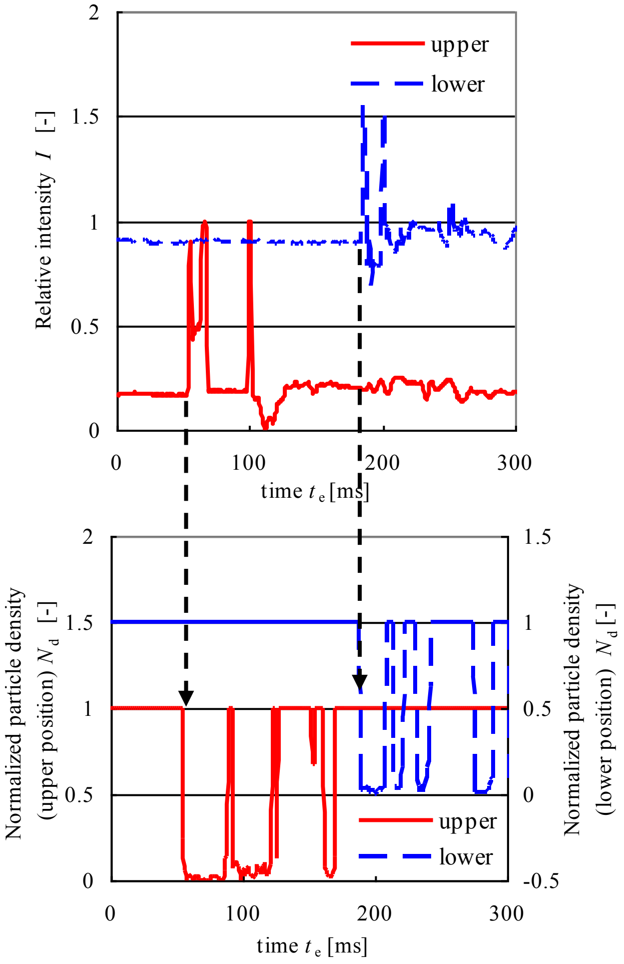
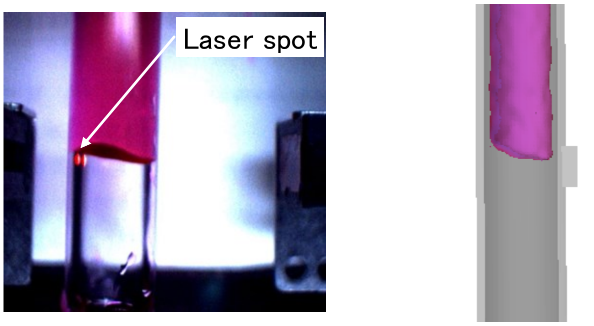


Figure 3 .Comparison between experimental relative intensity and simulated normalized particle density
(Top: Experiment, Bottom: Simulation)

B. Comparison with the configuration of the bolus front surface

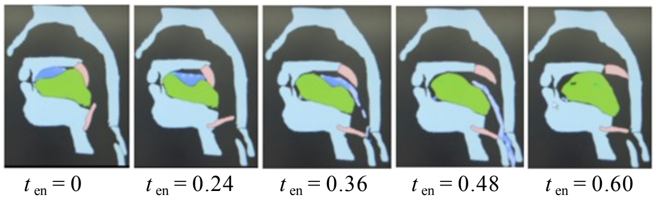
Fig. 4 shows a comparison of the bolus front surface in the experimental visualization and the 3D MPS method. In Fig. 4a, the bolus front surface corresponded to the laser spot that detected the arrival of the bolus. This result showed that the laser sensor detected the liquid bolus arrival exactly. The configuration of the liquid bolus surface was not flat and it seemed to have a hollow shape at the surface center. In the simulation results shown in Fig. 4b, a similar surface configuration was observed. This suggests that the 3D MPS method could estimate the bolus front surface accurately.



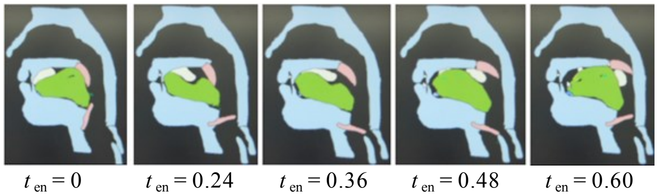
a. visualization experiment

b. 3D MPS method

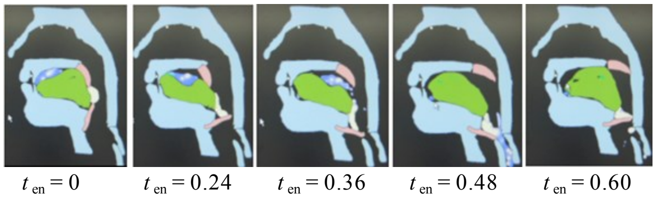
Figure 4 .Comparison of bolus front surface between experimental visualization and 3D MPS method



a. Normal swallowing action (liquid)



b. Normal swallowing action (adhesive food bolus)



c. Rinsing adhesive food remnants with liquid

Figure 5. Different swallowing mechanisms

C. Coupled simulation of organs and different food properties

Fig. 5 shows the results of the 2D MPS simulation of different food swallowing mechanisms. Fig. 5a shows the swallowing action with a liquid. The changes in the elapsed time, positions, and shapes of the moving parts are described in Table 3. The tongue produced a traveling wave in the direction of the medium movement and propagated the wave as the liquid was carried into the oropharynx. The epiglottis closed the laryngeal inlet before the liquid arrived at the entrance of the larynx. Thus, the liquid was swallowed without pulmonary aspiration. This series of liquid movements was similar to previous results [7].These results indicates that the 2D MPS method could include the effect of the coupled simulation of the elastic tongue, solid wall (moving parts in the tongue), and liquid.

Fig. 5b shows the swallowing action with an adhesive food bolus. This showed that the sticky food carried into the oropharynx adhered to the hard palate and it did not tear from the soft palate. This result showed that the 2D MPS method could treat adhesive food.

Fig. 5c shows the rinsing action. The adhesive food was washed away by liquid. However, a part of the adhesive food was retained on the vallecula between the tongue base and the epiglottis. This result showed that the 2D MPS method could handle food materials with different physical properties.

V. CONCLUSION

In this study, we evaluated the accuracy of the 3D MPS method using a simple falling model. This supported the possibility of the numerical simulation of the swallowing process using the MPS method, which involved a coupled simulation of the organs and the food bolus using several properties.

Thus far, there have been a few numerical simulations of swallowing actions using MPS and earlier studies performed simulations using 2D models that did not consider the coupled simulation of a elastic organ and various properties of the food bolus. In this study, we tested the coupled simulation of the 2D MPS methods and confirmed the accuracy of a 3D MPS method. Our results demonstrated the possibility of using the 2D MPS method for coupled simulations and the accuracy of the 3D MPS method for producing simple models. The verification was qualitative for the 2D MPS method, so a quantitative evaluation will still be required. The modeling of exact organs and coupled simulations of organs and viscoelastic food materials were the main issues in the 3D MPS method.

In this study, we confirmed that the MPS method could simulate the configuration of the liquid surface and the food falling time exactly, so it was clear that the MPS method could consider the coupled simulation of organs and the food bolus. Therefore, we suggest that the MPS method could be used for 3D simulations of the swallowing action.

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