

Development of Musculoskeletal Model to Estimate Muscle Activities During Swallowing

Takuya Hashimoto¹(✉), Atsuko Murakoshi¹, Takahiro Kikuchi²,
Yukihiro Michiwaki², and Takuji Koike¹

¹ The University of Electro-Communications, Tokyo, Japan
hashi.tak@uec.ac.jp

² Japanese Red Cross Musashino Hospital, Tokyo, Japan

Abstract. Swallowing, or deglutition, is well known as a process to transport bolus of food from mouth to stomach, whereas it is difficult to understand its physiological mechanism because it involves in complex neuromuscular coordination. In order to understand swallowing mechanism in terms of muscle activity, we develop a musculoskeletal model in which muscles around the hyoid bone and the thyroid cartilage are represented as wire actuators. The changes of muscle lengths are calculated to estimate muscle activities during normal swallowing as a static analysis using the musculoskeletal model. The results of this study would contribute to provide greater insight into swallowing and to improve treatments for dysphagia.

Keywords: Swallowing · Musculoskeletal analysis

1 Introduction

Swallowing, or deglutition, is well known as a process to transport bolus of food from mouth to stomach. The process requires complex neuromuscular coordination because it involves voluntary control and reflexive motion of more than 30 nerves and muscles [1]. Therefore, neuromuscular disorders affect swallowing function and are highly associated with difficulty of swallowing, called dysphagia. Dysphagia also can lead to aspiration pneumonia, malnutrition, dehydration, weight loss, and airway obstruction. Aspiration pneumonia is particularly a big health concern in aging societies in terms of high mortality and long hospitalization period. In fact, the number of pneumonia patients has been actually increased with increasing of aging population [2], and now pneumonia has been the third leading cause of death in Japan. Because most of pneumonia of elderly people are said to be aspiration pneumonia caused by dysphagia, prevention and treatment of dysphagia would contribute to extending healthy-life span and increasing quality of social welfare. Therefore, it is very important to assess swallowing disorders accurately at an early stage.

Videofluoroscopic examination (VF) [3] which uses a real-time x-ray called fluoroscopy has been generally considered as the gold standard method to evaluate patient's ability to swallow because of its comprehensive information, but it requires

special facilities and the use of a radiology equipment. Videoendoscopic examination (VE) [4] is also conducted as a reliable and portable method that can be done at bedside. However, these examinations mainly provide qualitative information on the movement of anatomical structure during swallowing. In order to evaluate swallowing function quantitatively, the use of a surface electromyography (sEMG) [5, 6] and swallowing sound [7] have been proposed. Because most of muscles related to swallowing construct a layered structure, sEMG measurement cannot avoid cross-talk effect even though sEMG measurement is considered as a reliable method to estimate muscle activities. In addition, the swallowing sound measurement cannot detect muscle activities. Therefore, it is difficult to understand muscle activities quantitatively during swallowing even though swallowing consists of complex neuromuscular coordination.

In this study, we develop a musculoskeletal model of swallowing to investigate swallowing function quantitatively in terms of muscle activity. The musculoskeletal model includes the hyoid bone and the thyroid cartilage as skeletal objects. Muscles around the hyoid bone and thyroid cartilage are also modeled as wire actuators based on anatomical knowledge. In order to investigate muscle activities during swallowing, we first analyzed the movements of the hyoid bone and thyroid cartilage during normal swallowing of a healthy subject. We then calculated the changes of muscle lengths as a static analysis based on analysis results.

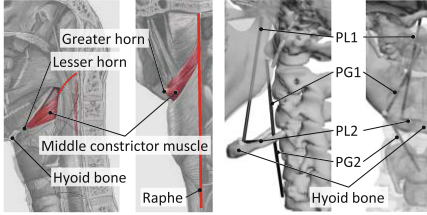
2 Development of Musculoskeletal Model of Swallowing

In order to investigate muscle activities statically and dynamically, we develop a musculoskeletal model of swallowing. In the musculoskeletal model, the skeleton consists of three parts: hyoid bone, thyroid cartilage, a set of skull and cervical spine. A CT-data obtained from a healthy 20's male was used to create the skeleton data. The hyoid bone and the thyroid cartilage are treated as rigid bodies with mass and inertia. In addition, the cricoid cartilage is treated as a part of the thyroid cartilage. Muscle is simplified as a kind of a wire actuator which generates only contractive force by reference to the previous study [8]. The musculoskeletal model of swallowing includes 10 kinds of muscles acting on the hyoid bone and/or the thyroid cartilage: (1) middle constrictor muscle of pharynx, (2) inferior constrictor muscle of pharynx, (3) digastric muscle, (4) stylohyoid muscle, (5) geniohyoid muscle, (6) mylohyoid muscle, (7) sternohyoid muscle, (8) superior belly of the omohyoid muscle, (9) thyrohyoid muscle, (10) sternothyroid muscle. The detailed description of each muscle model is described below.

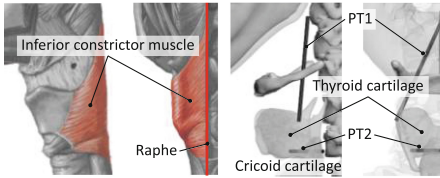
(1) *Middle constrictor muscle of pharynx from greater horn and lesser horn: PG, PL*

The middle constrictor muscle of pharynx is a kind of a fan-shaped muscle which partly forms the posterior wall of the pharynx as shown in Fig. 1(a). This muscle is divided into two parts according to attachment sites. One of them arises from the pharyngeal raphe and ends up with the greater horn (cornu) of the hyoid, and it is named PG in this paper. The other one also arises from the pharyngeal raphe and ends up with the lesser horn (cornu), and it is named PL. In our model, each muscle is

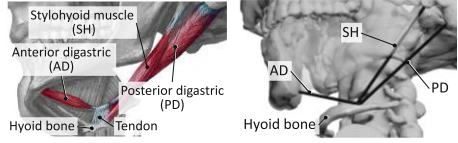
represented with four wires (PG1 and PL1 for upper part, PG2 and PL2 for lower part), because they are wide-spanned muscle.



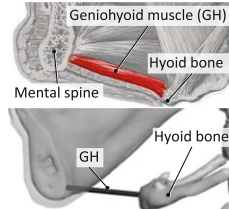
(a) Middle constrictor muscle (PG1, PL1, PG2, PL2)



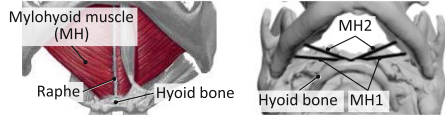
(b) Inferior constrictor muscle (PT1, PT2)



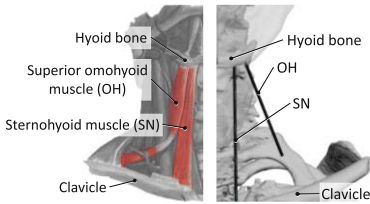
(c) Digastric muscle (AD, PD) and stylohyoid muscle (SH)



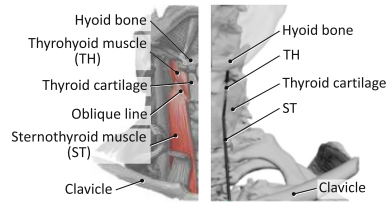
(d) Geniohyoid muscle (GH)



(e) Mylohyoid muscle (MH1, MH2)



(f) Sternohyoid muscle (SN) and omohyoid muscle (OH)



(g) Thyrohyoid muscle (TH) and sternohyoid muscle (ST)

Fig. 1. Anatomical images [9] and wire models of muscles around the hyoid bone and the thyroid cartilage.

(2) *Inferior constrictor muscle of pharynx: PT1, PT2*

Similarly to the middle constrictor muscle, the inferior constrictor muscle of pharynx is the part of posterior wall of the pharynx as shown in Fig. 1(b). This muscle is composed of two parts and both of them arise from the pharyngeal raphe. One of them ends up with the thyroid cartilage and the other ends up with the cricoid cartilage. In this study, only the muscle whose insertion is the thyroid cartilage is included. This muscle is represented with two wires (PT1 for upper part and PT2 for lower part).

(3) *Digastric muscle: AD, PD*

The digastric muscle is a slender muscle located under the jaw as shown in Fig. 1(c). This muscle is divided into two muscles by an intermediate tendon. One of them is the posterior belly which arises from the mastoid process of the temporal bone and inserts into the intermediate tendon. The other one is the anterior belly which arises from the intermediate tendon and inserts into the inner surface of the lower border of the mandible. In our model, each muscle is represented as a simple wire (AD, PD) and the intermediate tendon is assumed as a via-point [8].

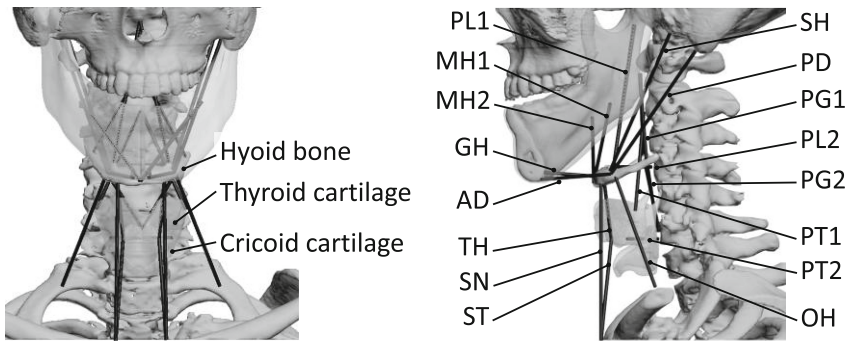


Fig. 2. Musculoskeletal model of swallowing

(4) *Stylohyoid muscle: SH*

As shown in Fig. 1(c), the stylohyoid muscle is a slender muscle which arises from the posterior surface of the styloid process of the temporal bone and inserts into the greater horn of the hyoid bone. A wire actuator, named SH, is assigned for this muscle.

(5) *Geniohyoid muscle: GH*

The geniohyoid muscle is a fusiform muscle passing parallel to the midline in an anterior-posterior direction as shown in Fig. 1(d). Its origin is the mental spine which located on the back of the mandible, and the insertion is an anterior surface of the hyoid bone. This muscle is represented as a simple wire actuator, named GH.

(6) *Mylohyoid muscle: MH1, MH2*

The mylohyoid muscle is a flat and triangular muscle which runs from the mandible to the hyoid bone. As shown in Fig. 1(e), this muscle forms the floor of oral cavity. Its origin is the mylohyoid line and the sublingual fossa of mandible. The insertion is an anterior surface of the hyoid bone and a midline raphe which connects the mental spine and the hyoid bone. Our model represents only a muscle whose origin is the hyoid, but a muscle whose origin is the midline raphe is not included for simplicity. This muscle is modeled as two wires (MH1, MH2).

(7) *Sternohyoid muscle: SN*

The sternohyoid muscle is a paired muscle in the superficial layers of the neck and runs parallel to the midline as shown in Fig. 1(f). The origin is the posterior part of the manubrium of sternum, the sternoclavicular articulation, and the first costal cartilage. The insertion is the lower border of the hyoid bone. In our model, the origin is defined as the posterior part of the manubrium of sternum because the skeleton data contains only an upper part of the collarbone. This muscle is simplified as a wire actuator, named SN.

(8) *Superior belly of the omohyoid muscle: OH*

The omohyoid muscle is located at the front of the neck as shown in Fig. 1(f). Similarly to the digastric muscle, the omohyoid muscle is divided into two bellies separated by an intermediate tendon. The inferior belly arises from the upper border of the scapula and inserts into the intermediate tendon. The other one, superior belly, arises from the intermediate tendon and inserts into the lower border of the hyoid bone. In this study, only the superior belly acting on the hyoid bone is included as OH.

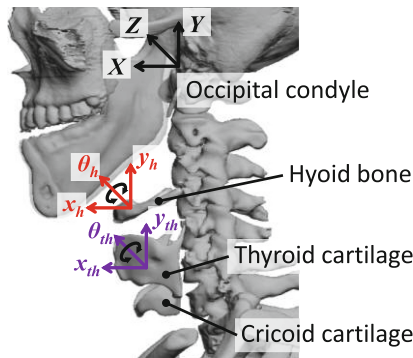


Fig. 3. Global and local coordinate systems

(9) *Thyrohyoid muscle: TH*

The thyrohyoid muscle is a thin muscle which connects the hyoid bone and the thyroid cartilage, and it runs parallel to the sternothyroid muscle as shown in Fig. 1(g). The origin is the oblique line on the thyroid cartilage, and the insertion is the lower border of the greater cornu of the hyoid bone. This muscle is represented as a simple wire, named TH.

(10) *Sternothyroid muscle: ST*

The sternothyroid muscle is a thin muscle located under the sternohyoid muscle (Fig. 1 (g)). The origin is the posterior part of the manubrium of sternum and the first costal cartilage, but the origin is defined as the manubrium of sternum as well as the

sternohyoid muscle in this study. The insertion is defined as the oblique line on the thyroid cartilage. This muscle modeled as a simple wire, named ST.

In this way, muscles are represented as wire actuators as shown in Fig. 2 based on anatomical knowledge [9] and the CT data. Arrangement of muscles in left and right sides is symmetrical about the sagittal plane for simplicity. In total, the number of muscle is 32 ($N = 32$). To describe the positions of muscles, the global coordinate system is defined at the center of left-right occipital condyles. The local coordinate systems are defined at the center of gravity of the hyoid bone and the center of gravity of the thyroid cartilage as shown in Fig. 3, respectively.

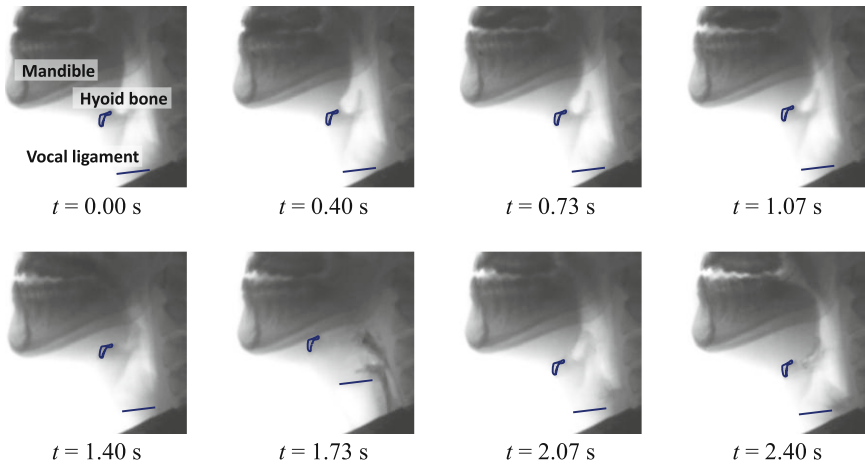


Fig. 4. Video fluoroscopic image of swallowing

3 Motion Analysis of the Hyoid Bone and the Thyroid Cartilage

The normal swallowing process is classified into three phase according to the location of bolus: oral phase, pharyngeal phase, and esophageal phase. The pharyngeal phase is particularly important, which transports bolus into the stomach from the pharynx. In this phase, the hyoid bone and the larynx move upward and forward. The thyroid cartilage is also elevated in association with hyoid motion. At that time, the posterior part of tongue moves in a posteroinferior direction. When the larynx and the posterior part of tongue move, the epiglottis falls down to prevent bolus from going into the trachea and instead propels it into the esophagus. If this process is not performed adequately, food and drink go into the trachea and it may cause dysphagia. Because this process is driven by muscles attaching to the hyoid bone and the thyroid cartilage, to analyze movements of the hyoid bone and the thyroid cartilage is important to evaluate swallowing function.

3.1 Analysis Method

We used a VF video to analyze two-dimensional movements of the hyoid bone and the thyroid cartilage. The video has been obtained from a video fluoroscopic examination of a healthy 20's male. In analysis, we manually extracted the region of hyoid bone and the vocal ligament of thyroid cartilage frame-by-frame as shown in Fig. 4. Displacements and posture of each object were measured based on each initial position and posture. Then, measured displacements and posture were transformed to the global coordinate system. In addition, the volumes of the hyoid bone and the thyroid cartilage were estimated from a skeletal data obtained from CT-data of the same male.

3.2 Analysis Results

Figure 5 shows the trajectories of the hyoid bone and the thyroid cartilage in the sagittal plane, which were smoothed by a simple moving average. Figure 5(a) shows that the hyoid bone moves upward from P_s^h ($t = 0.83$) to P_1^h ($t = 1.20$). From P_1^h to P_2^h ($t = 1.70$), it moves in an anterior-superior direction and achieves a maximal displacement at P_2^h .

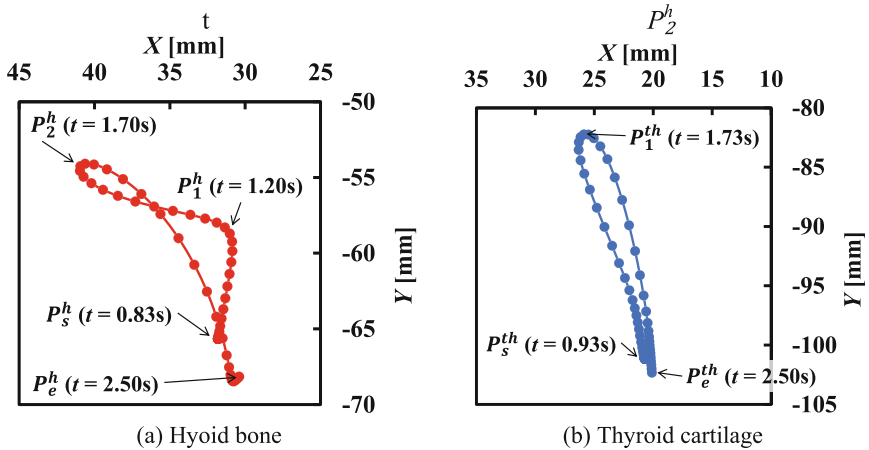


Fig. 5. Trajectories of the hyoid bone and the thyroid cartilage

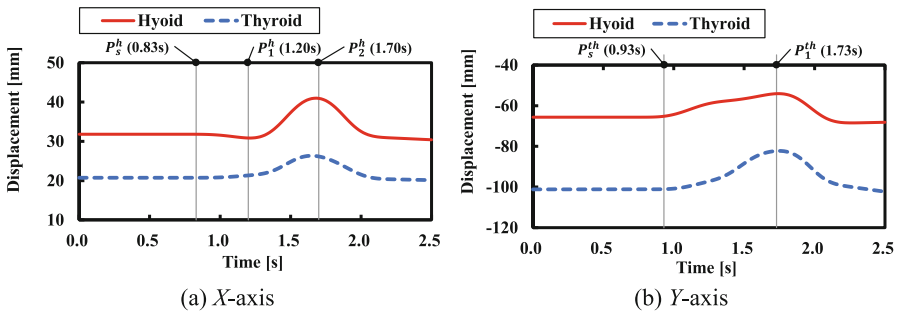


Fig. 6. Displacements of the hyoid bone and the thyroid cartilage in X- or Y-axis.

Then, it returns to an initial position from P_2^h to P_e^h ($t = 2.50$). Figure 5(b) shows that the thyroid cartilage mainly moves in an superior direction from P_s^{th} ($t = 0.93$) to P_1^{th} ($t = 1.73$). The thyroid cartilage achieves a maximal displacement along with the hyoid bone at P_1^{th} . From P_1^{th} to P_e^h ($t = 2.50$), it returns to an initial position. Figure 6 shows the displacements of the hyoid bone and the thyroid cartilage in X - or Y -axis.

4 Estimation of Muscle Activities During Swallowing

4.1 Method

In this analysis, the change of muscle length was calculated to estimate muscle activity using the musculoskeletal model as a static analysis, because muscle length would reflect a part of muscle activity. Muscle length is defined as the distance between the origin and insertion of a muscle, which is given by

$$l_i = \sqrt{(O_i^x - I_i^x)^2 + (O_i^y - I_i^y)^2 + (O_i^z - I_i^z)^2} \quad i = 1, 2, 3, \dots, N \quad (1)$$

Here, l_i is muscle length of i -th muscle. O_i^x , O_i^y , O_i^z , I_i^x , I_i^y , and I_i^z represent the positions of origin and insertion of i -th muscle in the global coordinate system, respectively. The lengths of all muscles included in the musculoskeletal model were calculated three-dimensionally along with the movements of the hyoid bone and the thyroid cartilage. Finally, each muscle length was normalized by each initial length as below:

$$L_i = \frac{l_i}{l_i^0} \quad (2)$$

Here, L_i and l_i^0 are the normalized and initial length of i -th muscle, respectively.

4.2 Results and Discussions

Figure 7 shows the calculation results. The mylohyoid muscle (MH1, MH2), the stylohyoid muscle (SH), the posterior belly of the digastric muscle (PD), and the upper part of the middle constrictor muscle (PG1, PL1) shortened along with the elevation of the hyoid bone. The thyrohyoid muscle (TH) stretched in the initial period of the elevation of the hyoid bone, but it shortened when the thyroid cartilage elevated followed by the hyoid bone. In addition, the upper part of the inferior constrictor muscle of pharynx (PT1) shortened simultaneously. The geniohyoid muscle (GH) and the anterior belly of the digastric muscle (AD) shortened when the hyoid bone moved forward. As the result, the following predictions are obtained:

- The mylohyoid muscle (MH1, MH2), the stylohyoid muscle (SH), the posterior belly of the digastric muscle (PD), and the upper part of the constrictor muscle (PG1, PL1) contribute to upward movement of the hyoid bone

- The geniohyoid muscle (GH) and the anterior belly of the digastric muscle (AD) contribute to forward movement of the hyoid bone
- The thyrohyoid muscle (TH) and the upper part of the inferior constrictor muscle (PT1) contribute to upward movement of the thyroid cartilage

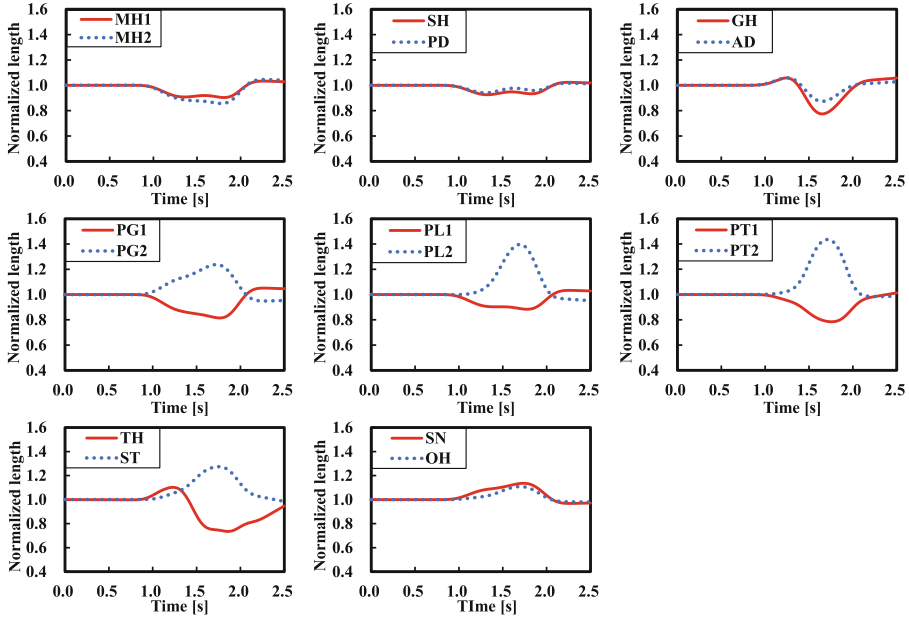


Fig. 7. Calculation results of the changes of muscle lengths

5 Conclusion

We developed the musculoskeletal model of swallowing based on anatomical knowledge to investigate swallowing function quantitatively in terms of muscle activity. In the musculoskeletal model, muscles around the hyoid bone and thyroid cartilage are modeled as wire actuators. In order to investigate muscle activities during swallowing, we calculated the changes in length of the muscle as a static analysis using the musculoskeletal model.

One of our future works is to realize dynamic analysis to estimate individual muscle force in swallowing by using inverse dynamics computation and optimization program [10]. In addition, it is important to verify the reliability of force estimation result by comparing with biological signal such as a surface electromyography (sEMG). To consider viscoelastic properties of physiological tissue including muscle is also important for dynamic analysis.

References

1. Jones, B. (ed.): Normal and Abnormal Swallowing: Imaging in Diagnosis and Therapy. Springer, New York (2003)
2. Fernandez-Sabe, N., Carratala, J., Roson, B., Dorca, J., Verdaguer, R., Manresa, F., Gudiol, F.: Community-acquired pneumonia in very elderly patients: causative organisms, clinical characteristics, and outcomes. *Medicine* **82**(3), 159–169 (2003)
3. Palmer, J.B., Kuhlemeier, K.V., Tippet, D.C., Lynch, C.: A protocol for the videofluorographic swallowing study. *Dysphagia* **8**(3), 209–214 (1993)
4. Leder, S.B., Sasaki, C.T., Burrell, M.I.: Fiberoptic endoscopic evaluation of dysphagia to identify silent aspiration. *Dysphagia* **13**(1), 19–21 (1998)
5. Neis, L.R., Logemann, J., Larson, C.: Viscosity effects on EMG activity in normal swallow. *Dysphagia* **9**(2), 101–106 (1994)
6. Crary, M.A., Baldwin, B.O.: Surface electromyographic characteristics of swallowing in dysphagia secondary to brainstem stroke. *Dysphagia* **12**(4), 180–187 (1997)
7. Nagae, M., Suzuki, K.: A neck mounted interface for sensing the swallowing activity based on swallowing sound. In: Proceedings of the 2011 Annual International Conference of the IEEE Engineering in Medicine and Biology Society, pp. 5224–5227 (2011)
8. Nakamura, Y., Yamane, K., Fujita, Y., Suzuki, I.: Somatosensory computation for man-machine interface from motion-capture data and musculoskeletal human model. *IEEE Trans. Rob.* **21**(1), 58–66 (2005)
9. McFarland, D.H.: *Netter's Atlas of Anatomy for Speech, Swallowing, and Hearing*. Elsevier Health Sciences, New York (2008)
10. Ueda, J., Ding, M., Krishnamoorthy, V., Shinohara, M., Ogasawara, T.: Individual muscle control using an exoskeleton robot for muscle function testing. *IEEE Trans. Neural Syst. Rehabil. Eng.* **18**(4), 339–350 (2010)