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ORIGINAL ARTICLE

Swallowing Kinematics and Factors Associated with Laryngeal Penetration and Aspiration in Stroke Survivors with Dysphagia

Han Gil Seo[1] · Byung-Mo Oh[1] · Tai Ryoon Han[2]

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Abstract The purpose of this study was to investigate swallowing kinematics and explore kinematic factors related with penetration-aspiration in patients with post-stroke dysphagia. Videofluoroscopic images of 68 patients with post-stroke dysphagia and 34 sex- and age-matched healthy controls swallowing a thin liquid were quantitatively analyzed using two-dimensional motion digitization. The measurements included the movement distances and velocities of the hyoid and larynx, and the maximal tilt angles and angular velocities of the epiglottis. All velocity variables were significantly decreased in the stroke patients compared to the controls. There was a significant difference in the maximal horizontal displacement of the larynx, but there were no significant differences in other displacements of the larynx, the maximal displacements of the hyoid bone, and the maximum tilt angle of the epiglottis between the two groups. The maximal tilt angle of the epiglottis was lower in the aspiration subgroup than in the no penetration/aspiration and penetration subgroups as well as the controls. The maximal tilt angle from the *y* axis showed a dichotomous pattern at 90° of the angle, and all 11 patients with an angle <90° showed either penetration or aspiration. In the ROC curve of the angle for prediction of aspiration, the area under the curve was 0.725 (95 % CI 0.557–0.892, $P = 0.008$). This study suggested that sluggish rather than decreased hyolaryngeal movements during swallowing are a remarkable feature of post-stroke dysphagia. The association of reduced epiglottic movement with the risk of aspiration in patients with post-stroke dysphagia was supported by the quantitative analysis.

Keywords Dysphagia · Deglutition · Stroke · Aspiration · Kinematics

Introduction

Dysphagia is a common post-stroke complication. The incidence of post-stroke dysphagia, based on objective evaluations, has been reported to be up to 80 % [1]. An important finding in swallowing evaluations is aspiration of food materials, which increases the risk of pneumonia in stroke patients [2]. Aspiration has been known to occur in 19.5–42 % of acute stroke patients [3]. Therefore, prevention of aspiration is of fundamental importance in the management of dysphagia in these patients.

Videofluoroscopic swallowing study (VFSS) is widely used to evaluate the safety and efficiency of swallowing, including the occurrence of penetration–aspiration. It visualizes the movements of essential structures for swallowing, and kinematic analyses of these movements have been used to investigate the physiology of swallowing. A recent systematic review reported several physiological factors related to aspiration risk, including kinematic measurements of hyoid movement [4]. Determining the association between various physiological measures and penetration–aspiration during swallowing in stroke patients is an ongoing issue [5].

Post-stroke dysphagia has been the primary subject of kinematic analysis performed using VFSS [5–15].

✉ Byung-Mo Oh
keepwiz@gmail.com

1 Department of Rehabilitation Medicine, Seoul National University College of Medicine, Seoul National University Hospital, Seoul, 101 Daehak-Ro, Jongno-Gu, Seoul 110-744, Republic of Korea

2 Department of Rehabilitation Medicine, Gangwon Do Rehabilitation Hospital, 24-16, Chungyeol-ro 142beon-gil, Chuncheon-si, Gangwon-do 200-939, Republic of Korea

However, several previous studies have been confined to the temporal aspects of swallowing; only a few studies included spatial measurements in the analysis [5–8, 15]. Moreover, only the distances of hyoid and laryngeal movements were analyzed as spatial parameters in most of these studies [5, 7, 8], except in our previous studies, which included kinematic analysis of epiglottis movement [6, 15]. Only one study included the velocity of hyoid movement as a kinematic parameter [6]. The effect of bolus consistency on hyoid velocity in swallowing in healthy adults has been reported in a recent study [16], which suggested that higher velocities of hyoid movement might be a mechanism underlying improved swallowing function. With regard to the movement distances, the actual distances have been commonly used as spatial parameters [6–8, 15], whereas anatomically normalized measures have been adopted by some researchers [5]. The relationship between the distances of hyolaryngeal movements and risk of aspiration has been controversial among these studies.

The goal of this study was to investigate swallowing kinematics in patients with post-stroke dysphagia compared to healthy controls. We also aimed to explore kinematic factors related with penetration–aspiration during swallowing of thin liquid in these patients. The movement of the epiglottis, known as an important mechanism of airway protection during swallowing, [17] and the velocities of all relevant structures were included in the analysis. In addition, both actual and anatomically normalized distances of hyolaryngeal movements were analyzed to investigate differences in outcomes between the two measures.

Materials and Methods

Participants

The data on swallowing were drawn from the motion analysis database of the dysphagia laboratory in the Department of Rehabilitation Medicine, Seoul National University Hospital. The data included VFSS images and digitized hyolaryngeal movements during 2-ml liquid barium swallow of 68 stroke patients (42 men and 26 women) who underwent VFSS from 2005 to 2008. This period was selected because the fluoroscopy device, image processing tools, and study protocol remained the same throughout. All patients had dysphagia following the first-ever stroke, a unilateral lesion, and no other cause for dysphagia. Patient clinical information including disease duration, stroke type, laterality, location, and dysphagia severity was reviewed retrospectively. The characteristics of the stroke patients are shown in Table 1.

Table 1 Characteristics of the stroke patients

Characteristics	Stroke patients (n = 68)
Age (years)	60.97 ± 12.08
Sex (n)	
Men	42
Women	26
Stroke type (n)	
Ischemic	45
Hemorrhagic	22
Mixed	1
Laterality (n)	
Right	20
Left	34
Bilateral	5
Location (n)	
Supratentorial	55
Infratentorial	13
Duration (day)	109.12 ± 240.76
Penetration–aspiration status	
No penetration/aspiration	35
Penetration	18
Before the swallow	1
During the swallow	17
Aspiration	15
Before the swallow	3
During the swallow	12
ASHA NOMS swallowing scale	
1	6
2	8
3	3
4	8
5	19
6	10
7	13
VDS	27.08 ± 15.90

ASHA NOMS, American Speech-Language-Hearing Association National Outcome Measure System; *VDS*, videofluoroscopic dysphagia scale

Sex- and age-matched healthy volunteers also participated in this study. Written informed consent was obtained from all participants prior to the VFSS. A total of 34 healthy subjects (21 men and 13 women) were included using 2:1 matching. There was no significant difference in the ages between the stroke patients and healthy controls (60.97 ± 12.08 and 60.22 ± 12.41 years, respectively; $P = 0.770$).

This study was approved by the Institutional Review Board of Seoul National University Hospital.

VFSS

Swallowing was measured using digital videofluoroscopy at a resolution of 720 × 480 pixels at 30 frames per second. For the dysphagia evaluation, the stroke patients were seated upright in a chair and were given 2 ml and 5 ml of liquid barium (35 % w/v), pudding, curdled yogurt, semi-blended food, boiled rice, and thickened liquid barium twice using a spoon. According to our VFSS protocol, initially, 2 ml of liquid barium was administered to all patients. Healthy participants were given 2 ml of liquid barium twice using the same method. Two coins with a diameter of 24 mm were attached under the chin and below the mastoid process to serve as a reference ruler for radiographic magnification. Under the lateral projection of videofluoroscopy, the modified barium swallow was recorded in digital image files (.avi) using a digital computer frame grabber board (Pinnacle Studio MovieBox DV, Pinnacle System, Inc., Mountain View, CA; Pegasus HD/SD Board, Grass Valley Inc., Honorine, France) and image processing software (Pinnacle Studio 9.0, Pinnacle System, Inc.; EDIUS 4.5, Grass Valley Inc.). The X-ray voltage was set at a peak of 40 kV, which allowed visualization of the soft tissues of the laryngeal and pharyngeal structures.

The results of VFSS were confirmed based on the consensus of two physiatrists who had at least 2 years of experience in dysphagia management. The stroke patients were classified into no aspiration/penetration, penetration, and aspiration subgroups according to the penetration–aspiration status with liquid barium. Penetration was defined as the entry of liquid into the larynx at some level down to but not below the true vocal cords, and aspiration was defined as the entry of liquid into the airway below the true vocal folds [18]. If any of the 2- or 5-ml liquid barium swallows showed penetration or aspiration, the patient was classified into the corresponding group. The videofluoroscopic dysphagia scale (VDS) [19] and American Speech-Language-Hearing Association National Outcome Measure System (ASHA NOMS) [20] swallowing scale were also rated as outcome measures.

Two-Dimensional Motion Digitization

Two-dimensional motion digitization of the hyoid bone, epiglottis, larynx, and liquid bolus during the 2-ml liquid barium swallow was performed, as previously described, with some modifications [6]. A researcher with 2 years of experience in swallowing motion analysis, who was blinded to the participants' information, analyzed the video clips. The initial frame for the analysis was the frame in which the head of the bolus passed the angle of the mandibular ramus at the base of the tongue. However, if the hyoid excursion began before the initial frame, the analysis included 15 frames (0.5 s) before the initial frame. The last frame was the frame in which the tail of the bolus passed the upper esophageal sphincter. The anterior–superior margin of the hyoid bone, base-to-tip margin of the epiglottis, anterior–superior margin of the subglottic airway column, the head of bolus, and the antero-inferior margins of the second and fourth cervical vertebral bodies were digitized for each frame using the motion analysis software system (Ariel Performance Analysis System; Ariel Dynamics, Inc., Trabuco Canyon, CA). To calculate the coordinates of the points, we defined zero point as the antero-inferior margin of the fourth cervical vertebral body, the *y* axis as the straight line connecting the zero point and the antero-inferior margins of the second body, and the *x* axis as the line perpendicular to the *y* axis, passing through the zero point (Fig. 1). All the digitized data were filtered with a quintic spline algorithm.

Measurements

The digitized motion data were imported to the MATLAB R2014b software (The MathWorks Inc., Natick, MA). Data were transformed into the actual distance using the known diameter of the reference coins. All coordinates were calculated relative to the zero point, which was the antero-inferior margin of the fourth cervical vertebral body.

The following variables were measured: (1) the maximal vertical and horizontal displacements (mm) of the hyoid bone and larynx (subglottic airway column); (2) the ratio of the maximal displacements to the distance between the

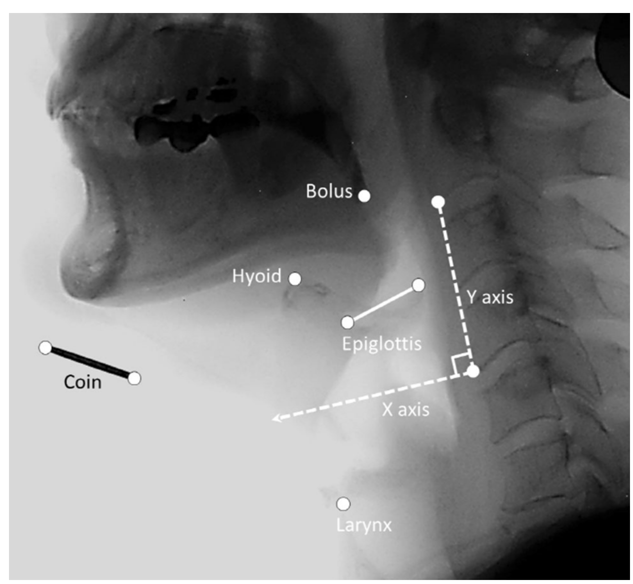

Fig. 1 Coordinates of the selected anatomical points and the control frame for the *x* and *y* axes

Table 2 Comparison of kinematic variables between stroke patients and healthy controls

Variables	Stroke patients ($n = 68$)	Control ($n = 34$)	*P* value*
Hyoid bone, maximal displacement (mm)			
Vertical	12.07 ± 5.11	12.48 ± 5.44	0.709
Horizontal	10.96 ± 3.80	11.40 ± 2.78	0.548
Hyoid bone, maximal displacement (% C2–C4)			
Vertical	34.85 ± 14.45	35.16 ± 13.50	0.917
Horizontal	31.89 ± 11.12	32.78 ± 8.49	0.681
Hyoid bone, maximal velocity (mm/s)			
Vertical	35.87 ± 25.93	46.78 ± 23.07	0.040
Horizontal	39.06 ± 18.57	58.56 ± 22.06	<0.001
Larynx, maximal displacement (mm)			
Vertical	19.95 ± 5.06	22.22 ± 6.66	0.059
Horizontal	4.45 ± 2.07	6.16 ± 2.26	<0.001
Larynx, maximal displacement (% C2–C4)			
Vertical	57.93 ± 14.09	63.19 ± 17.01	0.101
Horizontal	12.79 ± 5.43	17.64 ± 6.62	<0.001
Larynx, maximal velocity (mm/s)			
Vertical	64.85 ± 26.04	94.83 ± 35.35	<0.001
Horizontal	18.05 ± 12.16	30.50 ± 16.13	<0.001
Epiglottis, maximal tilt angle (°)			
From the initial position	89.50 ± 28.88	95.60 ± 24.36	0.293
From the *y* axis	123.07 ± 30.58	129.39 ± 23.88	0.294
Epiglottis, maximal angular velocity (°/s)	614.84 ± 363.79	857.86 ± 372.72	0.002
Liquid bolus, maximal velocity (mm/s)	348.19 ± 114.03	519.50 ± 145.17	<0.001

Data are presented as mean ± SD

* *P* value by the independent *t* test

second and fourth cervical vertebral bodies (% C2-4 distance); (3) the maximal vertical and horizontal velocities of the hyoid bone and larynx; (4) the maximal angle of the epiglottic tilt from the initial position and from the *y* axis; (5) the maximal angular velocity of the epiglottic tilt; and (6) the maximal velocity of the liquid bolus. Maximal displacement was defined as the difference between the highest and lowest values. For the maximal velocity, instantaneous velocity was calculated from the distance between two adjacent time points throughout the swallowing cycle, and then the maximal value was obtained. All variables were calculated automatically using an in-house software built in MATLAB. Intra- and inter-rater reliabilities of the measurements showed good-to-excellent agreement in a previous study [15]. The accuracy of our method in measuring the distance, linear velocity, and angular velocity has also been described previously [21].

Statistical Analysis

All kinematic variables are presented as means and standard deviations. Using the independent *t* test, we compared the variables between stroke patients and healthy controls and between stroke types. One-way ANOVA was used to evaluate the differences in swallowing kinematics between the penetration–aspiration subgroups. If there was statistical significance in one-way ANOVA, post hoc analysis was performed using Bonferroni correction. Further analyses were performed on the kinematic variables of the epiglottic tilt, because they showed significant results related with aspiration. Histograms, scatter plots, and ROC curves of those variables were drawn to explore the cut-off value to identify patients at a risk for aspiration. All statistical analyses were performed using IBM SPSS Statistics 21 (IBM, Armonk, NY). *P* values <0.05 were considered statistically significant.

Results

Table 2 shows the differences in kinematic variables between the stroke patients and healthy controls. There were no significant differences in the maximal displacements of the hyoid bone and the maximal tilt angle of the epiglottis between the two groups. The maximal horizontal displacement of the larynx was lower in the stroke patients

Table 3 Comparison of kinematic variables between the stroke subgroups according to the penetration–aspiration status with liquid barium

Variables	No penetration/aspiration ($n = 35$)	Penetration ($n = 18$)	Aspiration ($n = 15$)	Control ($n = 34$)	P value*
Hyoid bone, maximal displacement (mm)					
Vertical	12.77 ± 5.24	10.66 ± 4.07	12.15 ± 5.86	12.48 ± 5.44	0.559
Horizontal	10.85 ± 3.92	12.25 ± 3.82	9.65 ± 3.15	11.40 ± 2.78	0.173
Hyoid bone, maximal displacement (% C2–C4)					
Vertical	36.46 ± 14.53	30.91 ± 11.68	35.82 ± 17.12	35.16 ± 13.50	0.588
Horizontal	31.26 ± 11.15	35.48 ± 10.75	29.02 ± 11.07	32.78 ± 8.49	0.303
Hyoid bone, maximal velocity (mm/s)					
Vertical	35.55 ± 30.50	33.36 ± 21.91	39.64 ± 18.73	46.78 ± 23.07	0.197
Horizontal	35.11 ± 18.00†	45.17 ± 20.48	40.93 ± 16.21†	58.56 ± 22.06	<0.001
Larynx, maximal displacement (mm)					
Vertical	20.25 ± 5.54	19.99 ± 3.49	19.21 ± 5.72	22.22 ± 6.66	0.274
Horizontal	4.55 ± 1.95†	4.42 ± 2.67†	4.27 ± 1.59†	6.16 ± 2.26	0.004
Larynx, maximal displacement (% C2–C4)					
Vertical	58.24 ± 15.21	58.11 ± 8.39	57.01 ± 17.37	63.19 ± 17.01	0.434
Horizontal	13.03 ± 5.83†	12.38 ± 5.46†	12.70 ± 4.68†	17.64 ± 6.62	0.002
Larynx, maximal velocity (mm/s)					
Vertical	67.66 ± 29.54†	61.18 ± 23.56†	62.69 ± 20.23†	94.83 ± 35.35	<0.001
Horizontal	16.38 ± 9.42†	17.57 ± 15.84†	22.53 ± 12.60	30.50 ± 16.13	<0.001
Epiglottis, maximal tilt angle (°)					
From the initial position	98.00 ± 18.21	95.66 ± 25.60	62.26 ± 36.95§	95.60 ± 24.36	<0.001
From the y axis	133.91 ± 13.26	125.85 ± 31.58	94.41 ± 40.67§	129.39 ± 23.88	<0.001
Epiglottis, maximal angular velocity (°/s)	797.08 ± 365.23	496.57 ± 220.90‡	331.53 ± 251.28‡	857.86 ± 372.72	<0.001
Liquid bolus, maximal velocity (mm/s)	342.50 ± 117.54†	375.76 ± 127.05†	328.35 ± 87.13†	519.50 ± 145.17	<0.001

Data are presented as mean ± SD

* P value by the one-way ANOVA

† Significant difference compared with the control group

‡ Significant difference compared with the control group and no penetration/aspiration subgroup

§ Significant difference compared with the control group, no penetration/aspiration, and penetration subgroups ($P < 0.05$ by the post hoc Bonferroni method)

(4.45 ± 2.07 mm) than in the controls (6.16 ± 2.26 mm, $P < 0.001$ by the independent t test). The results of % C2–C4 distance were similar to those of the actual distance. On the other hand, all velocity variables of the hyoid bone, larynx, epiglottis, and liquid bolus were decreased in the stroke patients compared to the controls.

In comparisons between the stroke subgroups according to the penetration–aspiration status, the kinematic variables of the epiglottis showed significant differences between the subgroups (Table 3). The maximal tilt angle of the epiglottis was lower in the aspiration subgroup (62.26 ± 36.95° from the initial position and 94.41 ± 40.67° from the y axis) than in the no penetration/aspiration subgroup (98.00 ± 18.21° from the initial position and 133.91 ± 13.26° from the y axis) and penetration subgroup (95.66 ± 25.60° from the initial position and 125.85 ± 31.58° from the y axis) as well as the healthy controls (95.60 ± 24.36° from the initial position and 129.39 ± 23.88° from the y axis). The maximal angular velocity of the epiglottis was lower in the penetration (496.57 ± 220.90°/s) and aspiration subgroups (331.53 ± 251.28°/s) than in the no penetration/aspiration subgroup (797.08 ± 365.23°/s) and healthy controls (857.86 ± 372.72°/s), respectively ($P < 0.05$ by one-way ANOVA with post hoc Bonferroni correction).

For further analysis on the epiglottic tilt during swallowing, histograms of the maximal tilt angle from the initial position and the y axis, and the maximal angular velocity of the epiglottis were drawn (Fig. 2a). The maximal tilt angle from the y axis showed a dichotomous pattern at 90° of the angle. In the scatter plot, all 11 patients with an angle <90° showed either penetration or aspiration (Fig. 2b). In the ROC curve of the angle for prediction of aspiration, the area under the curve was 0.725 (95 % CI 0.557–0.892, $P = 0.008$) (Fig. 2c). Sensitivity, specificity,

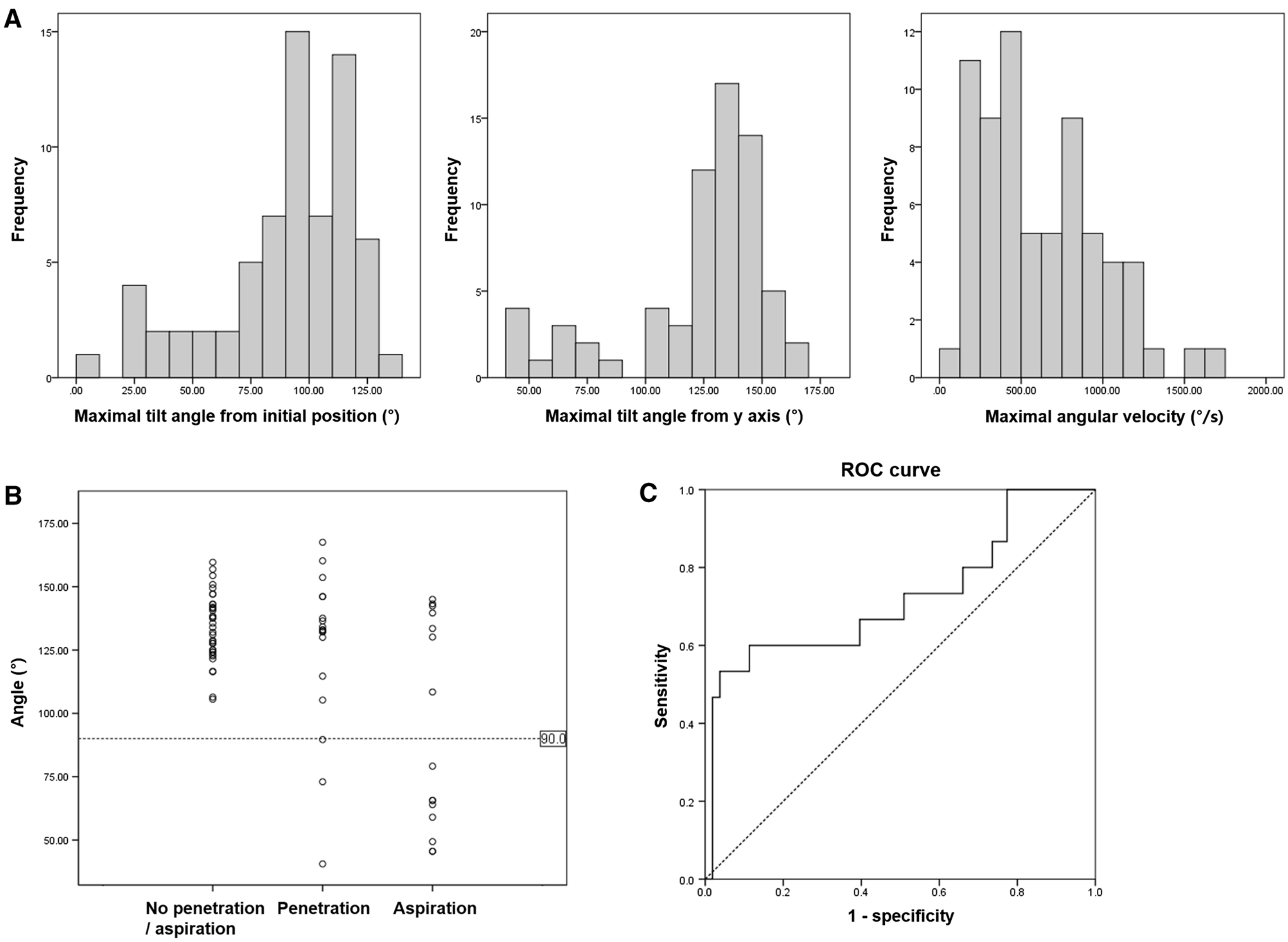

Fig. 2 **a** Distribution of maximal tilt angles and velocities of the epiglottis in the stroke patients. The maximal tilt angle from the *y* axis showed a dichotomous pattern at 90° of the angle. **b** Scatter plots of the maximal tilt from the *y* axis in the no aspiration/penetration, penetration, and aspiration subgroups of the stroke patients. All 11 patients with an angle <90° showed either penetration or aspiration. **c** The ROC curve of the maximal tilt angle from the *y* axis for prediction of aspiration. The area under the curve was 0.725 (95 % CI 0.557–0.892, $P = 0.008$)

Table 4 Sensitivity and specificity for aspiration according to the cut-off value of maximal tilt angle of the epiglottis from the *y* axis

Cut-off value (°)	Sensitivity	Specificity	Positive predictive value	Negative predictive value
60	0.267	0.981	0.800	0.825
70	0.467	0.962	0.875	0.867
80	0.533	0.962	0.800	0.879
90	0.533	0.943	0.727	0.877
100	0.533	0.943	0.727	0.877
110	0.600	0.887	0.600	0.887
120	0.600	0.811	0.500	0.880

positive predictive value, and negative predictive value for aspiration were 0.533, 0.943, 0.727, and 0.877, respectively, at the cut-off value of 90°. Table 4 shows the changes in these parameters according to the cut-off value.

Among stroke types, patients with hemorrhagic stroke had lower values of maximal vertical displacement and velocity of the hyoid bone and maximal vertical displacement of the larynx (9.27 ± 3.71 mm, 25.90 ± 16.00 mm/s, and 17.57 ± 5.68 mm, respectively) than patients with ischemic stroke (13.42 ± 5.22 mm, 40.89 ± 28.72 mm/s, and 21.11 ± 4.41 mm, respectively; $P < 0.05$ by independent *t* test). There was no significant difference in all measurements between patients with supratentorial and infratentorial lesions and between those with right- and left-brain lesions.

Discussion

A remarkable finding of this study was the decrease in the maximal velocities of all relevant structures for swallowing without decrease in the movement distances in stroke patients compared to healthy controls. This is a novel finding that has not been reported previously. Only the horizontal movement of the larynx decreased significantly in the stroke patients. Pharyngeal swallow is a rapid sequential activity, occurring within a second [17]. Because the maximal velocity presented the maximal instantaneous velocity in our analysis, these findings suggest that sluggish movement of hyolaryngeal structures during swallowing is one of the pathological changes seen in post-stroke dysphagia.

Two previous studies compared the distances of hyolaryngeal movements during swallowing between stroke and healthy subjects. Our previous pilot study, which presented the maximal vertical and horizontal movements of the hyoid bone in stroke and healthy subjects, showed no significant difference between the two groups [6]. In a large study comparing 105 stroke patients and 100 healthy controls [8], distances of hyolaryngeal movements during swallowing were comparable between stroke patients without aspiration and controls. The present study also showed no significant difference in these movement distances between stroke patients and healthy controls except the horizontal movement of the larynx. The horizontal movement of the larynx is well known to contribute to the opening of the upper esophageal sphincter [18]. Therefore, decreased bolus velocity or cricopharyngeal muscle dysfunction may cause this change after stroke. Taken together, these results indicate that the influence of stroke on the distances of hyolaryngeal movements during swallowing is minimal.

Both maximal tilt angle and angular velocity of the epiglottis during swallowing significantly decreased in stroke patients with aspiration. Stroke patients with penetration showed decreased maximal angular velocity but a similar maximal tilt angle of the epiglottis compared to those without penetration–aspiration and the healthy controls. The movement of the epiglottis has been known as an important mechanism of airway protection during swallowing [17]. During a normal swallow, the epiglottis moves from its vertical resting position to a complete downward tilt and then returns to the resting position [22–25]. The downward epiglottis tilt is a very rapid movement, which takes 100 ms or less during a normal swallow [23–25]. Decreased and blunted epiglottic movement may cause incomplete laryngeal protection when the food bolus reaches the lower pharynx; therefore, it could be the mechanism of penetration–aspiration in stroke patients. On the other hand, it has been suggested that thyrohyoid approximation by laryngeal elevation and anterior displacement of the hyoid bone produces an epiglottic tilt during swallowing [23]. Airway protection during swallowing occurs by contact of the epiglottic petiole with the arytenoids, which closes the laryngeal vestibule. Inadequate opening of the upper esophageal sphincter, which is related with anterior displacement of the hyoid bone, may also cause aspiration. Therefore, reduced epiglottic movement may represent abnormal hyolaryngeal movements causing aspiration.

The maximal tilt angle of the epiglottis from the *y* axis, which was defined by the cervical vertebral column, showed a dichotomous pattern at 90° in the histogram. Our previous study also showed a dichotomous pattern in the distribution of the maximal tilt angle of the epiglottis from the initial position in the early state of post-stroke dysphagia [15]. We postulated that the dysfunctional epiglottic tilt after stroke may occur in an “all or none” manner and subsequently show gradual improvement. Because the initial position of the epiglottis is variable, the tilt angle from the *y* axis may represent the functional angle of the epiglottic tilt for laryngeal protection. The 90° angle from the *y* axis represents an almost horizontal position of the epiglottis. Considering the passive mechanism of the epiglottic tilt, the downward tilt can be induced by anterior displacement of the hyoid bone only when the epiglottis reaches below the horizontal by thyrohyoid approximation [23]. Therefore, reaching the horizontal position, which is 90° from the *y* axis, may be the threshold for a complete downward tilt of the epiglottis during a swallow. In our study, all 11 patients with an angle <90° showed either penetration or aspiration, and among them, 8 patients (72.7 %) had aspiration. In a previous study on epiglottis dysfunction, 100 % of patients with no functional movement and posterior translocation and 70.7 % with a horizontal tilt showed aspiration during swallowing [26]. Our result corroborated the previous finding of epiglottis dysfunction. However, because values from the ROC curve and sensitivity/specificity analyses were approximate in this retrospective study, further study in a validation cohort would be required to determine the accurate predictive value of the epiglottic angle for aspiration.

Our study included both actual and anatomically normalized distances of hyolaryngeal movements during swallowing. A recent review article on physiological factors related to aspiration risk suggested anatomically normalized measures, but not actual distances, of hyoid movement as a parameter relevant to aspiration risk [4].

This argument was based on a previous study [27], but this result was not replicated in a subsequent investigation on stroke patients [5]. The present study suggested that both actual and normalized distances of hyolaryngeal movements during swallowing were not related with aspiration risk in stroke patients. Both measurements demonstrated the same results in our analysis. Although it was reported that anatomical normalization reduced the variation attributable to sex-based differences in measures of hyoid excursion [28], there has been no clear evidence regarding the measurement is considered appropriate kinematic analysis on swallowing. It is worthwhile to include both measurements in the analysis until further clarification is obtained based on future investigations.

The study population was heterogeneous because patients with all types of stroke were included to investigate swallowing kinematics of stroke patients in general. There was no significant difference in swallowing kinematics between patients with supratentorial and infratentorial lesions and between those with right and left lesions. On the other hand, vertical hyolaryngeal movements reduced significantly in patients with hemorrhagic stroke than in those with ischemic stroke. This finding might reflect reduced tongue movement during swallowing in patients with hemorrhagic stroke because the vertical hyoid motion is known to be primarily related to events in the oral cavity [29]. Functional differences between hemorrhagic and ischemic stroke patients have been reported [30, 31], whereas there has been no direct comparison of swallowing kinematics between these two stroke types. Although this heterogeneity might mask some differences, there was no significant difference in kinematic variables of the epiglottic tilt related with aspiration, between the stroke types. Further studies are needed to elucidate differences in swallowing kinematics between stroke types because ours is a preliminary analysis without a matched comparison.

This study has several limitations. A two-dimensional analysis may miss some features, such as vocal cord closure that can be detected only in the recently developed, three-dimensional dynamic computed tomography [32]. The three-dimensional analysis may elucidate additional pathophysiology of post-stroke dysphagia in future studies. Kinematic analysis of swallowing also does not include several physiological factors that may be related with aspiration risk, such as tongue strength [33], pharyngeal pressure [34], and swallowing coordination with respiration [35]. In addition, our kinematic analysis did not include timing of swallowing events. Temporal parameters such as delay in laryngeal elevation [10] or anterior hyoid excursion [11] and upper esophageal sphincter opening duration [5] have been suggested to be related with aspiration risk. Although our analysis suggested that decreased epiglottic movement could contribute to aspiration in stroke patients, 7 among 60 patients with maximal epiglottic tilt angle >90° from the *y* axis had aspiration. These patients may have had other aspiration-related pathophysiology besides kinematic abnormalities in swallowing. In addition, this was a retrospective study on selected patients in whom two-dimensional motion digitization was possible. Although the present study included a relatively large sample of stroke patients as well as age- and sex-matched healthy controls, the result is limited in its generalization to all stroke patients. Lastly, our analysis was based on one swallow per participant. Because swallowing kinematics may exhibit some variability on repeated testing in the same subject, more reliable results can be drawn from kinematic data that includes several swallows per participant.

Conclusions

This study suggested that sluggish rather than decreased hyolaryngeal movements during swallowing are a remarkable feature of post-stroke dysphagia. Our findings will be helpful in understanding the pathological changes in swallowing that are seen post-stroke. The association of reduced epiglottic movement with the risk of aspiration in patients with post-stroke dysphagia was supported by quantitative measurement of epiglottic tilt during swallowing. On the other hand, both actual and normalized distances of the hyolaryngeal movements were not related with aspiration risk. A prospective study involving a large number of participants and several swallows per participant is warranted to clarify the association between swallowing kinematics and aspiration in patients with post-stroke dysphagia.

Compliance with Ethical Standards

Conflict of interest The authors have no conflicts of interest to declare.

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Han Gil Seo MD

Byung-Mo Oh MD, PhD

Tai Ryoon Han MD, PhD