doi: 10.2490/prm.20250009 Progress in Rehabilitation Medicine 2025; Vol. 10, 20250009

ORIGINAL ARTICLE

Hyoid Bone Velocity and Distance during the Forward Phase Correlate with Pyriform Sinus Residue: A Retrospective Case Series

Hironori Arii, MD [a] and Tetsuro Sakai MS [b,c]

Objectives: This study investigated the relationship between the three phases of hyoid bone movement and pharyngeal residue using the videofluoroscopic swallowing study (VFSS). **Methods:** We retrospectively analyzed the data from 66 patients who underwent VFSS between April 2019 and December 2019. Hyoid bone movement was classified into three phases: upward, forward, and downward. We measured the velocity and distance of hyoid bone movement in each phase, as well as the pharyngeal residue after swallowing. The correlation between hyoid bone movement and the amount of pharyngeal residue was analyzed using Spearman's rank correlation coefficient. A receiver operating characteristic (ROC) analysis was performed to evaluate the presence of pyriform sinus residue. **Results:** Hyoid bone velocity and distance during the forward phase correlated with the amount of pyriform sinus residue (velocity: r=0.311, P=0.011; distance: r=0.255, P=0.0389). ROC analysis revealed that the cutoff value for hyoid bone velocity during the forward phase was 26.1 mm/s (0.846 sensitivity, 0.604 specificity) with an area under the curve of 0.717. **Conclusions:** The velocity and distance of the hyoid bone during the forward phase were significantly related to the amount of pyriform sinus residue. In VFSS assessment, it is important to classify hyoid bone movement into three phases—upward, forward, and downward—and to calculate its velocity and distance.

Key Words: aspiration; dysphagia; pyriform sinus; rehabilitation; swallowing dysfunction

INTRODUCTION

Dysphagia, which is a geriatric syndrome affecting 10% to 33% of older adults, is commonly seen in those who have experienced a stroke or neurodegenerative diseases such as Alzheimer's disease or Parkinson disease.[1] Additionally, dysphagia can lead to aspiration, which may result in severe complications such as aspiration pneumonia, malnutrition, and dehydration.[2–4] Therefore, the prevention and treatment of dysphagia are important in older adults.

A videofluoroscopic swallowing study (VFSS) is a tool used to assess hyoid bone movement and the swallowing function. Previous studies have shown that, particularly in the elderly, there is a decrease in the displacement of the hyoid bone during swallowing, even among healthy individuals.[5–7] Various studies have investigated the relationship between hyoid bone movement and swallowing. A reduction in the total distance of hyoid bone movement can lead to increased pharyngeal residue and aspiration, whereas the extent of anterior displacement of the hyoid bone is a predictive factor for the risk of aspiration.[8,9] Moreover, the maximum horizontal or vertical displacement of the hyoid bone is associated with the risk and severity of aspiration.[10] These studies clarified that decreased hyoid bone movement is associated with pharyngeal residue and aspiration.

In recent years, some studies have reported on the rela-

Received: December 4, 2024, Accepted: March 31, 2025, Published online: April 9, 2025
[a] Division of Rehabilitation, Gunma University Hospital, Maebashi, Japan
[b] Department of Speech-Language-Hearing Therapy, Gunma Paz University, Takasaki, Japan
[c] Division of Rehabilitation, Fujioka General Hospital, Fujioka, Japan
Correspondence: Hironori Arii, MD, 3-39-15, Showa-machi, Maebashi, Gunma 371-8511, Japan, E-mail: hiro-arii@gunma-u.ac.jp

tionship between hyoid bone velocity and dysphagia. Chen et al.[11] reported that stroke patients with aspiration were associated with a lower maximal horizontal instantaneous velocity of hyoid bone excursion when compared with non-aspirators. Lee et al.[12] found that maximal horizontal velocity in forward hyoid motions were significantly reduced in post-stroke patients with poor prognosis of swallowing function when compared with those with good prognosis. In these studies, they calculated the velocity of the hyoid bone at each moment during its movement, requiring numerous measurements of hyoid bone coordinates. Therefore, based on a study by Hasegawa et al.,[13] we divided hyoid bone movement into three phases: upward, forward, and downward, and measured only four hyoid bone coordinates to calculate the velocity and distance of each phase. To the best of our knowledge, we are the first to propose this simple and effective method for calculating hyoid bone velocity and distance of movement. The primary objective of this study was to investigate the correlation between hyoid bone movement in each phase and the amount of residue in the pyriform sinus and vallecula. Conventional evaluation of hyoid bone movement is based on displacement from the resting position to the point of maximum deviation and requires the measurement of two hyoid bone coordinates to calculate velocity and distance.[10,14] The secondary objective of our study was to compare this conventional method with our measurement approach.

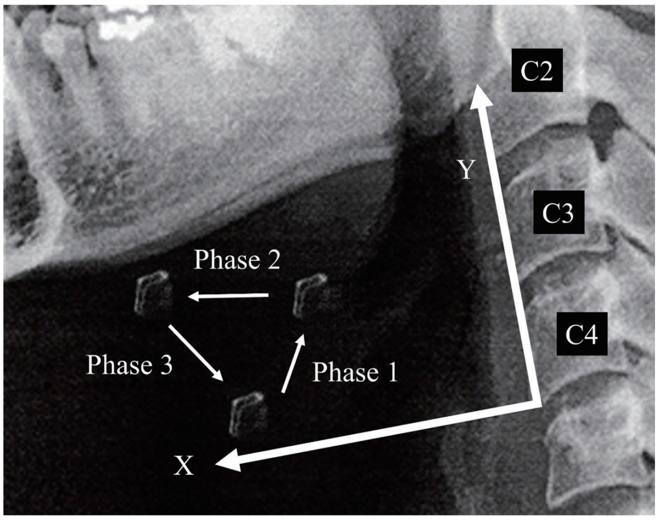

Fig. 1. Definition of the X and Y axes and the three phases of hyoid bone movement during swallowing: Phase 1 (upward phase), Phase 2 (forward phase), and Phase 3 (downward phase).

MATERIALS AND METHODS

We conducted a retrospective analysis of VFSS performed at Fujioka General Hospital between April 2019 and December 2019. Given the retrospective nature of the study, informed consent was obtained using an opt-out approach. Study details were disclosed on the hospital's website to provide participants with the opportunity to decline participation. This study was approved by the Ethics Committee of Fujioka General Hospital (Approval number: 02–30).

The inclusion criterion was all cases that underwent VFSS at our hospital during the study period. The following exclusion criteria were used: (1) absence of a swallowing reflex during the examination, (2) use of endoscopy or manometry during the examination, and (3) presence of a tracheostomy. Of the 90 eligible cases, 24 were excluded, and VFSS data from the remaining 66 patients were analyzed. We did not homogenize the diseases for the analysis, because we aimed to investigate whether the hyoid bone movement in each phase are measurable parameters for predicting the amount of pharyngeal residue, even in a heterogeneous population.

All VFSS were performed with images recorded during the ingestion of barium jelly. The barium jelly had consistent properties (yield stress, 4113 N/m^2; cohesion, 0.47; adhesion, 63.1 J/m^3) and all patients received the same quantity (4 g). The most appropriate backrest angle for the patient was determined through a pre-examination bedside assessment by a speech-language pathologist, and the VFSS was conducted at that angle. The filming speed of the VFSS was set to 30 frames per second. Image analysis was performed using ImageJ (ver. 1.53r; National Institutes of Health, Bethesda, MD, USA). A 10-mm-diameter iron ball was attached to the midline of the mandible to serve as a reference for the measurements. The origin was set at the anterior inferior aspect of the C4 vertebra, with a straight line drawn from the origin towards the anterior inferior aspect of the C2 vertebra, defining this line as the Y-axis. The X-axis was set perpendicular to the Y-axis (**Fig. 1**).

Hyoid bone movement during swallowing was classified into three phases based on a study by Hasegawa et al.[13] The phases were defined as follows: Phase 1 (upward phase), Phase 2 (forward phase), and Phase 3 (downward phase) (**Fig. 1**). The starting point of Phase 1 was defined as the point where the hyoid bone begins to move upward after being in the resting position. The endpoint of Phase 1 and the starting point of Phase 2 were defined as the point where the direction of movement changes from upward to forward. The endpoint

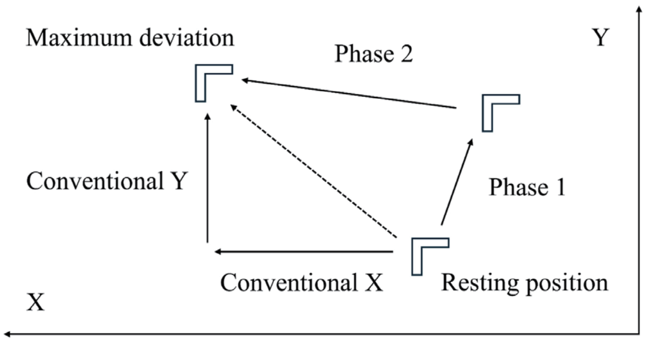

Fig. 2. Definition of conventional velocity and distance of hyoid bone movement. Conventional Velocity X, Conventional Distance X, Conventional Velocity Y, and Conventional Distance Y were calculated using the displacement in the X and Y directions from the starting point of Phase 1 to the endpoint of Phase 2.

of Phase 2 and the starting point of Phase 3 were defined as the point where the direction of movement changes from forward to downward. The endpoint of Phase 3 was defined as the lowest point reached by the downward movement. The hyoid bone distance in each phase was calculated using the Pythagorean theorem based on the measured X and Y coordinates of the start and endpoint of each phase. The hyoid bone velocity for each phase was determined by dividing the distance by time. Velocity and distance were labeled using the same numbering system, with Phase 1 velocity denoted as Velocity 1 and distance as Distance 1.

The conventional evaluation of hyoid bone movement is based on displacement from the resting position to the point of maximum deviation.[10,14] Following this method, we calculated Conventional Velocity X, Conventional Distance X, Conventional Velocity Y, and Conventional Distance Y using the displacement in the X and Y directions from the starting point of Phase 1 to the endpoint of Phase 2, as well as the time between them (**Fig. 2**).

In addition, based on the standard methods for VFSS from the Japanese Society of Dysphagia Rehabilitation,[15] pyriform sinus residue was categorized as follows: 3, none; 2, none to half of the pyriform sinus; and 1, half to filled pyriform sinus. Similarly, vallecular residue was classified as follows: 3, none; 2, none to half of the vallecula; and 1, half to filled vallecula.

Measurements were performed by a physician specializing in rehabilitation, who was responsible for assessing the hyoid bone movement. A speech-language pathologist, who was blinded to the results, measured the amount of pharyngeal residue.

Table 1. Characteristics of patients

Characteristic	n=66
Sex	
Male	49 (74%)
Female	17 (26%)
Age (years)	78.1±8.4
Height (m)	1.58±0.08
Body weight (kg)	49.9±11.5
Body mass index (kg/m^2)	20.0±4.0
Backrest angle	
30°	3 (5%)
45°	6 (9%)
60°	7 (11%)
75°	50 (75%)
Diagnosis	
Pneumonia	38 (58%)
Cerebrovascular disorders	14 (21%)
Other disease	14 (21%)
FILS	6.7±1.5

Data given as mean ± standard deviation or number (percentage).

Statistical analyses were performed using R (ver. 4.3.1). The correlation between hyoid bone movement and the amount of pharyngeal residue was analyzed using Spearman's rank correlation coefficient. Statistical significance was recognized for $P<0.05$. A receiver operating characteristic (ROC) analysis was conducted to evaluate whether hyoid bone velocity and distance could be used to detect the presence of pharyngeal residue.

RESULTS

The participant cohort included 49 men and 17 women (mean age 78.1 ± 8.4 years). All patients underwent VFSS to assess their swallowing function and determine a rehabilitation plan. The following backrest angles were used during VFSS: 30°, 3 patients (5%); 45°, 6 patients (9%); 60°, 7 patients (11%); and 75°, 50 patients (75%). The most common diagnosis was pneumonia in 38 patients (58%), followed by cerebrovascular disorders in 14 patients (21%) and other diseases in 14 patients (21%) (**Table 1**). If pneumonia was the reason for undergoing VFSS, patients with a history of cerebrovascular disorders were recorded as pneumonia. Among other diseases, there were 3 patients with bowel obstructions, and the following eleven conditions were each represented by 1 patient: tracheal injury, pseudogout, urinary tract infection, traumatic subarachnoid hemorrhage, lung ad-

Table 2. Correlation between hyoid bone movement and amount of pyriform sinus residue

Measurement	Mean ± SD	r	P value
Velocity 1 (mm/s)	41.8 ± 24.4	−0.127	0.308
Velocity 2 (mm/s)	28.4 ± 15.6	0.311	0.011*
Velocity 3 (mm/s)	24.1 ± 12.9	0.0752	0.549
Conventional Velocity X (mm/s)	20.6 ± 10.8	0.0664	0.596
Conventional Velocity Y (mm/s)	14.7 ± 13.6	−0.0630	0.615
Distance 1 (mm)	8.43 ± 4.94	−0.105	0.399
Distance 2 (mm)	8.97 ± 4.01	0.255	0.0389*
Distance 3 (mm)	14.8 ± 4.53	0.0558	0.656
Conventional Distance X (mm)	10.5 ± 4.72	0.0976	0.436
Conventional Distance Y (mm)	7.87 ± 6.76	−0.0835	0.505

* P<0.05, statistically significant.

enocarcinoma, lumbar spine compression fracture, chronic obstructive pulmonary disease, heart failure, symptomatic epilepsy, femoral neck fracture, and pleural effusion. The average Food Intake Level Scale (FILS) score before VFSS was 6.7 ± 1.5.

Significant correlations were found between Velocity 2 and the amount of pyriform sinus residue (r=0.311, P=0.011), as well as between Distance 2 and pyriform sinus residue (r=0.255, P=0.0389) (**Table 2**, **Fig. 3**). In contrast, no significant correlation was found between hyoid bone movement and the amount of vallecular residue (**Table 3**). In addition, no significant correlation was found between conventional measurements and the amount of pyriform sinus or vallecular residue (**Tables 2 and 3**). ROC analysis for detecting the presence of pyriform sinus residue revealed that the cutoff value for Velocity 2 was 26.1 mm/s, with 0.846 sensitivity, 0.604 specificity, and an area under the curve (AUC) of 0.717 (**Table 4**, **Fig. 4**).

We performed a post hoc power analysis using G*Power (version 3.1.9.7, Heinrich Heine University, Düsseldorf, Germany) to evaluate the statistical power of the Spearman's correlation analysis. The achieved power (1−β) was calculated based on the observed correlation coefficient between Velocity 2 and pyriform sinus residue (r=0.311), an alpha level of 0.05, and a sample size of 66. The statistical power for detecting this correlation was 0.824, indicating that the sample size was sufficient to detect a significant association.

DISCUSSION

VFSS is widely used to evaluate swallowing function, and many studies have reported on the hyoid bone movement and swallowing function.[8–10] In this study, we divided

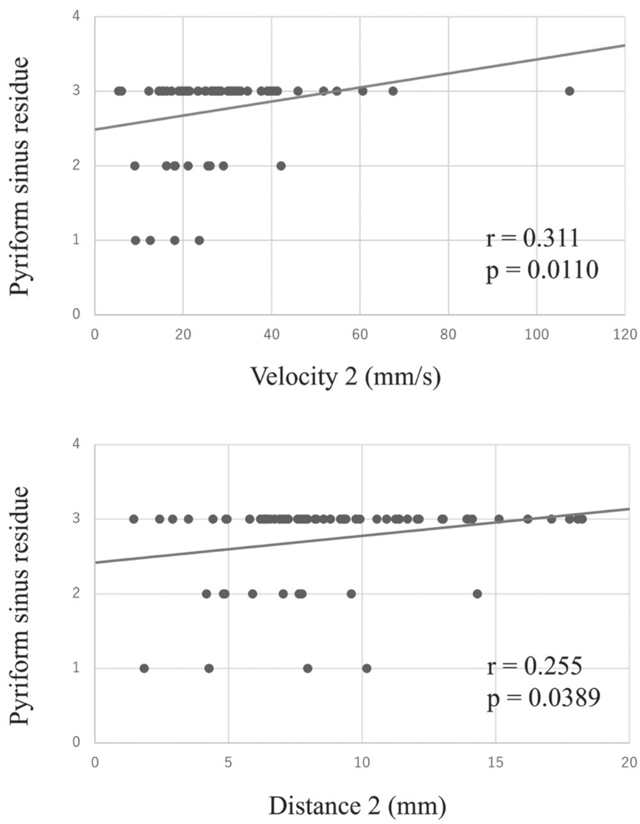

Fig. 3. Scatter plots of hyoid bone movement and pyriform sinus residue. In the upper plot, Velocity 2 represents the velocity of the hyoid bone during the forward phase. In the lower plot, Distance 2 represents the distance of the hyoid bone during the forward phase. The amount of pyriform sinus residue was classified as follows: 3, none; 2, none to half of the pyriform sinus; and 1, half to filled pyriform sinus.

Table 3. Correlation between hyoid bone movement and amount of vallecular residue

Measurement	Mean ± SD	r	P value
Velocity 1 (mm/s)	41.8 ± 24.4	0.241	0.0514
Velocity 2 (mm/s)	28.4 ± 15.6	0.00438	0.972
Velocity 3 (mm/s)	24.1 ± 12.9	0.193	0.120
Conventional Velocity X (mm/s)	20.6 ± 10.8	0.141	0.259
Conventional Velocity Y (mm/s)	14.7 ± 13.6	0.0639	0.610
Distance 1 (mm)	8.43 ± 4.94	0.198	0.111
Distance 2 (mm)	8.97 ± 4.01	−0.0513	0.682
Distance 3 (mm)	14.8 ± 4.53	0.234	0.0586
Conventional Distance X (mm)	10.5 ± 4.72	0.149	0.231
Conventional Distance Y (mm)	7.87 ± 6.76	0.0643	0.608

Table 4. ROC analyses for predicting pyriform sinus residue

Measurement	AUC	95% Confidence interval	Cutoff value	Sensitivity	Specificity
Velocity 1 (mm/s)	0.398	0.224–0.572	35.5	0.538	0.528
Velocity 2 (mm/s)	0.717	0.564–0.87	26.1	0.846	0.604
Velocity 3 (mm/s)	0.567	0.369–0.87	20.7	0.615	0.585
Conventional Velocity X (mm/s)	0.469	0.283–0.655	20.5	0.538	0.547
Conventional Velocity Y (mm/s)	0.541	0.381–0.702	2.12	1.000	0.170
Distance 1 (mm)	0.559	0.391–0.726	3.94	1.000	0.226
Distance 2 (mm)	0.684	0.521–0.846	7.96	0.769	0.556
Distance 3 (mm)	0.552	0.373–0.73	11.9	0.462	0.717
Conventional Distance X (mm)	0.560	0.375–0.746	8.23	0.462	0.698
Conventional Distance Y (mm)	0.453	0.287–0.619	17.2	1.000	0.113

hyoid bone movement into three phases and examined the correlation between pharyngeal residue and the velocity and distance of hyoid bone movement in each phase.

Previous studies have reported associations between forward velocity and distance of the hyoid bone and aspiration or swallowing disorders.[10–12] These reports suggest that forward movement of the hyoid bone is closely related to swallowing function. In our study, significant correlations were observed between Velocity 2 and pyriform sinus residue and between Distance 2 and pyriform sinus residue. These findings suggested that faster and greater movement of the hyoid bone during the forward phase is important for reducing pyriform sinus residue. Previous studies have reported that forward movement of the hyoid bone is associated with opening of the upper esophageal sphincter.[8,16–18] Therefore, faster and greater forward movement of the hyoid bone can lead to sufficient opening of the upper esophageal sphincter, reducing stasis in the pyriform sinus.

In our study, Conventional Velocity X and Conventional Distance X did not show significant correlations with pyriform sinus residue. In addition, ROC analysis for detecting the presence of pyriform sinus residue indicated that Velocity 2 was the most practical indicator and that the AUC of Conventional Velocity X was smaller than that of Velocity 2. The conventional method calculates the forward hyoid bone velocity using coordinates from the resting position to the point of maximum deviation during swallowing.[10,14] As a result, the conventional measurement combined the upward (Phase 1) and forward (Phase 2) phases of hyoid bone movement as defined in our method. These methodological differences in measurement may explain the discrepancies in the Spearman correlation coefficient and ROC analysis results. Our measurement method, which classifies hyoid bone movement into three phases, was considered more useful than the conventional method.

It is known that upward movement of the hyoid bone is associated with epiglottis closure.[6,19] We expected that the velocity and distance of the upward phase would be correlated with vallecular residue. However, our study did not find significant correlation between the amount of vallecular

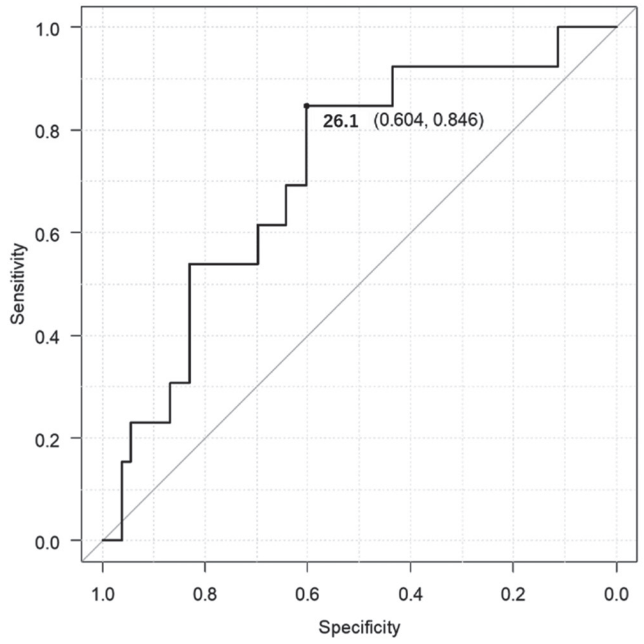

Fig. 4. ROC curve of hyoid bone velocity during the forward phase for predicting pyriform sinus residue. The cutoff value for predicting pyriform sinus residue was 26.1 mm/s for Velocity 2, with 0.846 sensitivity, 0.604 specificity, and an AUC of 0.717. Velocity 2 represents the velocity of the hyoid bone during the forward phase.

residue and any measurement of hyoid bone movement. The highest correlation coefficient was found for Velocity 1 (r=0.241, P=0.0514), but it was not statistically significant. Vallecular residue may also be influenced by other factors, such as increased maximum pharyngeal constriction area and decreased tongue driving force, which might explain the lack of correlation with the upward movement of the hyoid bone in our study.[20,21]

The method of dividing hyoid bone movement into three phases and measuring the distance and velocity during VFSS requires time and effort. Therefore, it is impractical to measure hyoid bone movement during each VFSS. However, recent advancements, such as deep learning methods for automated measurement of hyoid bone movement, may resolve this problem.[22,23]

In this study, we emphasize the importance of hyoid bone movement during swallowing. The movement of the hyoid bone is particularly influenced by the suprahyoid muscles, and various rehabilitation techniques aimed at strengthening these muscles have been reported, including Shaker exercises, chin tuck against resistance, jaw-retraction exercises, tongue pressure resistance exercises, and neuromuscular electrical stimulation.[13,24–28] Future research will focus on determining which of these rehabilitation methods most effectively improves hyoid bone movement and the swallowing function.

This study had one limitation. The backrest angle during VFSS could not be standardized. Previous studies have reported that the muscle activity of the suprahyoid and infrahyoid muscles varies depending on the backrest angle and sitting posture.[29,30] Therefore, the backrest angle during VFSS may have influenced the results of our study.

CONCLUSION

The velocity and distance of the hyoid bone during the forward phase are significant VFSS parameters related to the amount of pyriform sinus residue. In VFSS assessment, it is important to classify hyoid bone movement into three phases—upward, forward, and downward—and to calculate its velocity and distance.

ACKNOWLEDGMENTS

The authors thank the study participants.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

REFERENCES

1. Thiyagalingam S, Kulinski AE, Thorsteinsdottir B, Shindelar KL, Takahashi PY: Dysphagia in older adults. Mayo Clin Proc 2021;96:488–497. https://doi.org/10.1016/j.mayocp.2020.08.001, PMID:33549267
2. Cook IJ, Kahrilas PJ: AGA technical review on management of oropharyngeal dysphagia. Gastroenterology 1999;116:455–478. https://doi.org/10.1016/S0016-5085(99)70144-7, PMID:9922328
3. Gordon C, Hewer RL, Wade DT: Dysphagia in acute stroke. BMJ 1987;295:411–414. https://doi.org/10.1136/bmj.295.6595.411, PMID:3115478
4. Humbert IA, Robbins J. Dysphagia in the elderly. Phys Med Rehabil Clin N Am 2008;19:853–866. https://doi.org/10.1016/j.pmr.2008.06.002, , PMID:18940645
5. Molfenter SM, Steele CM: Physiological variability in the deglutition literature: hyoid and laryngeal kinematics. Dysphagia 2011;26:67–74. https://doi.org/10.1007/s00455-010-9309-x, PMID:20927634

6. Kim Y, McCullough GH: Maximum hyoid displacement in normal swallowing. Dysphagia 2008;23:274–279. https://doi.org/10.1007/s00455-007-9135-y, PMID:17962998
7. Kang BS, Oh BM, Kim IS, Chung SG, Kim SJ, Han TR: Influence of aging on movement of the hyoid bone and epiglottis during normal swallowing: a motion analysis. Gerontology 2010;56:474–482. https://doi.org/10.1159/000274517, PMID:20068282
8. Steele CM, Bailey GL, Chau T, Molfenter SM, Oshalla M, Waito AA, Zoratto DC: The relationship between hyoid and laryngeal displacement and swallowing impairment. Clin Otolaryngol 2011;36:30–36. https://doi.org/10.1111/j.1749-4486.2010.02219.x, PMID:21414151
9. Zhang Z, Perera S, Donohue C, Kurosu A, Mahoney AS, Coyle JL, Sejdić E: The prediction of risk of penetration–aspiration via hyoid bone displacement features. Dysphagia 2020;35:66–72. https://doi.org/10.1007/s00455-019-10000-5, PMID:30919104
10. Molfenter SM, Steele CM: Kinematic and temporal factors associated with penetration–aspiration in swallowing liquids. Dysphagia 2014;29:269–276. https://doi.org/10.1007/s00455-013-9506-5, PMID:24445381
11. Chen SY, Wei KC, Cheng SH, Wang TG, Hsiao MY: The hyoid bone kinematics in dysphagic stroke patients: instantaneous velocity, acceleration and temporal sequence matters. Dysphagia 2023;38:1598–1608. https://doi.org/10.1007/s00455-023-10587-w, PMID:37231195
12. Lee WH, Lim MH, Seo HG, Oh BM, Kim S: Hyoid kinematic features for poor swallowing prognosis in patients with post-stroke dysphagia. Sci Rep 2021;11:1471. https://doi.org/10.1038/s41598-020-80871-4, PMID:33446787
13. Hasegawa S, Nakagawa K, Yoshimi K, Yamaguchi K, Nakane A, Ishii M, Okumura T, Hara K, Minakuchi S, Tohara H: Jaw-retraction exercise increases anterior hyoid excursion during swallowing in older adults with mild dysphagia. Gerodontology 2022;39:98–105. https://doi.org/10.1111/ger.12595, PMID:34672024
14. Wei KC, Cheng SH, Hsiao MY, Wang YC, Weng CH, Chen JY, Wang TG: Swallowing kinematic analysis might be helpful in predicting aspiration and pyriform sinus stasis. Sci Rep 2022;12:1354. https://doi.org/10.1038/s41598-022-05441-2, PMID:35079109
15. Takaharu N, Akitoshi K, Tamami K, Koji T, Itaru T, Yoji H, Yuri F, Hiroko Y, Ichiro F: Method of videofluoroscopic swallowing study. Japanese Society of Dysphagia Rehabilitation. 2014. https://www.jsdr.or.jp/wp-content/uploads/file/doc/VF18-2-p166-186.pdf. Accessed 29 Jan 2025.
16. Jacob P, Kahrilas PJ, Logemann JA, Shah V, Ha T: Upper esophageal sphincter opening and modulation during swallowing. Gastroenterology 1989;97:1469–1478. https://doi.org/10.1016/0016-5085(89)90391-0, PMID:2583413
17. Zhang J, Zhou Y, Wei N, Yang B, Wang A, Zhou H, Zhao X, Wang Y, Liu L, Ouyoung M, Villegas B, Groher M: Laryngeal elevation velocity and aspiration in acute ischemic stroke patients. PLoS One 2016;11:e0162257. https://doi.org/10.1371/journal.pone.0162257, PMID:27583413
18. Ishida R, Palmer JB, Hiiemae KM: Hyoid motion during swallowing: factors affecting forward and upward displacement. Dysphagia 2002;17:262–272. https://doi.org/10.1007/s00455-002-0064-5, PMID:12355141
19. Yokoyama M, Mitomi N, Tetsuka K, Tayama N, Niimi S: Role of laryngeal movement and effect of aging on swallowing pressure in the pharynx and upper esophageal sphincter. Laryngoscope 2000;110:434–439. https://doi.org/10.1097/00005537-200003000-00021, PMID:10718434
20. Stokely SL, Peladeau-Pigeon M, Leigh C, Molfenter SM, Steele CM: The relationship between pharyngeal constriction and post-swallow residue. Dysphagia 2015;30:349–356. https://doi.org/10.1007/s00455-015-9606-5, PMID:25920993
21. Dejaeger E, Pelemans W, Ponette E, Joosten E: Mechanisms involved in postdeglutition retention in the elderly. Dysphagia 1997;12:63–67. https://doi.org/10.1007/PL00009520, PMID:9071804
22. Kim HI, Kim Y, Kim B, Shin DY, Lee SJ, Choi SI. Hyoid bone tracking in a videofluoroscopic swallowing study using a deep-learning-based segmentation network. Diagnostics 2021;23;1147. https://doi.org/10.3390/diagnostics11071147 , PMID:34201839
23. Hsiao MY, Weng CH, Wang YC, Cheng SH, Wei KC, Tung PY, Chen JY, Yeh CY, Wang TG: Deep learning for automatic hyoid tracking in videofluoroscopic swallow studies. Dysphagia 2023;38:171–180. https://doi.org/10.1007/s00455-022-10438-0, PMID:35482213

24. Pearson WG Jr, Langmore SE, Zumwalt AC: Evaluating the structural properties of suprahyoid muscles and their potential for moving the hyoid. Dysphagia 2011;26:345–351. https://doi.org/10.1007/s00455-010-9315-z, PMID:21069388
25. Shaker R, Kern M, Bardan E, Taylor A, Stewart ET, Hoffmann RG, Arndorfer RC, Hofmann C, Bonnevier J: Augmentation of deglutitive upper esophageal sphincter opening in the elderly by exercise. Am J Physiol Gastrointest Liver Physiol 1997;272:G1518–G1522. https://doi.org/10.1152/ajpgi.1997.272.6.G1518, PMID:9227489
26. Yoon WL, Khoo JK, Rickard Liow SJ: Chin tuck against resistance (CTAR): new method for enhancing suprahyoid muscle activity using a Shaker-type exercise. Dysphagia 2014;29:243–248. https://doi.org/10.1007/s00455-013-9502-9, PMID:24337867
27. Namiki C, Hara K, Tohara H, Kobayashi K, Chantaramanee A, Nakagawa K, Saitou T, Yamaguchi K, Yoshimi K, Nakane A, Minakuchi S: Tongue-pressure resistance training improves tongue and suprahyoid muscle functions simultaneously. Clin Interv Aging 2019;14:601–608. https://doi.org/10.2147/CIA.S194808, PMID:30962680
28. Lim J, Lee JC, Jang EG, Choi SY, Seo KH, Lee SY, Park D, Oh BM, Seo HG, Ryu JS. Kinematic mechanism of the rehabilitative effect of 4-channel NMES: post-hoc analysis of a prospective randomized controlled study. Sci Rep 2023;18:13445. https://doi.org/10.1038/s41598-023-40359-3, , PMID:37596323
29. Koshi N, Matsumoto H, Hiramatsu T, Shimizu Y, Hagino H: Influence of backrest angle on swallowing musculature activity and physical strain during the head lift exercise in elderly women compared with young women. J Oral Rehabil 2018;45:532–538. https://doi.org/10.1111/joor.12645, PMID:29761543
30. Moon IY, Yi CH, Park IW, Yong JH: Effects of sitting posture and bolus volume on activation of swallowing-related muscles. J Oral Rehabil 2020;47:577–583. https://doi.org/10.1111/joor.12934, PMID:31926028