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Effortful swallow enhances vertical hyolaryngeal movement and prolongs duration after maximal excursion

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SUMMARY Effortful swallowing (EFS) is a common compensatory swallowing manoeuver for dysphagia patients. We investigated the influence of EFS on temporal and spatial characteristics of the movements of the hyoid bone, larynx and epiglottis in healthy subjects. A total of 41 volunteers swallowed 10 mL of diluted barium solution using two swallowing strategies: usual and effortful swallowing (USS and EFS). The motions of the hyoid bone, larynx and epiglottis were tracked using frame-by-frame kinematic motion analysis of videofluoroscopic images. Maximal velocities and maximal displacements of hyoid and larynx, the maximal angle of the epiglottic tilt, and the durations of hyoid excursion, laryngeal elevation and epiglottic tilt were measured. Compared to USS, EFS was associated with significantly greater vertical displacement of the hyoid ($P < 0{\cdot}001$), vertical and horizontal displacement of the larynx ($P = 0{\cdot}003$, $P = 0{\cdot}019$), and maximal angle of the epiglottic tilt ($P = 0{\cdot}001$). In addition, the durations of the vertical and horizontal excursions of the hyoid, vertical excursion of the larynx and the epiglottic tilt were greater in EFS, compared with USS. Effortful swallowing was also associated with significantly greater maximum velocities of the hyoid and larynx during swallowing. In conclusion, the EFS manoeuver facilitates vertical speed and distance of hyolaryngeal excursion and epiglottic tilt and extends the duration of excursion and the epiglottic tilt, especially after reaching maximal excursion in healthy subjects. These results confirm the temporal and kinematic benefits of airway protection induced by the EFS manoeuver.

KEYWORDS: deglutition, dysphagia, rehabilitation, hyoid bone, larynx, epiglottis

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Introduction

Various neurological or structural disorders affecting the swallowing function may cause swallowing difficulty, putting patients at risk of dehydration, malnutrition, and aspiration pneumonia, and compromising quality of life. There are various strategies used to alleviate dysphagia, including exercise therapy, dietary modification and training for compensatory swallowing manoeuvers.

Effortful swallowing (EFS) is a common compensatory swallowing manoeuver. Initially devised by Pouderoux and Kahrilas (1), EFS is for patients who have reduced retraction of the tongue base towards the posterior pharyngeal wall. The patients are taught to squeeze all of the swallowing muscles as hard as they could while swallowing. This manoeuver presses the base of tongue to the posterior pharyngeal wall, and the bolus is forcibly squeezed downward into the oesophagus. It is believed that the increased effort augments the posterior movement of the tongue base, which improves clearance of vallecular residue (2).

Several researchers have investigated the biomechanical changes that occur during EFS in healthy subjects to illuminate the mechanism of the improved swallowing function. Most of these have measured intra-oral or pharyngeal pressures and have reported increases in the duration and amplitude of pharyngeal

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pressure during EFS (3–8), which accords with the proposed mechanism.

Other researchers have evaluated the movements of the anatomic structures involved in swallowing in healthy volunteers to understand the mechanism of airway protection during EFS. However, only a few reports have described motion analyses of the EFS manoeuver. Bülow *et al.* (9) reported that EFS showed reduced hyoid-mandible distance before swallowing 'due to an elevation of the hyoid and the larynx, which caused a significantly reduced maximal hyoid movement and a significantly reduced laryngeal elevation during swallow'. Hind *et al.* (10) have shown that the durations of maximum anterior hyoid excursion, laryngeal vestibular closure and upper oesophageal sphincter opening increased in EFS, and that the amplitude of the superior movement of the hyoid bone increased, whereas the amplitude of the anterior movement of the hyoid decreased.

In terms of the effect of EFS in patients with dysphagia, Lazarus *et al.* (11). found that EFS increased the pressure and duration of contact between the tongue base and the pharyngeal wall in head-and-neck cancer patients and Bülow *et al.* (12) showed that EFS reduced the depth of misdirected swallows in patients with moderate to severe pharyngeal dysfunction, but did not reduce the frequency of misdirected swallows. Regarding the training effect of EFS, Felix *et al.* (13) demonstrated that a 2-week swallowing therapy programme consisting of EFS and biofeedback increased pharyngeal pressure in patients with Parkinson's. Park *et al.* (14) showed that a 4-week programme of EFS combined with motor electrical stimulation enhanced the vertical movement of the larynx. These findings are in accord with the conventional belief in the benefit of EFS. However, in another study, Bülow *et al.* (15) reported different results, showing that the peak amplitude and duration of intra-bolus pressure at the inferior pharyngeal constrictor were not altered by EFS in patients with dysphagia due to cerebrovascular accidents or head-and-neck cancer. Thus, the effect of EFS in patients with dysphagia remains a subject of debate, which warrants further investigation with high statistical power.

In addition, there are other issues that need exploration. Strong muscle contraction may result in increased movement velocity. Although hyoid velocity was proposed to be important in protective mechanisms against aspiration (16), few studies have explored the velocity changes with EFS, which is quite unlike durations and distances of movements. Epiglottic movement can be considered as an important additional parameter in assessing swallowing function (17), although laryngeal closure plays the most critical role in airway protection during deglutition. Perlman *et al.* (18) revealed that deviant epiglottic function was a significant indicator of aspiration independent of reduced hyoid elevation. Nevertheless, previous studies on EFS have not investigated biomechanical changes of epiglottic tilt.

Therefore, we aimed to explore the EFS-induced changes in movement distances and velocities of important anatomical structures including the epiglottis, and hypothesised that EFS would increase the speed as well as maximal distances of the hyolaryngeal excursion and the degree of epiglottic tilt.

Methods

Subjects

Forty-one healthy adults (20 males and 21 females, mean age 52·89 ± 17·93 years, range 23–78 years) volunteered to participate in this study (Table 1). Medical history data were collected via questionnaire prior to enrolment, and volunteers who reported neither symptoms nor signs of swallowing problems, had no history of pulmonary disease and no neurologic diseases such as cerebral infarction, syncope, or transient ischaemic attack, were included. Informed consent was obtained from all participants. The study was approved by the Institutional Review Board of Seoul National University Hospital.

Procedures

A videofluoroscopic swallowing study (VFSS) was performed with the subjects seated upright. The volunteers

Table 1. Age distribution of subjects

Age	Male (*n*)	Female (*n*)
20–29	4	5
30–39	1	0
40–49	2	2
50–59	3	3
60–69	4	11
70–79	6	0

were instructed to drink 10 mL of barium solution (Solutop Suspension®*) diluted to 35% in weight per volume twice, first in usual manner and then with the EFS manoeuver. To perform EFS, volunteers were instructed to squeeze the muscles of throat and tongue hard during swallowing. The subjects practiced EFS twice without any bolus presented to be swallowed before actually swallowing the liquid. If multiple swallows were required to clear the material, the first swallow was analysed. No subject showed penetration or aspiration during the swallowing.

VFSS images were recorded using a mobile fluoroscopy system (Medix 3000†) with a digital computer frame grabber board (Pegasus HD/SD Board‡) and image processing software (EDIUS 4.5‡). Clips were recorded in a high-resolution (1980 × 1080 pixels) digital format with a sampling frequency of 30 frames per second. Defining the start point of swallowing cycle as when the liquid head reached the lower mandibular margin, and the end point as when the tail of liquid completed its passage through the upper oesophageal sphincter, each clip was edited to include the frames from 0·5 s before the start to 0·5 s after the end of swallowing. A coin was attached to the midline of each subject's chin to serve as a reference ruler. The longer diameter of elliptical shadow of a coin was constant as 24 mm. Although vertical distortion is potential error in using a frame grabber, this error was corrected before analysis using MATLAB (R2007a§).

VFSS clips were analysed by a blinded research assistant who had 2 years of experience in swallowing motion analysis. Pre-defined anatomical landmarks marked using motion analysis software (Ariel Performance Analysis System¶) in each frame were the anterior–superior margin of the hyoid bone, the base and tip of the epiglottis, and the anterior–superior margin of the subglottic airway column, which represented the larynx. To provide coordinates for these landmarks, a coordinate system was established that defined the y-axis as the straight line connecting the anterior–inferior margin of the fourth cervical vertebra (the 'zero' point) to the anterior–inferior margin of the second cervical vertebra and the x-axis as the straight line crossing the y-axis perpendicularly at the 'zero' point (Fig. 1). The angle of epiglottic tilt was measured by defining the initial epiglottic angle as 0°.

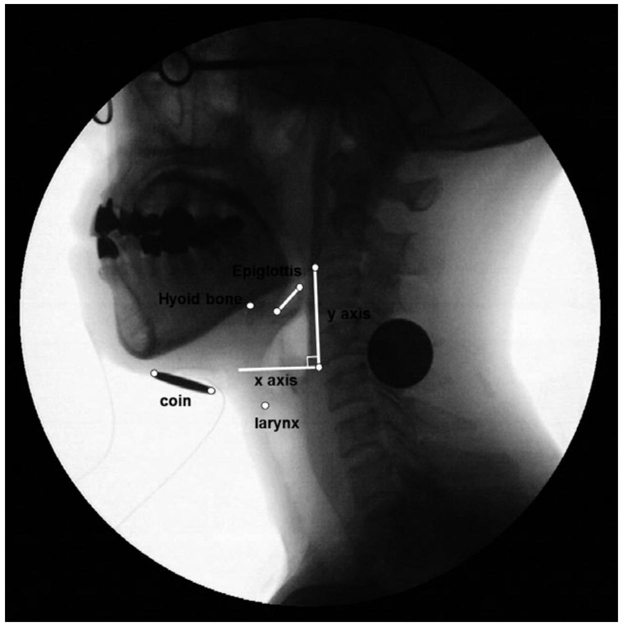

Fig. 1. Anatomical landmarks and the coordinate system. The anterior–superior margin of the hyoid bone, base and tip of the epiglottis, and anterior margin of the subglottic airway column, which represents the larynx, are shown.

Measurements

An in-house MATLAB script was written to extract the outcome variables. The units of distance and velocity were converted to millimetres and millimetres per second, respectively. All measurements were made using MATLAB by one trained investigator who was blind to the swallowing method used in each clip.

Spatial variables. The vertical, horizontal maximal displacements of the hyoid and the larynx were calculated as the differences between the highest and the lowest values of each variable during whole swallowing cycle including 0·5 s before its start and 0·5 s after its end. The two-dimensional (2-D) maximal displacements of the hyoid and the larynx were calculated as the maximum values among distances along the trajectory from the resting point (0·5 s before the start of swallowing cycle). The maximal angle of the epiglottic

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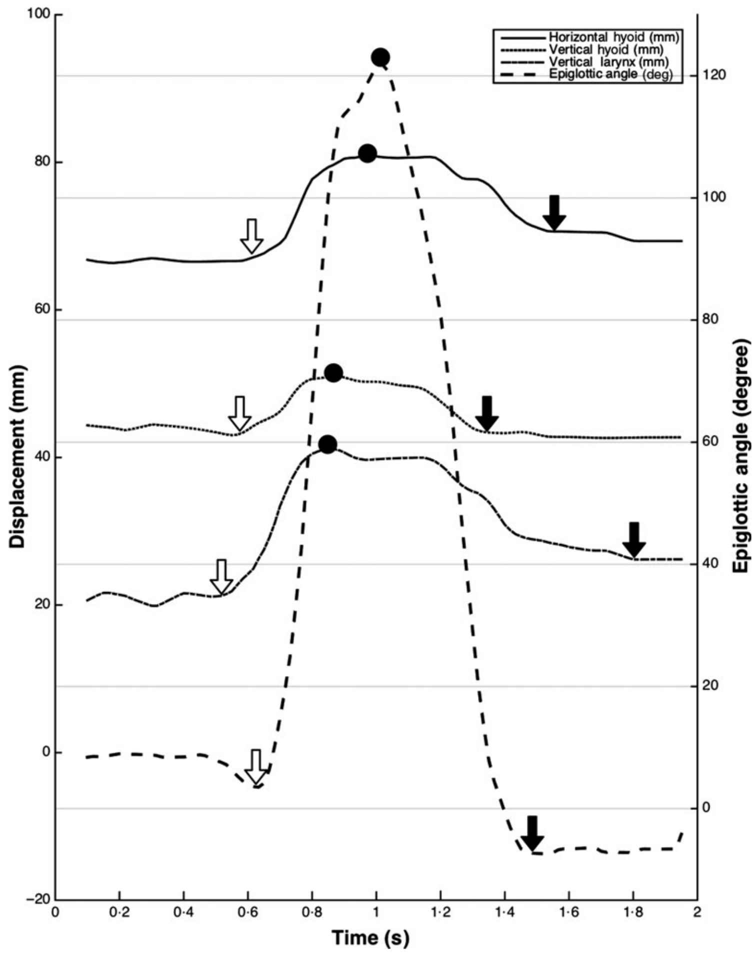

Fig. 2. An example graph for temporal analysis showing the displacement of the hyoid bone and larynx and the angle of epiglottic tilt during swallowing. The start (open arrow), maximum (solid circle), and end (solid arrow) points of the motions are depicted in the graph. For the horizontal movements, positive values mean anterior movements in sagittal anatomical planes; and for the epiglottic angle, positive values mean tilting angles towards posterior direction.

tilt was calculated as the difference of the highest and the lowest value during whole swallowing cycle including 0·5 s before its start and 0·5 s after its end.

Temporal variables. The durations of swallow-related motions including vertical and horizontal hyoid excursion, laryngeal elevation and epiglottic tilt were measured. Start and end of a motion were defined as the initiation and termination of rapid and sustained displacement of the anatomical structures (Fig. 2), based on the following parameters (19).

Start-to-max: time from the start of the swallow-related motion to the moment of maximal displacement.

Max-to-end: time from the moment of maximal displacement to the termination of the swallow-related motion.

Start-to-end: time from the start to the termination of swallow-related motion.

Velocities. The maximal velocities of hyoid and larynx motion during swallowing were measured in the vertical, horizontal and 2-D directions using the coordinate system described.

Statistical analysis

Paired *t*-tests were run to compare variables between usual swallow (USS) and EFS. All statistical analyses were performed using SPSS 18.0**. *P*-values < 0·05 indicated significance.

As the swallowing behaviour can vary depending on the age, an additional subgroup analysis was conducted to explore whether there was any difference in effect of EFS by age. The study group was divided into elder (age ≥ 60 years, $n = 21$) and younger

**SPSS Inc., Chicago, IL, USA.

(age < 60 years, $n = 20$) group. And statistical analyses of each group were conducted for every measurement.

Results

Spatial analysis

Table 2 displays mean ± standard deviations of the maximal displacement of the hyoid and the larynx in each dimension (vertical, horizontal and 2-D) by swallowing method, along with the maximal angle of the epiglottic tilt. Compared to USS, EFS produced larger maximal vertical (17·48 ± 6·07 vs. 13·88 ± 5·48 mm; $P < 0{\cdot}001$) and 2-D displacements ($P = 0{\cdot}015$) of the hyoid. Maximal vertical (26·24 ± 8·29 vs. 23·54 ± 6·84 mm; $P = 0{\cdot}003$), horizontal (8·01 ± 2·89 vs. 6·97 ± 2·42 mm; $P = 0{\cdot}019$) and 2-D displacements ($P = 0{\cdot}022$) of the larynx were larger in EFS than in USS. The angle of epiglottic tilt was also larger in EFS (115·19 ± 15·13 vs. 103·30 ± 22·35°; $P = 0{\cdot}001$).

Temporal analysis

Table 3 displays the temporal data. Mean ± standard deviations by swallowing method of the durations of vertical and horizontal excursions of the hyoid and those of the vertical excursion of the larynx are shown, along with those of the epiglottic tilt. The max-to-end (0·94 ± 0·53 vs. 0·73 ± 0·21 s; $P = 0{\cdot}019$) and start-to-end (1·57 ± 0·60 vs. 1·35 ± 0·26 s; $P = 0{\cdot}027$) durations of the vertical excursion of the hyoid were greater in EFS than in USS, as were the max-to-end duration (0·93 ± 0·53 vs. 0·67 ± 0·16 s; $P = 0{\cdot}005$) and the start-to-end durations (1·60 ± 0·58 vs. 1·34 ± 0·25 s; $P = 0{\cdot}012$) of vertical excursion of the larynx. The start-to-max (0·81 ± 0·31 vs. 0·65 ± 0·17 s; $P = 0{\cdot}005$) and start-to-end (1·66 ± 0·52 vs. 1·35 ± 0·22 s; $P = 0{\cdot}001$) durations of hyoid horizontal excursion and max-to-end (0·56 ± 0·37 vs. 0·37 ± 0·11 s; $P = 0{\cdot}002$) and start-to-end (1·12 ± 0·53 vs. 0·88 ± 0·17 s; $P = 0{\cdot}004$) durations of the epiglottic tilt were also longer in EFS than in USS.

Velocities

Table 4 displays mean ± standard deviations of the maximal velocities of the hyoid and larynx in each dimension (vertical, horizontal and 2-D) by swallowing method. EFS achieved greater maximal vertical and 2-D velocities of the hyoid ($P < 0{\cdot}001$ and 0·045, respectively) compared to USS. Maximal velocities of the larynx in the vertical ($P = 0{\cdot}034$), horizontal ($P = 0{\cdot}017$) and 2-D ($P = 0{\cdot}010$) directions were also greater in EFS than in USS.

Subgroup analysis

Although both groups, the elder and the younger group, showed similar tendencies to the entire group in spatial, temporal and velocity analysis, the younger subgroup exhibited more prominent difference whereas the elder subgroup showed compromised statistical significance. (e.g. *P*-value for comparison of maximal vertical displacement of hyoid between EFS and USS was <0·001 in younger group and 0·074 in elder group).

Discussion

This study was a quantitative motion analysis based on VFSS in healthy subjects that was conducted with

Table 2. Maximal displacements of hyoid and larynx and maximal angle of epiglottic tilt

	Usual swallowing (Mean ± s.d.)	Effortful swallowing (Mean ± s.d.)	*P*-value
Maximal displacement of hyoid (mm)			
Vertical	13·88 ± 5·48	17·48 ± 6·07	<0·001**
Horizontal	11·96 ± 2·66	12·77 ± 2·91	0·097
2-dimensional	16·23 ± 4·92	18·04 ± 6·32	0·015*
Maximal displacement of larynx (mm)			
Vertical	23·54 ± 6·84	26·24 ± 8·29	0·003**
Horizontal	6·97 ± 2·42	8·01 ± 2·89	0·019*
2-dimensional	23·85 ± 7·05	26·08 ± 9·24	0·022*
Maximal angle of epiglottic tilt (°)	103·30 ± 22·35	115·19 ± 15·13	0·001**

$^*P < 0{\cdot}05$; $^{**}P < 0{\cdot}01$ by paired *t*-test.

Table 3. Duration of hyoid excursion, laryngeal elevation and epiglottic tilt

	Duration (s)		
	Usual swallowing (mean ± s.d.)	Effortful swallowing (mean ± s.d.)	*P*-value
Hyoid vertical excursion			
Start-to-max	0·62 ± 0·22	0·64 ± 0·25	0·736
Max-to-end	0·73 ± 0·21	0·94 ± 0·53	0·019*
Start-to-end	1·35 ± 0·26	1·57 ± 0·60	0·027*
Hyoid horizontal excursion			
Start-to-max	0·65 ± 0·17	0·81 ± 0·31	0·005**
Max-to-end	0·70 ± 0·19	0·85 ± 0·51	0·075
Start-to-end	1·35 ± 0·22	1·66 ± 0·52	0·001**
Laryngeal vertical excursion			
Start-to-max	0·67 ± 0·18	0·68 ± 0·21	0·898
Max-to-end	0·67 ± 0·16	0·93 ± 0·53	0·005**
Start-to-end	1·34 ± 0·25	1·60 ± 0·58	0·012*
Epiglottic tilt			
Start-to-max	0·51 ± 0·16	0·56 ± 0·23	0·231
Max-to-end	0·37 ± 0·11	0·56 ± 0·37	0·002**
Start-to-end	0·88 ± 0·17	1·12 ± 0·53	0·004**

Start-to-max indicates the duration from initiation to maximal point. Max-to-end indicates the duration from maximal point to termination. Start-to-end indicates the duration from initiation to termination.
*$P < 0{\cdot}05$; **$P < 0{\cdot}01$ by paired *t*-test.

Table 4. Maximal velocities of the hyoid and the larynx

	Maximal velocity (mm s^{-1})		
	Usual swallowing (mean ± s.d.)	Effortful swallowing (Mean ± s.d.)	*P*-value
Hyoid			
Vertical	64·54 ± 32·24	82·81 ± 38·07	<0·001**
Horizontal	56·78 ± 28·07	67·63 ± 35·09	0·083
2-dimensional	116·37 ± 55·07	137·29 ± 62·24	0·045*
Larynx			
Vertical	140·23 ± 57·49	155·74 ± 61·96	0·034*
Horizontal	35·21 ± 19·52	47·39 ± 31·76	0·017*
2-dimensional	148·37 ± 57·02	170·73 ± 76·32	0·010*

*$P < 0{\cdot}05$; **$P < 0{\cdot}01$ by paired *t*-test.

the aim of estimating the biomechanical changes that occur during EFS. The maximal displacements of both hyoid and larynx and the maximal angle of epiglottic tilt were larger in EFS compared to USS. The durations of vertical and horizontal excursion of the hyoid, vertical excursion of the larynx and epiglottic tilt were greater in EFS, and the maximal velocities of the hyoid and the larynx during EFS exceeded those of USS.

There were no previous studies examining the velocity of hyoid/larynx movement during EFS in healthy subjects. Our study showed that the maximal velocities of hyoid (vertical, 2-D) and larynx (vertical, horizontal, 2-D) motions were increased in EFS. Although no study has been conducted on the relationship between hyoid velocity and swallowing function, swift hyoid elevation in a timely manner is regarded important for effective airway protection (20). And it has been suggested that the velocity of hyoid bone movement is important to protect the airway and reduce aspiration (21).

In the present study, the maximal angle of epiglottic tilt was 103·30° in USS and 115·19° in EFS. This difference would have no effect of tightening up the airway protection as the laryngeal inlet gets covered by the epiglottic tubercle at a lesser rotation angle. However, considering this study was conducted for normal participants, the increment of epiglottic rotation induced by EFS may have a different impact on the swallowing process in dysphagic patients with reduced epiglottic rotation.

Bülow *et al.* (9) reported that EFS showed reduced hyoid-mandible distance before swallowing 'due to an elevation of the hyoid and the larynx, which caused a significantly reduced maximal hyoid movement and a significantly reduced laryngeal elevation during swallowing'. Thus, Hind *et al.* (10) set the post-swallow resting position as a reference point. In this study, to avoid the underestimation of movements that results from pre-swallow muscle activation in EFS, maximal displacement was defined as the difference between the highest and the lowest values during the whole swallowing cycle including 0·5 s before its start and 0·5 s after its end. The highest values were observed invariably during swallowing, but the lowest values could be in before, during or after swallowing, on a case-by-case basis. However, the resting position before and after the entire swallowing cycle was sufficiently covered by the present analysis (Fig. 2). Hind *et al.* (10) demonstrated that the maximum superior excursion of the hyoid increased and the maximum anterior excursion of the hyoid decreased, which was similar to findings obtained from the spatial analysis in the present study. Additionally, we assessed laryngeal movement to find that laryngeal excursion increased vertically, horizontally and 2-dimensionally during EFS.

Hind *et al.* (10) also reported that pharyngeal response duration, that is, the total duration of hyoid excursion, was significantly longer in EFS. Similar results were noted in this study, which showed longer total durations of the vertical and horizontal excursions of the hyoid. An increased duration of laryngeal elevation during EFS was also demonstrated in the present study. It is notable that the total durations of hyoid and laryngeal elevation increased, while the time taken to reach the maximal point did not show significant change. Thus, as with Mendelsohn's manoeuver, the hyoid/larynx elevation did not slacken but remained elevated for a longer period. This can be regarded as favourable for improved airway protection and upper oesophageal sphincter opening.

Unlike Hind *et al.* (10), we did not measure the duration of laryngeal vestibular closure. Instead, we measured the duration of epiglottic tilt and found it to be longer in EFS than in USS. As reported with hyoid/larynx elevation, the latency to reach the maximal angle did not change meaning that the time the epiglottis covered the laryngeal entrance was lengthened without affecting the promptness with which the maximal point was reached.

Our results demonstrated some clear similarities to the results of previous kinematic studies of Mendelsohn's manoeuver, which enhance the upper oesophageal opening through volitional prolongation of the superoanterior displacement of the larynx in mid-swallow (22). Firstly, we showed that the duration of hyolaryngeal excursion was longer with EFS, which is also a major characteristic of the Mendelsohn manoeuver. Secondly, increased hyoid displacement was one of the main findings for EFS in our study, and this has also been identified as a notable biomechanical change seen during the Mendelsohn manoeuver (23). Although each manoeuvers have been applied for patients with different swallowing abnormalities, the two have in common the improved excursion the hyolaryngeal complex as well as prolonged swallowing activity after reaching the maximal excursion.

In the present study, every maximal excursions and maximal velocities of the hyolaryngeal complex increased in EFS, except the horizontal excursion and velocity of hyoid. From this, we surmised that there might be a posteriorly acting counterforce directly acting on the hyoid bone, which offsets the anterior directional force. The possible force generators are the posterior belly of the digastric muscle and the stylohyoid muscle, which usually elevate and can also retract the hyoid bone during swallowing process. As well, the retraction force of the tongue, which would be reinforced on EFS, might also play a role, as the tongue is directly connected to the hyoid bone by the hyoglossus muscle. In the present study, the subjects squeezed the muscles of throat and tongue hard, and this might make retraction power of aforementioned muscles relatively stronger than usual. Similarly, only the horizontal hyoid movement showed different trends in the temporal analysis. In case of vertical movements of hyoid/larynx and epiglottic rotation, total duration increased, while reaching at maximal point did not slacken in EFS. However, regarding horizontal hyoid movement, the time taken to reach the maximal point increased as well as total duration. We suppose this also can be explained by the increased muscle activity that retract hyoid and impede the anterior displacement of the hyoid. To prove our hypothesis, studies with electromyographic as well as biomechanical analysis of the individual muscles are required.

The lack of manometric pressure data may be a limitation of this study. However, we believe that excluding manometry may have allowed more accurate observation of biomechanical changes in EFS because of the possibility of pressure probes interfering with the swallowing process.

The volume of liquid swallowed by subjects was determined based on the previous study, which reported that a graded increase in bolus volume up to 10 mL was associated with a progressive increase in magnitude of hyoid movement, whereas, for volumes of 15 mL and 20 mL, no additional increases occurred beyond those observed for 10 mL bolus (24). Volume of 10 mL was the least volume that would cause the maximal hyoid displacement, which was expected to maximise the differential characteristics between the hyoid movement in USS and in EFS.

Although thin barium solution has been considered as comparable media for water by some researchers (25, 26) and used as testing material mimicking water in modified barium swallow test, barium may affect the bolus characteristics such as viscosity, density or taste, all of which can influence the kinematics of swallowing (19, 27–29). Even though direct kinematic comparison between water and barium solution and is sparse, slightly higher viscosity of barium solution as compared to water might have strengthened the hyolaryngeal movement in the present study. However, 35% w/v barium solutions in the present study are quite thin. Furthermore, barium's effect on swallowing kinematics, if any, must have affected both USS and EFS. The paired t-test could lessen any possible bias stemming from this.

Conclusion

EFS increases the velocity, amplitude and duration of hyolaryngeal complex excursion and epiglottic tilt. These changes should contribute to improved airway protection. Effortful swallowing has usually been recommended for patients with impaired tongue base retraction and related vallecular residue. However, our results imply that EFS may also be helpful to patients who suffer from misdirected swallowing due to reduced hyolaryngeal excursion and epiglottic tilt.

To date, there has been a paucity of the literature about EFS in dysphagia patients with sufficient statistical power. The present study indicates that a sufficiently powered study could demonstrate the biomechanical effects of EFS and provide insight on its most appropriate indications.

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