Biomechanical Correlates of Surface Electromyography Signals Obtained During Swallowing by Healthy Adults

Michael A. Crary
Giselle D. Carnaby (Mann)
University of Florida Health Science Center, Gainesville

Michael E. Groher
University of Redlands, Redlands, CA

Purpose: The purpose of this study was to describe biomechanical correlates of the surface electromyographic signal obtained during swallowing by healthy adult volunteers.
Method: Seventeen healthy adults were evaluated with simultaneous videofluoroscopy and surface electromyography (sEMG) while swallowing 5 mL of liquid barium sulfate. Three biomechanical swallowing events were analyzed: hyoid elevation, pharyngeal constriction, and opening–closing of the pharyngoesophageal segment. For each biomechanical event and from the sEMG signal, the authors identified onset, peak, and offset time points. From these points, duration measures were calculated. Means and 95% confidence intervals were calculated for each measure. Subsequently, correlations were evaluated between timing aspects of the sEMG traces and each biomechanical event.
Results: Swallow onset in the sEMG signal preceded the onset of all biomechanical events. All biomechanical events demonstrated a strong correspondence to the sEMG signal. The strongest relationship was between hyoid elevation–anterior displacement and the sEMG signal.
Conclusions: These results suggest that the sEMG signal is a useful indicator of major biomechanical events in the swallow. Future studies should address the impact of age and disease processes, as well as bolus characteristics, on the biomechanical correlates of sEMG signals obtained during swallowing.

KEY WORDS: electromyography, videofluoroscopy, swallowing assessment

Swallowing is a complex sensorimotor function that incorporates activity from multiple muscle groups in the upper aerodigestive tract. Muscle activity associated with swallowing movements may be evaluated with intramuscular or surface electromyographic techniques. The intramuscular approach uses various forms of needle electrodes placed directly into specific muscles. Intramuscular electromyography is used primarily to evaluate activation patterns of specific muscles and timing coordination among various muscles. Conversely, the surface electromyographic signal is obtained from electrodes adhered to the skin over a group of muscles to be studied. Unlike intramuscular electromyography, the surface technique lacks muscle specificity. Electromyographic signals obtained through surface electrodes represent simultaneous muscle activity from multiple muscles in the region of interest. Thus, although both techniques provide data that can be used to estimate the muscular activity associated with swallowing, each technique provides different information.

Using the intramuscular technique with a variety of animal models, Doty and Bosma (1956) demonstrated a systematic and consistent timing

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pattern of muscle activation during swallowing. In juxtaposition, recent studies involving human participants have demonstrated considerable intersubject variability across activation patterns of specific muscles during swallowing (Gay, Rendell, & Spiro, 1994; Spiro, Rendell, & Gay, 1994). Furthermore, intramuscular electromyographic results have demonstrated variability in the activation of specific muscles across various swallowing tasks (McCulloch, Perlman, Palmer, & VanDaele, 1996; Ertekin et al., 1997). The primary contribution of the intramuscular approach to electromyography (EMG) is the ability to study individual muscles. The timing and pattern of muscle activation are common foci of this approach in the study of swallowing.

Surface EMG (sEMG) has been used primarily as follows: (a) to identify the presence of swallowing activity, (b) to analyze swallowing functions (timing and amplitude), and (c) as a biofeedback strategy in the treatment of swallowing disorders (Bryant, 1991; Crary, 1995; Crary, Carnaby (Mann), Groher, & Helseth, 2004; Haynes, 1976; Huckabee & Cannito, 1995; McKeown, Torpey, & Ghem, 2002; Vaiman, Segal, & Eviatar, 2004). Despite extensive research and clinical applications of this technique, limited information exists regarding specific swallowing biomechanical activities that may be associated with sEMG correlates of swallowing. sEMG does not provide information about the activity of specific muscles or movements; however, studies have evaluated specific muscles that are associated with sEMG signals obtained during swallowing. For example, Palmer, Luschei, Jaffe, and McCulloch (1999) evaluated specific muscle activity contributing to sEMG signals obtained from the submental site. These investigators concluded that the mylohyoid, geniohyoid, and anterior belly of the digastric muscles contributed the most information to the submental sEMG signal obtained during swallowing. In related work, Perlman, Palmer, McCulloch, and VanDaele (1999) used both intramuscular and surface electromyography to study activation patterns and timing relationships among laryngeal, pharyngeal, and submental muscles involved in swallowing. Specific muscles revealed a volume-dependent response for duration and pattern of activation during swallowing. Furthermore, although the pattern of muscle activation demonstrated high intrasubject agreement, considerable variability was observed across participants.

Few studies have evaluated movement correlates of electromyographic signals during swallowing. Ertekin et al. (1995, 1997) studied relationships among laryngeal elevation, as measured by a movement transducer on the anterior neck over the larynx; submental sEMG signals; and intramuscular EMG signals obtained from the cricopharyngeus muscle during swallowing. These studies revealed that laryngeal elevation was significantly related to both submental and cricopharyngeal muscle activity. Specifically, laryngeal elevation was significantly related to increased submental sEMG activity and to decreased cricopharyngeal muscle activity. Ding, Larson, Logemann, and Rademaker (2002) also identified a strong temporal relationship between laryngeal elevation and the submental sEMG signal. Using electroglottography as a measure of laryngeal elevation, these investigators reported a close temporal relationship between submental sEMG signals and laryngeal elevation in both normal swallows and in swallows using the Mendelsohn maneuver (sustained laryngeal elevation during the swallow).

Although these studies have addressed laryngeal elevation during swallowing in reference to sEMG activity, few studies have evaluated other biomechanical events in reference to the sEMG signal. For example, researchers believe that the submental muscle complex has an indirect influence on the opening of the pharyngoesophageal segment (PES). The PES typically remains closed at rest and opens during a swallow. Goyal (1984) observed that submental muscle activation contributes to superior and anterior displacement of the hyo–laryngeal complex. This movement provides the traction necessary to distend the PES, contributing to lowered pressure in this sphincter that facilitates opening during swallowing. This relationship among submental muscle activation, hyo–laryngeal elevation, and opening of the PES is so well recognized that clinical techniques to improve PES opening have focused on strengthening the submental muscles (Shaker et al., 1997, 2002). Despite this clinical application, no study has described potential direct relationships between submental sEMG activity and opening of the PES.

Comparison of specific biomechanical events with sEMG signals requires a method to simultaneously observe the swallowing events while recording the EMG activity. Using simultaneous fluoroscopic examination and sEMG information from four muscles sites (orbicularis oris, masseter, submental group, and laryngeal strap muscles) in 5 healthy participants, Vaiman, Eviatar, and Segal (2004) evaluated sEMG signals in reference to the sequence or stages of swallowing events. Although these investigators reported "synchronism" between the fluoroscopic images and the sEMG signals, no details were provided regarding the simultaneous technique or the interpretation of their results in reference to specific biomechanical events occurring during swallowing.

Prior reports have demonstrated that laryngeal elevation, as measured by indirect methods, is related to muscle activity in the submental region and in the PES (cricopharyngeus muscle). Beyond these reports, little information is available documenting specific biomechanical correlates of sEMG signals obtained during swallowing. Information within the sEMG signal may be important in understanding clinical applications for this technique. For example, knowledge of specific biomechanical events contributing to the sEMG signal obtained from a specified location during swallowing may help clinicians develop and apply effective swallowing therapies.

In the present study, we evaluated specific biomechanical correlates of sEMG activity obtained from the submental region of the anterior neck during swallowing by healthy adults. Our purpose was to identify and describe timing relationships between three biomechanical aspects of swallowing and the corresponding sEMG signal. Specifically, we evaluated timing aspects of hyoid elevation and anterior movement, pharyngeal constriction, and PES opening compared with the timing of sEMG events recorded simultaneously with each swallow. These biomechanical swallow aspects were selected as representative of cardinal events during swallowing: elevation, constriction, and bolus outlet. We anticipated that hyoid movement would be strongly related to sEMG activity during swallowing. Hyoid elevation is strongly tied to laryngeal elevation during swallowing, and both are the result of activity in muscles close to the surface in the submental region. Because hyoid and laryngeal elevation and anterior movement during swallowing are thought to facilitate opening of the PES, we also anticipated a strong relationship between this swallowing event and the sEMG signal. Because muscles responsible for pharyngeal constriction are deeper than submental muscles, we anticipated that pharyngeal constriction during swallowing would demonstrate the weakest relationship with the sEMG signal.

Method

Participants

Seventeen healthy, adult volunteers participated in this study. The study group included 8 women and 9 men with an average age of 28.17 years (range = 21–39 years). All participants completed a health survey questionnaire to ascertain whether there was a history of swallowing difficulties or medical problems, or current medical problems or medications that might influence swallowing function. All participants signed an informed consent form. This study was approved by the Institutional Review Board and the Human Radiology Review Committee at the University of Florida Health Science Center.

Procedures and Materials

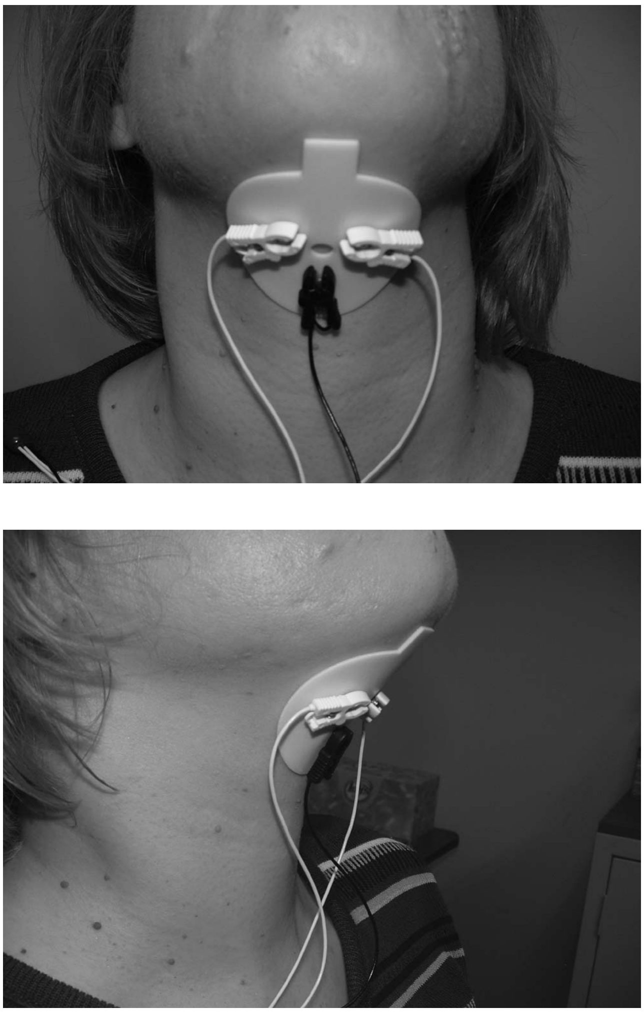
Participants stood during the study and were examined within a fluoroscopic unit. Simultaneous videofluoroscopic and sEMG data were collected using the Kay Swallowing Workstation. Videofluoroscopic images obtained at a rate of 30 frames per s from the lateral view were used to verify the presence of a swallow event and to calculate the timing parameters of each swallow. sEMG signals were obtained from a single three-point, circular, dry, disposable electrode with a 2.25-in. diameter. Each patch contained three electrodes in a triangle configuration. Two electrodes were recording electrodes and the third served as the ground. Interelectrode distance was 0.25 in. edge-to-edge and 0.75 in. center-to-center. To facilitate consistent electrode placement across participants, the center point of each electrode patch was placed inferior to the hyoid bone in the midline, anterior neck. Recording electrodes were oriented toward the chin whereas the ground electrode was oriented toward the larynx (Figure 1). Obtained sEMG signals were processed by the Kay Swallowing Signals Lab, which was interfaced with the Kay Elemetrics Swallowing Workstation. Sampling rate was 500 Hz and the raw signal was bandpass filtered (50–250 Hz), integrated (time constant = 50 ms), and rectified. Simultaneous videofluoroscopic and sEMG examinations were recorded on formatted 0.50-in. videotape using a video recorder. The video recorder and the Swallowing Signals Lab are computer integrated within the swallowing workstation. The video recorder contains a vertical interval time-code generator and reader with video field resolution (.0167 s). The system allows physiologic and video data to be recorded and analyzed (postacquisition) concurrently. Software is able to read and link time-code data from the video signal and digital data from the Swallowing Signals Lab.

Three swallows were analyzed from each participant swallowing 5 mL of standard barium liquid contrast for a total of 51 swallow events. Liquid barium contrast was provided to each participant from a medicine cup. Participants were instructed to hold the liquid in their mouth and remain still until asked to swallow. The request to swallow was provided only when the sEMG baseline activity returned to resting levels (<4 mV root-mean-square) after the participant placed the liquid bolus in his or her mouth.

Data Analysis

Videofluoroscopic images were analyzed independent of the sEMG signal by an experienced judge (the third author) who was blinded to the sEMG signal. Three biomechanical aspects of each swallow were evaluated from the fluoroscopic image: hyoid elevation and return to baseline, pharyngeal constriction and return to baseline, and PES opening and closing. The baseline position prior to swallowing was established during quiet breathing (rest position) with the bolus held in the mouth. The video was viewed in slow motion until the posterior movement of the bolus in the mouth indicated the initiation of a swallow. Biomechanical events were measured individually beginning with hyoid movement and followed

Figure 1. Anterior and lateral views of electrode placement on anterior neck. Center point on the electrode patch was placed in the midline neck slightly inferior to the hyoid bone. Recording electrodes were oriented toward the chin (white leads). The ground electrode (black lead) was oriented toward the larynx.



in order by pharyngeal constriction and PES opening. For each biomechanical component, the onset, peak, and offset of movement were identified from the fluoroscopic video. Onset was identified as the first video frame depicting movement of that structure that continued into the swallow event. Peak movement was identified as the point of maximum excursion of each structure. For PES opening, peak excursion was determined visually as that time point in which the PES demonstrated its widest point of opening during bolus transit. The offset point was the video frame in which the structure returned to the resting, preswallow position.

sEMG traces were also evaluated for onset, peak, and offset of activity during swallowing events. Each sEMG trace was evaluated independent of the videofluoroscopic images by an experienced judge (the third author). Onset was identified as the point of upward excursion of the sEMG trace from resting baseline that led into the swallowing event. Peak was the highest amplitude point of the sEMG swallow trace. Offset was the point at which sEMG activity returned to baseline.

Because subjective judgment was used for both videofluoroscopic and sEMG measures, interjudge reliability was estimated. To establish interjudge reliability of these measures, a second judge (the first author), who was blinded to the original results, measured the same parameters of 10 randomly selected samples from the 51 total swallow events. As with the original measures, videofluoroscopic images and sEMG traces were evaluated independently. Intraclass correlation coefficients were high for all comparisons (range of lower 95% confidence interval [CI] = .9989–1.000), suggesting strong consistency between raters.

To compare specific time points (onset, peak, offset) across biomechanical events and with the sEMG signal, the respective time points for hyoid movement were set to Time 0. Differences between hyoid time points and other events were calculated from this zero point.

Three additional temporal parameters were calculated from the direct measures for each biomechanical event and from the sEMG trace. Onslope represented the time from the onset to the peak amplitude. Offslope represented the time from the peak amplitude to the offset point. Total duration represented the time between the onset and offset points for each measure. The respective measures are depicted graphically in Figure 2.

Correlation analyses (Pearson product–moment r and R^2) were used to evaluate the relationship between

Figure 2. Graphic depiction of timing measures obtained from surface electromyography signals and the fluoroscopic video of three biomechanical swallowing events.

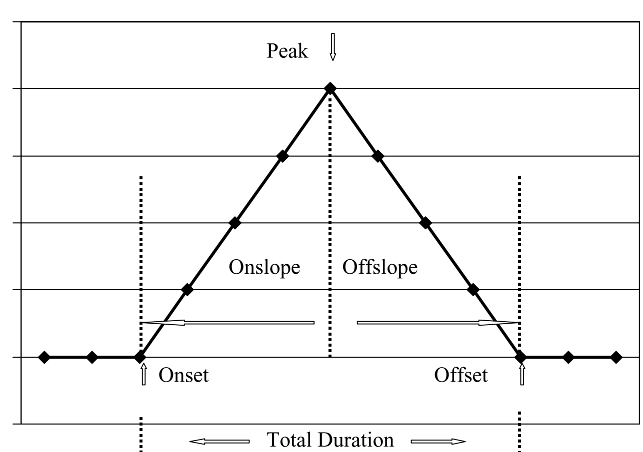


Table 1. Average onset, peak, and offset times relative to hyoid movement time points.

Event	Onset	Peak	Offset	Onslope	Offslope	Total duration
sEMG activity	–0.062	–0.095	–0.028	0.520	0.826	10.35
	(–0.132, 0.007)	(–0.144, –0.047)	(–0.107, 0.052)	(0.438, 0.572)	(0.722, 00.931)	(10.24, 10.45)
Hyoid movement	0	0	0	0.572	0.740	10.31
				(0.500, 0.644)	(0.667, 0.814)	(10.22, 10.41)
Pharynx constriction	0.141	0.126	0.108	0.573	0.736	10.31
	(0.077, 0.205)	(0.095, 0.156)	(0.046, 0.171)	(0.519, 0.627)	(0.679, 0.793)	(10.24, 10.38)
PES Open/close	0.457	0.001	–0.418	0.123	0.345	00.477
	(0.384, 0.530)	(–0.027, 0.028)	(–0.484, –0.351)	(0.111, 0.134)	(0.332, 0.376)	(0.455, –0.499)

Note. sEMG = surface electromyography; PES = pharyngoesophageal segment. Average onslope, offslope, and total durations are calculated measures. Means and 95% confidence intervals (in parentheses) are presented. Data are presented in seconds.

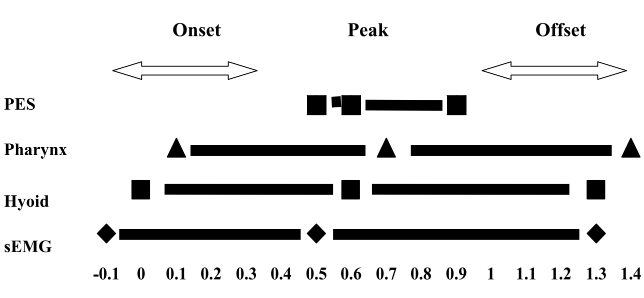
each of the three biomechanical events and the corresponding sEMG information. For these analyses, hyoid movement values were not set to Time 0. All statistical analyses were completed using SPSS software (Version 11.0).

Results

Descriptive results are presented as mean duration of each measure and the corresponding 95% CI (Table 1). On the basis of the mean data (Figure 3), sEMG activity preceded all biomechanical events for each time point (onset, peak, and offset). Hyoid movement appeared most closely related to the sEMG signal. On average, onset of pharyngeal constriction followed onset of hyoid elevation, with PES opening occurring last. PES peak opening is nearly simultaneous with peak hyoid elevation and precedes the peak point for pharyngeal constriction. Offset points are similar for hyoid elevation and the sEMG signal, but pharyngeal constriction follows these points and PES closure precedes each of the events.

Calculated measures (onslope, offslope, and total duration) indicated that durations for sEMG activity, hyoid movement, and pharyngeal constriction were comparable with offslope being longer than onslope in each case. Average total durations for these three measures were nearly identical. In contrast, PES calculated durations were shorter than all other measures. PES onslope was approximately 75% shorter than the other measures. PES offslope and total durations were approximately 50%–60% shorter than other measures.

Figure 3. Graphic depiction of timing results (onset, peak, offset) for the surface electromyography (sEMG) signal and three biomechanical events during the swallow. Data are mean values for each time point.



Correlations and corresponding variance estimates between each biomechanical event and the sEMG signal were high for onset, offset, and peak measures (Table 2). Calculated duration measures of onslope, offslope, and total duration did not result in the same strength of relationship. Overall, hyoid movement was most strongly related to the sEMG signal.

Discussion

The empirical and clinical uses of sEMG analyses of swallowing activity are dependent on a basic understanding of the relationship between the sEMG signal and swallow-related movements. Results from this study identified hyoid bone movement as the biomechanical swallowing event most closely linked to the sEMG signal. This link is logical because muscles responsible for hyoid movement are superficial and close to the region of measurement from the surface electrodes. In addition, because hyoid movement is among the earliest of biomechanical events during the swallow, the sEMG signal may have been dominated by this activity, overshadowing other swallow movements. In the normal swallow, hyoid movement is closely tied to laryngeal movement. Thus, the primary result of the present study extends previous findings of Ertekin and colleagues (1995, 1997) and Ding et al. (2002): Both hyoid and laryngeal movements are closely related to sEMG signals obtained from the upper anterior neck midline.

The sequence of biomechanical movements compared with the sEMG signal is in general agreement with earlier EMG findings of Perlman and colleagues

Table 2. Results of correlation analyses between sEMG and biomechanical data points.

	sEMG measure					
Biomechanical event	**Onset**	**Peak**	**Offset**	**Onslope**	**Offslope**	**Total duration**
Hyoid	1.00	1.00	1.00	.502	.524	.539
	.9998	.9999	.9997	.2516	.2742	.2908
Pharynx	1.00	1.00	1.00	.299	*ns*	ns
	.9997	.9999	.9996	.0894		
PES	1.00	1.00	1.00	−.358	*ns*	−.345
	.9997	.9999	.9997	.1280		.1188

Note. sEMG = surface electromyography. The top number represents the correlation value (r) and the bottom number represents the accountable variance (R^2). *ns* = not significant; all other values are significant at $p < .05$.

(1999), who reported that the submental sEMG signal preceded muscle activation in the superior pharyngeal constrictor, thyroarytenoid, interarytenoid, and cricopharyngeus muscles. Present findings on sequence of activities also concur with sEMG sequences reported by McKeown et al. (2002). Specifically, submental muscle activation precedes laryngeal elevation, whereas cricopharyngeus activation follows laryngeal elevation. In the present study, sEMG activation preceded initiation of hyoid bone elevation, followed in order by onset of pharyngeal constriction and then PES opening. Kendall, Leonard, and McKenzie (2003) noted a similar sequence. They reported that peak hyoid elevation typically precedes peak PES opening (mean differences between 0.04 s to 0.10 s depending on bolus volume). Our results support their findings but suggest a closer temporal relationship between peak hyoid elevation and PES opening (mean difference of 0.001 s). This discrepancy may have resulted from different bolus volumes used between the two studies (5 mL in the present study vs. 1, 3, and 20 mL in Kendall's study). In fact, the smallest difference between peak hyoid elevation and maximum PES opening in Kendall et al.'s study was identified for the 3-mL bolus that was closest to the 5-mL bolus volume used in the present study.

The calculated measures of onslope, offslope, and total duration did not result in the same strength of association as the specific point measures (onset, peak, offset). This result seems to reflect increased intersubject variance in the calculated measures that are perhaps inherent to timing pattern differences among the respective biomechanical components of the swallow. In prior studies, researchers have commented on extensive intersubject variability in muscle activation patterns (Gay et al., 1994; Spiro et al., 1994; Palmer et al., 1999; Perlman et al., 1999) and in biomechanical events (Kendall, 2002). In the present study, substantial intersubject variability was reflected in the 95% CIs obtained for both the sEMG and biomechanical results. Collectively, these findings point to variation in muscle activation patterns and the resulting biomechanical movements in normal swallowing, even when the swallow is limited to a single material and volume. Thus, although the individual time-point measures of onset, peak, and offset varied systematically with corresponding measures on the sEMG graphic trace, the relative timing between these point measures appears to have varied substantially, thus decreasing the strength of the obtained correlations.

One clinical application of sEMG techniques has been to provide patients with biofeedback regarding muscle activation during swallowing attempts (Bryant, 1991; Crary, 1995; Crary et al., 2004; Huckabee & Cannito, 1995). Results from the present study suggest that such approaches would be helpful in treating patients with dysphagia, whose problems reside in the pharyngeal aspects of swallowing, specifically hyoid elevation, and by extension, laryngeal elevation. However, in our study, specific time-point measures associated with both pharyngeal constriction and PES opening–closing were strongly associated with concurrent measures obtained from the sEMG signal. This observation suggests that some characteristics of these biomechanical events may be incorporated within sEMG biofeedback provided to patients with pharyngeal dysphagia. In addition, hyoid elevation has been linked to PES opening (Goyal, 1984; McConnel, 1988). Therefore, biofeedback that facilitates increased hyoid elevation during swallowing attempts may facilitate PES opening as well.

The present study was limited to evaluation of a single bolus size and consistency swallowed by a cohort of young, healthy adults. Accommodation is a well-known aspect of swallowing activity in which swallow physiology adapts to materials that are swallowed. Leonard, Kendall, McKenzie, and Gonçalves (2000) identified volume-specific adjustments in hyoid elevation, pharyngeal constriction, and PES opening but not in hyoid-to-larynx approximation in healthy adults. Thus, volume is one variable that may differentially impact swallowing biomechanics. Given the impact of what may be selective accommodation within the normal swallowing mechanism, the current biomechanical evaluation should be reassessed in consideration of characteristics that may alter swallow physiology. Furthermore, future studies should incorporate additional biomechanical events closely tied to hyoid movement (e.g., laryngeal movement), to challenge and/or expand the current results. Last, both age and disease impact swallow physiology. Thus, it is likely that the interpretation of sEMG correlates of swallowing activity also will be impacted by these factors. It will be important to replicate these findings in adults across the age span and in patients with dysphagia resulting from different disease processes. Comparison of results addressing these factors with the present results obtained from healthy, young adults will help to expand researchers' understanding of the relationship between swallow biomechanics and sEMG signals obtained during swallowing.

Results of the present study indicate a strong association between the sEMG signal and certain biomechanical events occurring during swallowing, specifically hyoid movement. These results are encouraging but should be viewed as an initial step toward enhanced use of sEMG technology in the areas of swallowing physiology and the treatment of swallowing disorders. Improved understanding of the contribution of sEMG technology to the study and rehabilitation of swallowing activity will advance research and clinical applications of this technology.

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Contact author: Michael A. Crary, Box 100174, Gainesville, FL 32610-0174. E-mail: mcrary@phhp.ufl.edu