Research Article

The Relationship Between Submental Surface Electromyography and Hyo-Laryngeal Kinematic Measures of Mendelsohn Maneuver Duration

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Purpose: The Mendelsohn Maneuver (MM) is a commonly prescribed technique that is taught to individuals with dysphagia to improve swallowing ability. Due to cost and safety concerns associated with videofluoroscopy (VFS) use, submental surface electromyography (ssEMG) is commonly used in place of VFS to train the MM in clinical and research settings. However, it is unknown whether ssEMG accurately reflects the prolonged hyo-laryngeal movements required for execution of the MM. The primary goal of this study was to examine the relationship among ssEMG duration, duration of laryngeal vestibule closure, and duration of maximum hyoid elevation during MM performance.

Method: Participants included healthy adults and patients with dysphagia due to stroke. All performed the MM during synchronous ssEMG and VFS recording.

Results: Significant correlations between ssEMG duration and VFS measures of hyo-laryngeal kinematic durations during MM performance ranged from very weak to moderate. None of the correlations in the group of stroke patients reached statistical significance.

Conclusion: Clinicians and researchers should consider that the MM involves novel hyo-laryngeal kinematics that may be only moderately represented with ssEMG. Thus, there is a risk that these target therapeutic movements are not consistently being trained.

Swallowing maneuvers are widely incorporated into dysphagia therapy because of known immediate physiological changes that can improve airway protection kinematics (Bülow, Olsson, & Ekberg, 2001; Hind, Nicosia, Roecker, Carnes, & Robbins, 2001; Kahrilas, Logemann, Krugler, & Flanagan, 1991; Lazarus, Logemann, & Gibbons, 1993; Masako & Logemann, 1996; McCullough et al., 2012; Nagaya, Kachi, Yamada, & Sumi, 2004; Ohmae, Logemann, Kaiser, Hanson, & Kahrilas, 1996). The Mendelsohn Maneuver (MM) is a swallowing maneuver that involves volitionally prolonging the duration of hyo-laryngeal elevation during swallowing, which also affects upper esophageal sphincter opening durations, according to some reports (Boden, Hallgren, & Witt Hedström, 2006;

Hoffman et al., 2012; Kahrilas et al., 1991). Since the kinematics of swallowing are internal, hyo-laryngeal movements during MM performance have been viewed with videofluoroscopy (VFS; Kahrilas et al., 1991). VFS, however, has known disadvantages including high cost, reduced accessibility, and exposure to ionizing radiation.

Surface electromyography (EMG) offers a low-cost, easily accessible alternative that eliminates the negative health impact associated with VFS. Thus, investigations of long-term effects of MM training in patients have used submental surface electromyography (ssEMG) to teach the MM and as biofeedback during training (Crary, Carnaby Mann, Groher, & Helseth, 2004; McCullough et al., 2012). The submental region is targeted for EMG recording during swallowing because it houses muscles that play an integral role in hyo-laryngeal elevation, namely the mylohyoid, geniohyoid, and anterior belly of the digastrics (Pearson, Hindson, Langmore, & Zumwalt, 2013). However, ssEMG lacks specificity for defining hyo-laryngeal function during swallowing because it records submental muscle activation during other swallowing events, in addition to hyo-laryngeal excursion. For example, it records submental muscle activation that

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occurs when stabilizing the floor of mouth during tongue movements (Palmer et al., 2008). Furthermore, ssEMG is unable to record activity of other muscles that contribute to hyo-laryngeal elevation during the MM, such as the longitudinal pharyngeal muscles (Pearson et al., 2013). At this time, the relationship between swallowing hyo-laryngeal kinematics and ssEMG during performance of swallowing maneuvers, such as the MM, warrants more investigation.

Several investigations have shown strong relationships between ssEMG activity and swallowing kinematics during natural swallows (swallowing without a therapeutic technique) (Alfonsi et al., 2013; Chi-Fishman & Sonies, 2000; Crary, Carnaby Mann, & Groher, 2006, 2007; Dantas & Dodds, 1990; Zamir, Ren, Hogan, & Shaker, 1996). Wheeler-Hegland, Rosenbek, and Sapienza (2008) conducted an insightful study that correlated hyoid kinematics (seen on VFS) and ssEMG during MM performance. Significant correlations were found between hyoid displacement and ssEMG activity during MM performance for discrete events such as time of maximum EMG and maximum hyoid displacement. However, the purpose of the MM training is for patients to prolong hyo-laryngeal displacement for at least 1.5 s (Ding, Larson, Logemann, & Rademaker, 2002; McCullough et al., 2012), but duration of the MM was not examined in the Wheeler-Hegland et al. study. Thus, given the prolongation goal of the MM, the relationship between ssEMG and kinematic durations is pertinent and clinically relevant.

Our study was also motivated by inclusionary criteria reported in the methods of Wheeler-Hegland et al. (2008). Participants were initially taught the MM with ssEMG, which was defined as increased ssEMG signal for at least 2 s. Then, the investigators confirmed proper MM performance with VFS. Although ssEMG training indicated that all participants performed the MM successfully, VFS identified that 24% of the participants were incorrectly performing the MM. These individuals were performing *partial MM*, which is defined as prolonged hyoid elevation, but no laryngeal vestibule closure (LVC). Furthermore, one participant in the Wheeler-Hegland et al. study had successful ssEMG MM training, but did not prolong hyoid elevation or LVC, and was subsequently excluded from the study (see Wheeler-Hegland et al., 2008, Table 2, p. 1078). These discrepancies were described as inclusionary criteria, but the relationship between ssEMG and hyo-laryngeal kinematics were not directly examined and reported in the results of the Wheeler-Hegland et al. study.

The goal of this investigation was to assess the relationship among the durations of ssEMG duration, hyoid elevation, and LVC during MM performance in healthy adults and in stroke patients. We hypothesize that the relationship between ssEMG signals and hyo-laryngeal kinematics will be weak when measuring MM swallow durations for two reasons: (a) ssEMG is not specific to hyo-laryngeal movements, as it also records activity when stabilizing the floor of the mouth during tongue movements (Palmer, et al., 2008); and (b) ssEMG does not record other major contributors to hyo-laryngeal elevation, including posterior belly of the digastrics, stylohyoid, stylopharyngeus, and

palatopharyngeus (Pearson et al., 2013). Therefore, ssEMG may not represent the extent of the activity of hyo-laryngeal elevators required for the maneuver, affecting accurate measures of MM swallow duration.

Method

Ethical Considerations

The Johns Hopkins University Institutional Review Board (IRB) approved this study. Written informed consent was obtained from all participants.

Participants

Participants included 21 healthy adults (mean age = 32 years, range = 18–54 years, eight women, 13 men) and three participants with dysphagia due to cortical stroke (mean age = 68.3 years, range = 60–80 years, one woman, two men). All healthy adults reported a negative history of speech, language, swallowing, and cognitive impairment. One stroke patient had oropharyngeal dysphagia that led to regular deep penetration due to delayed LVC onset. The other two stroke patients frequently aspirated due to reduced upper esophageal sphincter opening as well as delayed LVC onset.

Procedure

Training Participants to Achieve the MM

Participants were seated upright in view of a monitor displaying real-time VFS. First, a lateral view still-shot of the participants' oropharyngeal anatomy was used to orient them to the oral cavity, the pharynx, and the larynx. They were then instructed to palpate their thyroid notch to feel its movement during a saliva swallow. Instructions on how to perform the MM were "swallow and hold your Adam's apple up as high and as long as possible." Participants swallowed their saliva during all MM trials in this study.

Performing the MM

Once participants demonstrated the first accurate MM performance, healthy participants performed an additional six MM trials. Stroke patients performed an additional 16 MM trials to increase their chances of learning the behavior. Healthy adults were told to hold the MM for as long as possible. Patients were instructed to hold the maneuver for no longer than 6 s to prevent fatigue. Although clinical training of the MM does not require MM performance up to 6 s, we were interested in understanding the relationship among VFS and ssEMG in a wide range of MM durations.

Recording and Analyzing ssEMG and VFS

Recording

ssEMG and VFS were synchronously recorded during all MM swallows. All swallows were recorded with continuous VFS, acquired in the sagittal plane with a video

capture rate of 30 frames per second. The image intensifier included the oral cavity, pharynx, larynx, cervical vertebrae, and cervical esophagus. A time code was simultaneously recorded and facilitated frame-by-frame data analysis. Bipolar ssEMG electrodes (Motion Lab Systems, Inc., Baton Rouge, LA) were placed on the left and right sides of the submental muscle group, approximately halfway between the hyoid bone and the mentalis of the mandible. We expect that we were recording floor of mouth muscles (primarily anterior belly of the digastrics, mylohyoid, geniohyoid), and it is also possible that we recorded activity from hyoglossus and genioglossus. In order to ensure accurate surface EMG interpretation, there are technical data acquisition settings that must be considered. The rate of sampling is an important factor. Using a low sampling frequency can result in distortion of the signal and affect the reliability of the study (Ives & Wigglesworth, 2003). Therefore, we also considered the effects of sampling frequency on the data obtained, comparing the results in two groups with different sampling rates, 1 kHz (low sampling frequency) versus 10 kHz (high sampling frequency; see Figure 1). ssEMG was recorded throughout the study at a sampling rate of 1000 Hz (1 kHz) for 78 swallows and 10000 Hz (10 kHz) for 117 swallows (including interswallow intervals; rationale provided in the EMG section below).

ssEMG Analysis

No standard method for analyzing the onset and offset of the MM with ssEMG has been reported in previous studies. Ding et al. (2002) compared ssEMG signals between normal and MM swallows and determined that the onset for both normal and MM swallows is 2 *SDs* above the preswallow baseline. Cray et al. (2004) used ssEMG to demonstrate the effects of biofeedback in patients learning the MM, but did not report EMG analysis methods. Wheeler-Hegland et al. (2008) defined sEMG activity as a “departure of the sEMG signal from a resting baseline level associated specifically with biomechanical events occurring on the fluoroscopic image indicative of the beginning of each task.” Last, McCullough et al. (2012) specified that “an sEMG target line for amplitude was then set at 5 microvolts above their mean established from three baseline swallows” (p. 5).

Our aim was to investigate an ssEMG method that is typical for clinicians who train this maneuver in a clinical setting (i.e., ssEMG in the absence of complex analyses). However, in the current study, some ssEMG analyses were necessary to ensure that our measures of ssEMG duration were valid. The ssEMG data were digitally rectified and filtered at a low- and high-pass filter of 450 and 20 Hz, respectively. The rationale for our settings is based on known theories about use of surface EMG on the submental region for speech and swallowing tasks (Stepp, 2012). To be specific, in ssEMG signals for speech and swallowing systems, most of the power of the signal is in the 0–450 Hz range, thus our low-pass filter cut off of 450 Hz. Furthermore, movement artifacts are found in the 0–20 Hz range, thus our high-pass filter cut off at 20 Hz. Stepp (2012) also indicated

that when a low-pass filter is set at 500 Hz, ssEMG should be acquired at least 2 times higher than the highest frequency, which is approximately 1 kHz in our data, to prevent undersampling. However, because 1 kHz is the lowest allowable frequency, we also sampled at 10 kHz to prevent aliasing (undersampling). The electrode (left or right) with the cleanest signal was used for analysis. MM onset was defined as the point at which the ssEMG signal breached a threshold of 4 times the magnitude of rest ssEMG. MM offset was defined as the point at which the ssEMG signal breached this same threshold on its return to rest. The threshold of 4 times the baseline signal was used to ensure that we were determining onset and offset points of the MM in our participants and not some other movement that was not swallowing. For example, an anticipatory postural adjustment of the tongue or a throat clear just prior to MM performance increased the EMG signal 2 or even 3 times from the baseline. Setting our onset point at 2 or 3 times the baseline level would result in nonswallowing tasks being mistakenly identified as the onset of the MM. Baseline ssEMG was obtained by averaging a rest period of 1 s following the completion of the maneuver. VFS was used to ensure no tongue or swallow-related movements occurred during the time we derived the baseline. Postmaneuver rest was preferred to premaneuver rest to avoid anticipatory muscle activations that could influence the baseline ssEMG signal. VFS was not viewed for the purpose of determining MM onset or offset of ssEMG data.

Our ssEMG methods are similar to Wheeler-Hegland et al. (2008), because we compared MM ssEMG signal to baseline and considered VFS. However, in our case, VFS was considered after each ssEMG analysis was complete (blinded to VFS) by confirming that the ssEMG signal that was analyzed actually occurred during the time of MM performance (as opposed to some other task; i.e., speaking, yawning). We did not adjust our ssEMG measures to match hyo-laryngeal kinematics as in the Wheeler-Hegland et al. study. Similar to Ding et al. (2002), we also determined the threshold that best suited onset and offset on the basis of our baseline signals.

VFS

For VFS analysis, we obtained two temporal measures: duration of maximum hyoid elevation (dMHE) and duration of LVC (dLVC). The definition of dMHE was the time between the hyoid bone first reaching its maximum superior position after swallowing initiation, until the last frame before its descent, ending the MM. The definition of dLVC was the duration of contact between the arytenoids and epiglottis base during the swallow (Bisch, Logemann, Rademaker, Kahrilas, & Lazarus, 1994; Logemann et al., 1992; Park, Kim, Ko, & McCullough, 2010; Power et al., 2007). We also differentiated between full and partial LVC MM swallows. Full LVC MM swallows were characterized by dMHE and dLVC that were different by less than 1.5 s. Partial LVC MM swallows had differences

Figure 1. Raw and rectified data (y-axis: volts; x-axis: seconds) are shown for 1-kHz data (A = Raw, B = Rectified) and 10-kHz data (C = Raw, D = Rectified). EMG = electromyography; MM = Mendelsohn Maneuver.

between dMHE and dLVC that were equal to or greater than 1.5 s. This differentiation is significant because hyoid elevation and laryngeal elevation co-occur to achieve LVC (Fink, 1974; Fink & Demarest, 1978; Fink, Martin, & Rohrmann, 1979; Logemann et al., 1992). It is unknown whether ssEMG can differentiate between these two kinematic components involved in hyo-laryngeal excursion and LVC. Also, LVC duration is associated with penetration and aspiration in individuals with dysphagia (Park et al., 2010; Power et al., 2007), and, therefore, it is of clinical relevance to determine whether patients are learning to perform partial or full LVC MM, and whether ssEMG is sensitive to these differences. In the cohort sampled at 1 kHz, there were 55 full LVC MM swallows (43 healthy, 12 stroke) and 23 partial LVC MM swallows (20 healthy, three stroke). For the 117 swallows sampled at 10 kHz, there were 104 full LVC MM swallows (73 healthy, 31 stroke) and 13 partial LVC MM swallows (nine healthy, four stroke).

Experienced research assistants conducted all analyses. The raters were blinded to participant information, but aware of the purpose of the study.

Statistical Analysis

Linear regression analyses assessed the relationships among dMHE, dLVC, and ssEMG durations in the following five comparisons: (a) full MM swallows in all participants; (b) partial MM swallows in all participants; (c) full MM swallows in healthy participants; (d) partial MM swallows in healthy participants; and (e) full MM swallows in stroke participants. Partial MM swallows were not considered in stroke patients because there were too few samples. Statistical significance was adjusted to an alpha level of $p < .008$ to correct for multiple comparisons (five comparisons).

Results

All participants were able to complete all study tasks without an adverse event. Table 1 lists the results, including mean durations of ssEMG, dMHE, dLVC (seconds), correlations (R^2), probability values (p), and confidence intervals (CI) for each of the two comparisons in both sampling

Table 1. Correlations for 1-kHz data for each comparison, including the linear regression correlation (R^2), p value (* indicates statistical significance), 95% confidence interval (CI) of R^2 , and means (seconds) and standard deviations for ssEMG (submental surface electromyography), dMHE (duration of maximum hyoid elevation), and dLVC (duration of laryngeal vestibule closure). MM = Mendelsohn Maneuver.

Subject group	1-kHz comparisons									<i>M (SD)</i>		
	ssEMG vs. dMHE			ssEMG vs. dLVC			dMHE vs. dLVC			ssEMG	dMHE	dLVC
	R^2	p	CI	R^2	p	CI	R^2	p	CI			
1. All subjects												
Full LVC MM trials												
All Interpretation	.118	.010	(0.083 to 0.586)	.114	.007* Very weak, positive	(0.99 to 0.590)	.996	<.001* Very strong, positive	(0.964 to 0.997)	8.6 (8.4)	14.7 (8.7)	14.8 (8.9)
Partial LVC MM trials												
All Interpretation	.056	.278	(−0.197 to 0.652)	.065	.239	(−0.281 to 1.000)	.010	.647	(−0.558 to 0.879)	12.7 (10.4)	17.3 (10.8)	9.9 (6.8)
2. Healthy separate from stroke												
Full LVC MM trials												
Healthy Interpretation	.260	.306	(−0.158 to 0.492)	.033	.247	(−0.134 to 0.505)	.996	<.001* Very strong, positive	(0.991 to 1.000)	10.4 (8.7)	17.1 (8.3)	17.3 (8.5)
Stroke Interpretation	.358	.040	(0.210 to 0.724)	.330	.051	(−0.002 to 0.656)	.910	<.001* Very strong, positive	(0.679 to 1.000)	2.0 (.87)	6.1 (1.4)	5.9 (1.5)
Partial LVC MM trials												
Healthy	.001	.875	(−0.470 to 0.547)	.011	.666	(−0.602 to 0.920)	.022	.537	(−0.957 to 0.516)	11.0 (6.6)	19.4 (10.0)	14.4 (10.3)

Note. The interpretation of the significant relationships is also shown.

Table 2. Correlations for 10-kHz data for each comparison including the linear regression correlation (R^2), p value (* indicates statistical significance), 95% confidence interval (CI) of R^2 , and means (seconds) and standard deviations for ssEMG (submental surface electromyography), dMHE (duration of maximum hyoid elevation), and dLVC (duration of laryngeal vestibule closure). MM = Mendelsohn Maneuver.

Subject group	10-kHz Comparisons									<i>M (SD)</i>		
	ssEMG vs. dMHE			ssEMG vs. dLVC			dMHE vs. dLVC					
	<i>R</i> ²	<i>p</i>	CI	<i>R</i> ²	<i>p</i>	CI	<i>R</i> ²	<i>p</i>	CI	ssEMG	dMHE	dLVC
1. All subjects												
Full LVC MM trials												
All Interpretation	.428	<.001* Moderate, positive	(0.250 to 0.603)	.432	<.001* Moderate, positive	(0.258 to 0.618)	.994	<.001* Very strong, positive	(0.991 to 1.035)	5.7 (5.3)	4.7 (5.3)	4.6 (5.2)
Partial LVC MM trials												
All Interpretation	.473	.051	(−0.102 to 0.963)	.548	.026	(−0.011 to 1.629)	.349	.121	(−0.442 to 1.574)	6.2 (6.60)	7.8 (7.30)	2.2 (4.50)
2. Healthy separate from stroke												
Full LVC MM trials												
Healthy Interpretation	.423	<.001* Moderate, positive	(0.204 to 0.624)	.430	<.001* Moderate, positive	(0.215 to 0.641)	.998	<.001* Very strong, positive	(1.002 to 1.032)	6.4 (5.80)	5.7 (6.00)	5.6 (5.90)
Stroke Interpretation	.140	.226	(−0.390 to 0.853)	.118	.264	(−0.439 to 0.837)	.903	<.001* Very strong, positive	(0.758 to 1.093)	4.2 (3.40)	2.4 (2.10)	2.3 (2.02)
Partial LVC MM trials												
Healthy	.452	.111	(−0.310 to 1.130)	.579	.051	(−0.209 to 1.825)	.344	.182	(−0.762 to 1.820)	7.1 (7.60)	9.3 (8.30)	2.3 (5.40)

Note. The interpretation of the significant relationships is also shown.

groups. Reliability was excellent for EMG and VFS measures (dMHE = .996, dLVC = .999, ssEMG = -.998).

Comparisons

All partial LVC MM correlations were nonsignificant for all comparisons. Therefore, only full LVC MM will be discussed.

Full LVC MM in All Participants

The 1-kHz ssEMG data were very weakly, but significantly correlated with dLVC ($r = .114$; Figure 2, Part A). This means that for any change in the duration of LVC, approximately 10% of that change is reflected by a change in the duration of the ssEMG signal. In the 10-kHz ssEMG data, ssEMG duration was moderately and significantly correlated with dMHE ($r = .428$) and with dLVC ($r = .432$; see Figure 2, Part A). Thus, in the 10-kHz data, for any change in the duration of a kinematic event (dMHE or dLVC), approximately 40% of that change is reflected by a

change in the duration of the ssEMG signal. A significant strong positive relationship was found between dLVC and dMHE during full LVC MM trials in all participants ($r = .99$; Figure 2, Part B).

Full LVC MM in Healthy Adults

No 1-kHz correlation was significant for this comparison (see Figure 3). The 10-kHz ssEMG data rendered a significant, moderate, positive relationship with both dMHE ($r = .423$) and with dLVC ($r = .430$). A significant, very strongly positive relationship between dMHE and dLVC was found for full LVC MM swallows ($r = .99$).

Full LVC MM in Stroke Patients

No significant relationship was found for full LVC MM swallows in stroke participants with either 1- or 10-kHz ssEMG (see Figure 3). A significant, very strongly positive relationship between dMHE and dLVC was found for full LVC MM swallows ($r = .90$).

Figure 2. A: Full LVC MM trials of ssEMG and kinematics measure in all participants (seconds) at 1-kHz (white) and 10-kHz (black) sampling frequency. B: Full LVC MM trials of kinematic measures in all participants (seconds). LVC = laryngeal vestibule closure; MM = Mendelsohn Maneuver; ssEMG = submental surface electromyography; dMHE = duration of maximum hyoid elevation; dLVC = duration of laryngeal vestibule closure.

A Full LVC MM trials of ssEMG and kinematics measures in all subjects (seconds) at 1kHz (white) and 10kHz (black) sampling frequency.

B Full LVC MM trials of kinematic measures in all subjects (seconds)

Figure 3. Full LVC MM trials of ssEMG and kinematic measures separated by healthy adults (black dots, left graphs) and stroke patients (white dots, right graphs). LVC = laryngeal vestibule closure; MM = Mendelsohn Maneuver; ssEMG = submental surface electromyography; dMHE = duration of maximum hyoid elevation; dLVC = duration of laryngeal vestibule closure.

Discussion

The goal of this investigation was to examine temporal relationships between hyo-laryngeal kinematics and submental muscle group activation during the MM. Our main outcome is that, overall, the strength of the relationship between ssEMG duration and either dMHE and dLVC varies depending upon how the MM is performed (full vs. partial LVC MM), the ssEMG sampling rate (1 vs. 10 kHz), and possibly the population being measured (stroke vs. healthy). Under the best circumstances (full LVC MM with 10-kHz ssEMG in healthy adults), the duration of ssEMG signals demonstrate a moderate, positive relationship ($R^2 = 0.43$) with dMHE and dLVC. This means that for every change in hyo-laryngeal kinematics, approximately 40% is reflected in ssEMG duration signal changes. In the stroke group, no correlation reached statistical significance between ssEMG and hyo-laryngeal kinematics. A possible explanation for this finding is that weakness of the muscles in the stroke patients produced a less robust or even inconsistently robust signal on EMG. The threshold of 4 times the amplitude at rest to mark the onset and offset of the MM may not have been reached by the patient's weaker and more fatigable submental musculature.

We have also examined the two behavioral patterns of MM performance including LVC maintained throughout the MM (full LVC MM) and LVC ending before hyoid elevation has terminated (partial LVC MM), noted by

Wheeler-Hegland et al. (2008). Partial LVC MM swallows did not have statistically significant relationships between ssEMG and either kinematic measure or between the two kinematic measures. During partial MM LVC performance, our data show that ssEMG durations (10 kHz) were shorter than dMHE. Thus, it is possible that not achieving LVC lead to decreased submental muscle activation that caused the ssEMG signal to breach our specified threshold, reducing the ssEMG duration measures.

Our data also highlight the importance of sampling frequency in ssEMG data as evidenced by the variations in comparison strength between the 1- and 10-kHz groups. The correlation of ssEMG to laryngeal kinematics in full LVC MM trials from healthy adults was strengthened by using a higher sampling frequency. A review of the use of surface EMG in the swallowing system suggests that to ensure signal integrity, data acquisition of at least 2 kHz is recommended (Stepp, 2012). It is possible that sampling at a frequency of 1 kHz was undersampling the data, resulting in a signal that is not truly representative of the muscle activity, an effect known as *aliasing*. Increasing the sampling frequency to 10 kHz appeared to improve ssEMG to hyo-laryngeal kinematic correlations, likely because the baseline could more clearly be differentiated from the signal increase of MM swallows (see Figure 1).

Overall, submental ssEMG likely did not demonstrate strong correlations with hyo-laryngeal kinematics during MM swallowing because longitudinal pharyngeal muscles,

also involved in hyo-laryngeal elevation during MM swallowing, are not included in recordings from this region (Pearson et al., 2013). Longitudinal pharyngeal muscles are infrequently measured during swallowing because they are inaccessible for noninvasive ssEMG recordings. Their role in airway protection is poorly characterized by the research literature and warrants more scientific investigation. Furthermore, LVC is a phenomenon that occurs due to epiglottic inversion (also affected the pharyngeal squeeze and the bolus), arytenoid adduction, and aryepiglottic fold bunching, not just hyo-laryngeal elevation (Ekberg, 1982; Ekberg & Sigurjonsson, 1982; Fink, 1974; Fink & Demarest, 1978; Fink et al., 1979; Logemann et al., 1992). These many mechanistic contributors cannot all be reflected in the ssEMG signal. Despite frequent, accepted use of ssEMG for both research and clinical purposes when training the MM, no previous study has determined whether duration of ssEMG signals accurately represent duration of hyo-laryngeal movements for the goal of prolonged hyo-laryngeal elevation and/or LVC. Understanding the relationship among the durations of hyoid elevation, LVC and ssEMG are important because ssEMG is widely used to initially teach the MM and as biofeedback tool, aimed to improve MM performance over time in dysphagia rehabilitation (Crary et al., 2004; McCullough et al., 2012). The goal of biofeedback is to provide information about movement accuracy so that motivation and faster learning are increased, whereas losses in intrinsic feedback (i.e., proprioception) are supplemented over the long term (Salmoni, Schmidt, & Walter, 1984; Sidaway et al., 2008; van Vliet & Wulf, 2006). Thus it is critical that ssEMG accurately reflects the target kinematic events of the therapeutic task that is being trained. Our findings are significant because we show that without imaging swallowing kinematics when training novel movements, there is a risk that the target therapeutic movements (i.e., hyo-laryngeal elevation, LVC) are not consistently being reflected in ssEMG data. For example, if the goal is for patients to perform full LVC MM swallows, then ssEMG might not be able to distinguish them from partial LVC MM swallows. Since the goal of therapy is to induce beneficial changes over time, it is possible that ssEMG used in isolation for acquisition or training of novel movements could misrepresent improvement, stagnation, or decline.

We conclude that ssEMG is, at best, moderately correlated with the hyo-laryngeal kinematics of the MM. Our findings also point to an important, but addressable, barrier to dysphagia management. That is that complicated internal swallowing events are best visualized with expensive and potentially harmful instrumentation that is not widely accessible. Although VFS presents a number of challenges, it is still the gold standard for imaging hyo-laryngeal swallowing kinematics. More studies are needed to explore the ways in which VFS can be used to train swallowing maneuvers, without increasing harm to patients and without substantial increases in cost or decreases in clinical productivity. We also need to further investigate swallowing treatments or maneuvers for which ssEMG is best suited. This study is limited by the small patient sample and single etiology, so

future studies are necessary to investigate a larger cohort of patients with dysphagia. Furthermore, we investigated ssEMG methods that were typical for clinicians who train this maneuver in a clinical setting. It is possible that more complex ssEMG analyses that are meant to infer complex characteristics of muscle contraction might yield different outcomes when compared to videofluoroscopic hyo-laryngeal kinematics. Outcomes from these future studies may lead to important changes in the way that dysphagia rehabilitation techniques are learned by patients and hopefully improve training target behaviors of specific therapeutic techniques.

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