Clinical Measurement of Pharyngeal Surface Electromyography: Exploratory Research

Sebastian H. Doeltgen, MSLT, Andrea Hofmayer, MA, Freya Gumbley, BSLT,
Ulrike Witte, MSLT, Catherine Moran, PhD,
Grant Carroll, BSc, DipSci, and Maggie-Lee Huckabee, PhD

Background. Dysphagia diagnosis is limited by our inability to evaluate underlying neuromuscular pathology of swallowing. A novel approach using pharyngeal surface electromyography (PsEMG) has been reported in the literature. *Objective*. Three exploratory projects were undertaken to provide data toward the validation of PsEMG as a clinical measure of pharyngeal physiology. The first evaluates laterality of electrode placement in the pharynx. The second and third evaluate PsEMG using a circumferential and unidirectional electrode, respectively, during swallowing maneuvers. *Methods*. In experiment 1, a catheter housing 3 manometric sensors and 1 bipolar PsEMG electrode was randomly inserted in each nares of 10 participants. Moving jaw radiographs were taken, and the PsEMG electrode was measured in millimeters from midline. In experiments 2 and 3, the catheter was placed in 22 and 40 research participants, respectively. Waveform characteristics were collected during swallowing maneuvers. The 2 experiments differed by type of electrode (circumferential, unidirectional) and swallowing maneuver (noneffortful and effortful swallow; noneffortful, effortful, and tongue-hold swallow). *Results*. Midline electrode placement occurred on 20% of trials with deviation of up to 14.7 mm on all other trials. Maneuver-specific differences in amplitude were not detected with PsEMG; unacceptable levels of intrasubject and intersubject variability were identified. Temporal relationships of PsEMG and pharyngeal manometric pressure appeared appropriate. The unidirectional electrode revealed a unique bimodal PsEMG pattern that may reflect sequential contraction of muscles of the posterior pharyngeal wall. *Conclusions*. The current PsEMG design and procedures do not validly measure pharyngeal muscle activity. Recommendations for improved methods are provided.

Key Words: *Electromyography—Pharyngeal—Deglutition—Dysphagia—Measurement.*

The clinical gold standard in diagnostic dysphagia assessment and the test most accessible to the clinical community is the videofluoroscopic swallowing study. This examination allows clinicians to clearly visualize biomechanical, deglutitive events that facilitate and/or inhibit bolus transfer through the upper aerodigestive tract and into the proximal esophagus.[1,2] Unfortunately, videofluoroscopic imaging of swallowing cannot expose the underlying neuromuscular nature of biomechanical movement; it images only movement patterns. Often, there appears to be an assumption of weakness when assessing pharyngeal motility disorders.

Weakness as a characteristic of dysphagia is frequently cited in the literature.[3-6] However, other types of neuromuscular impairment are not. For example, a Medline search using the terms *spasticity* and *deglutition* or *dysphagia* produced 42 references. Careful review of these articles reveals that most relate to spasticity in a general sense as an outcome of neurologic disease, such as cerebral palsy or amyotrophic lateral sclerosis. There are multiple references that discuss specific spasticity of the cricopharyngeus muscle and subsequent treatment.[7-13] However, there are only very recent specific references to spastic dysphagia or pharyngeal spasticity as a diagnostic entity. The concept that pharyngeal hyperfunction may contribute to swallowing impairment has been discussed in recent articles by Clark[14] and Huckabee and Kelly.[15] However, hesitancy to incorporate these concepts into clinical management appears to reflect a diagnostic bias and is quite apparent on review of rehabilitation techniques that are applied to swallowing management. Most of these exercises are primarily directed toward increasing pharyngeal pressure through muscle strengthening.[16,17]

Specific muscle function is best evaluated with intramuscular electromyography (EMG). Several research

From the University of Canterbury Department of Communication Disorders (SHD, AH, FG, UW, CM, M-LH); Van der Veer Institute for Parkinson's and Brain Research (SHD, AH, FG, UW, CM, GC, M-LH); Canterbury District Health Board, Department of Neurology (GC); and the Christchurch School of Medicine and Health Sciences, University of Otago (GC), Christchurch, New Zealand.

Address correspondence to Maggie-Lee Huckabee, PhD, Swallowing Rehabilitation Research Laboratory, Van der Veer Institute for Parkinson's and Brain Research, 16 St. Asaph Street, Christchurch, New Zealand. E-mail: maggie-lee.huckabee@vanderveer.org.nz.

Doeltgen SH, Hofmayer A, Gumbley F, Witte U, Moran C, Carroll G, Huckabee M-L. Clinical measurement of pharyngeal surface electromyography: exploratory research. *Neurorehabil Neural Repair*. 2006;XX:1–13.

DOI: 10.1177/1545968306293448

groups have investigated normal deglutitive behavior using intramuscular EMG.[18-22] This research has been valuable for increasing our understanding of normal processes, and several other researchers have extended this work toward an understanding of pathophysiology.[23,24] However, despite the diagnostic value identified through the studies, the use of intramuscular EMG has resisted widespread application to clinical diagnosis. This lack of translation from science to clinic may be due in part to measurement difficulties. In addition, the routine dysphagia assessment is generally completed by the speech language pathologist who does not have training in invasive, intramuscular EMG recording techniques.

Ertekin[25] explored the use of surface EMG (sEMG) of external muscle groups in an attempt to quantify muscle characteristics in individuals with swallowing impairment. However, this work addressed submental, or collective floor of mouth, muscle activity and thus cannot be considered to represent characteristics of pharyngeal swallowing. Bipolar pharyngeal surface EMG (PsEMG) via intraluminal catheter insertion was reported by Hamdy and colleagues[26,27] in several articles as a means of measuring motor-evoked potentials (MEPs) generated by transcranial magnetic stimulation. Corticopharyngeal electromyographic responses generated from transcranial magnetic stimulation were recorded via surface electrodes housed in a flexible catheter that was passed either transorally or transnasally. Results of these studies have identified several intriguing findings. First, the pharyngeal muscles involved in swallowing are somatotopically represented on the motor and premotor cortex of both hemispheres but with a significant interhemispheric asymmetry. Second, this hemispheric asymmetry appears to predispose an individual to dysphagia subsequent to stroke; those presenting with dysphagia had a smaller pharyngeal representation in the nonlesioned hemisphere and smaller MEPs than their nondysphagic counterparts did. Finally, swallowing recovery appeared to be secondary to mechanisms of hemispheric reorganization, as measured by a significant increase in the area of pharyngeal representation in the contralateral hemisphere in patients with resolved dysphagia postinfarct. Further research by this group used this same technique to document both positive and negative influences of electrical stimulation[28,29] and repetitive transcranial magnetic stimulation[30] on neural transmission as measured by adaptation of latency and amplitude of the generated MEP.

Hamdy and colleagues have offered a creative solution for the measurement conundrum of pharyngeal EMG. Their overall research results of hemispheric asymmetry have been confirmed using functional magnetic resonance imaging techniques[31]; however, they have not fully investigated the validity of the derived electrophysiologic measures. Certainly, there is an obvious methodological limitation in this approach to measuring pharyngeal EMG: the intraluminal electrode is not secured to the skin surface overlying the targeted muscles, nor is it imbedded directly in muscle tissue. However, this technique could offer great potential for clinical management as it may allow for assessment of the underlying pathophysiology of biomechanical impairment and is substantially less invasive than intramuscular EMG. It is therefore important to pursue the viability of PsEMG as a measure of pharyngeal swallowing physiology and to document the validity and stability of this measure.

We present in this article a series of 3 exploratory projects that were designed to evaluate the potential validity and complications associated with PsEMG. The first evaluates laterality of placement of the catheter within the pharynx and follows work discussed in the preceding paragraph in which MEPs measured with PsEMG were used to comment on cortical hemispheric dominance. The second study evaluates PsEMG measures using a circumferential electrode during 2 swallowing maneuvers to investigate its utility as a measure of pharyngeal physiology. The third and final study reports on unidirectional measurement of PsEMG, again comparing output between several swallowing maneuvers.

EXPERIMENT 1

Research Aims

The aim of this study was to evaluate the influence of method of catheter placement (left vs right nares) on the pharyngeal location of the bipolar surface electrode in healthy research participants. Results of this study could have implications on assumptions made regarding cortical representation of swallowing. This is of particular interest in the analysis of MEPs recorded with PsEMG.

Method

Participants. Ten healthy volunteers (1 male and 9 female), with a mean age of 25.9 years (range, 20-32 years), were investigated. No research participant had a history of neurological disease, dysphagia, or anatomic abnormalities affecting pharyngeal motility. Informed consent was obtained prior to initiation of data collection; ethics approval was obtained by the appropriate institutional review board.

Procedure. Data were collected in the Department of Clinical Neurophysiology at a regional hospital. Research participants were seated in a comfortable chair. An intraluminal catheter with an outer diameter of 2.1 mm housing a paired bipolar sEMG electrode was inserted

Figure 1. Experiment 1: moving jaw radiograph with the pharyngeal catheter at approximately midline. The arrow points to the pharyngeal surface electromyography electrode.

through the nares. As the catheter reached the upper pharynx, identified by resistance at the posterior pharyngeal wall, participants were asked to rapidly ingest a glass of water through a straw. In doing so, the catheter was swallowed into the proximal esophagus. The catheter was swallowed until it measured 40 cm from the tip of the nose. It was then slowly retracted, during which time research participants were asked not to swallow, speak, or cough. Catheter location was standardized by pulling the catheter 4 cm beyond the point at which the researcher identified a sudden increase of EMG amplitude, indicating placement of the PsEMG electrodes in the cricopharyngeus muscle. The catheter was then taped securely to the external nose with standard medical tape. PsEMG activity used to confirm placement was recorded on a Dantec keypoint electrophysiology system. The side of nares insertion was counterbalanced.

Subsequently, a single still radiograph was taken in the anterior-posterior plane from the cervical spinal region (between level C1 and C6). The catheter was then removed by the researcher and inserted into the respective other nares before a second radiograph was taken to document electrode placement. Radiographs were taken in the moving-jaw manner to ensure good visibility of the electrode through the blurred radiographic image of the mandible. Thus, 2 radiographic images were captured for each participant, 1 with the catheter inserted through each of the nares.

Data analysis. The radiographs were calibrated to allow for comparable measurement in millimeters. The side of nares insertion was not documented on the radiographic images. For each radiograph, the cervical vertebra at the level of the sEMG electrode was identified. A horizontal line was then drawn at the level of the electrode, extending from the left to the right outer margin of this vertebra. With the vertebral midline expressed as 0, the electrode position was expressed in millimeters from midline, with positive and negative values in millimeters suggesting placement to the right and left of midline, respectively. Data were analyzed for intrasubject differences as a function of laterality of placement.

Results

Interrater reliability. A random 20% of all radiographic images were evaluated by a second researcher. Interrater reliability using the intraclass correlation coefficient was significant at the $P < .001$ level, with $r = 0.98$.

PsEMG electrode localization. The pharyngeal sEMG electrode localized at midline of the pharynx in 20% of trials (Figure 1). In 55% of placement trials, the electrode crossed the midline of the pharynx and thus localized to the side contralateral to insertion (Figure 2). Deviation from midline ranged from 2.1 to 14.7 mm. In 55% of the trials, the electrode remained ipsilateral to the side of insertion. In these cases, deviation from the pharynx midline ranged from 1.7 to 8.5 mm.

Four distinct patterns of electrode placement were identified. Four participants consistently displayed electrode placement ipsilateral to the side of insertion, 1 participant displayed contralateral electrode positioning, and in 1 participant, the electrode localized at midline in both conditions. In 4 research participants, the electrode localized to the same pharyngeal side irrespective of side of insertion, leading to a mixed laterality of electrode positioning.

Summary of Findings

- The data collected in this preliminary study reveal that midline electrode placement cannot be ensured using this method of catheter placement.
- Considering that the posterior pharyngeal wall (PPW) consists of paired muscle groups, the position of this electrode (left, right, or midline) during measurement of MEPs may have implications for the subsequent assessment of cortical laterality.
- In a future study, it would thus be important to evaluate whether a differing lateral electrode placement has an effect on the measurement of MEPs.

Figure 2. Experiment 1: moving jaw radiograph with the pharyngeal catheter deviating substantially to the contralateral pharynx. The arrow points to the pharyngeal surface electromyography electrode.

EXPERIMENT 2

Research Aims

The focus of this second exploratory study was to identify means and standard deviations of PsEMG measures using paired 2.1-mm circumferential electrodes and to determine if differential degrees of pharyngeal muscle activation associated with 2 swallowing techniques could be detected. In addition, the relationships between amplitude and temporal characteristics of PsEMG were correlated with similar measures of pharyngeal manometric pressures to identify existing relationships.

Method

Participants. Twenty-two young (mean age = 27.9, *SD* = 4.6), healthy research participants (gender equally represented) provided data for this project. Research participants reported no history of dysphagia or neurologic disease. Informed consent was obtained prior to initiating data collection; ethics approval was obtained by the appropriate institutional review board.

Procedure. Surface electrodes were adhered to the undersurface of the chin to measure electromyographic activity of the collective floor of mouth and anterior suprahyoid muscles during swallowing. Digital 12-bit samples were obtained with a sampling frequency of 500 Hz. The resulting rectified and averaged signal was displayed on a computer monitor within view of the research participant. Before proceeding with further sensor placement or data collection, subjects were given demonstration and directions concerning the performance of the 2 research tasks (a noneffortful dry swallow and an effortful dry swallow) and were allowed to practice these tasks using the sEMG output to guide performance and mastery. (Initially described as a compensatory swallowing technique to increase pharyngeal pressure and thus reduce pharyngeal residual,[32] effortful swallow has recently been described as a rehabilitative technique.[16] Simply stated, an individual is instructed to swallow hard or swallow with effort.)

After practice research tasks were mastered, a thin transnasal flexible endoscope was inserted into 1 nares to allow for direct visualization of the oropharynx. Once the oropharynx was visualized, a thin flexible catheter (Model CT/S3+emg, 2.1 mm in diameter; Medical Measurements Inc, Hackensack, NJ) housing 3 manometric sensors and a circumferential bipolar sEMG electrode was placed in the other nares, through the pharynx, and into the proximal esophagus. The manometric sensors measuring 5 mm in length were oriented toward the posterior pharyngeal wall. The uppermost manometric sensor was positioned immediately superior to the epiglottis but below the soft palate. The first sEMG electrode was placed 5 mm below the proximal manometric sensor and just inferior to the tip of the epiglottis, with the second ring electrode 1 mm below the first; the second manometric sensor was placed 5 mm below the PsEMG, approximately level with the arytenoids; and the most distal manometric sensor was placed within the circumferential cricopharyngeus muscle, 10 mm below the midpharyngeal sensor. Correct catheter placement was verified using endoscopic visualization and confirmed using the subsequent pharyngeal pressure recordings (with low pressure at rest in the first and second manometric sensors and high pressure at rest in the third manometric sensor); the "M" wave was clearly observed on swallowing to ensure high pressure in the third sensor at rest.[33] Once correct placement was achieved (Figure 3), the catheter was secured to the nose with medical tape, and the transnasal endoscope was withdrawn. Although electrode to skin contact was not consistent at rest, during swallowing, the pharynx was observed to close around the catheter, thus approximating the electrode to the pharyngeal surface (Figure 4).

Data collection. Each subject was asked to complete 10 repetitions of 2 counterbalanced research tasks: normal

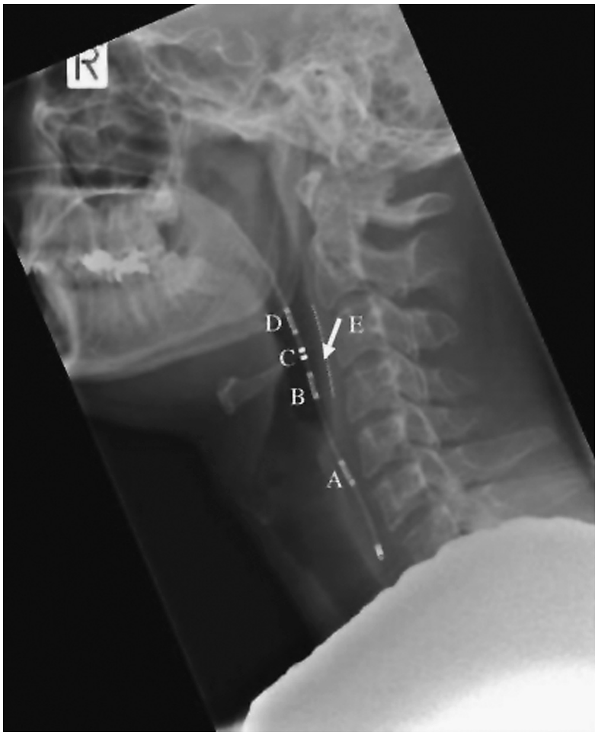

Figure 3. Experiments 2 and 3: lateral radiograph with the pharyngeal catheter in situ and at rest. A = lowermost manometric sensor in the upper esophageal sphincter; B = midpharyngeal manometric sensor; C = pharyngeal surface electromyography electrode; D = uppermost pharyngeal manometric sensor; E = posterior pharyngeal wall.

Figure 4. Experiments 2 and 3: lateral radiograph with the pharyngeal catheter in situ and during swallowing. Pharyngeal compression allows for electrode to skin contact such that no air column is visualized in the hypopharynx. A = lowermost manometric sensor in the upper esophageal sphincter; B = midpharyngeal manometric sensor; C = pharyngeal surface electromyography electrode; D = uppermost pharyngeal manometric sensor.

dry (saliva) swallows and effortful dry (saliva) swallows. Manometric and sEMG data were visually displayed and stored on the Kay Elemetrics Digital Swallowing Workstation (Lincoln Park, NJ). Digital 12-bit samples were obtained at a frequency of 500 Hz for both PsEMG and manometric recordings.

Data preparation and analysis. Peak PsEMG and submental sEMG amplitudes and peak manometric pressure recordings were collected off-line. These values were defined as the amplitude of the signal (either in microvolts or millimeters of mercury) at the nadir of the waveform surrounding swallowing behavior. In addition, temporal measures were also extracted from the waveforms. Duration of sEMG activity (submental and pharyngeal) and manometric pressure was defined as the time, in milliseconds, from the point at which the waveform departed from the resting average immediately preceding the nadir to the point at which the waveform returned to resting average, postnadir. Finally, to evaluate the sequencing of pharyngeal measures, submental sEMG and pharyngeal manometric pressure onsets were calculated relative to onset of PsEMG, which was identified as time point 0 for this analysis.

Intraclass correlation coefficients based on variance estimates obtained through an analysis of variance were employed to characterize interrater and intrarater reliability for all measures. Differences in swallowing condition (effortful vs noneffortful swallow) at all sensors were evaluated using repeated-measures ANOVA. Pearson correlation coefficients were used to investigate the relationship between PsEMG and other measures of swallowing physiology.

Results

Interrater and intrarater reliability. Twenty percent of all measures used in this analysis were randomly selected for reanalysis to establish intrarater and interrater reliability. All measures of reliability were significant at the $P < .001$ level, with intraclass correlation coefficients ranging from a high of $r = 0.98$ for identification of peak pharyngeal sEMG amplitude and a low of $r = 0.83$ for identification of peak upper esophageal sphincter (UES) manometric pressure.

Table 1. Experiment 2: Means (±*SD*) for Both Amplitude (in microvolts) and Duration (in milliseconds) of Pharyngeal Surface Electromyography for Noneffortful and Effortful Swallowing Conditions

	Noneffortful Swallowing	Effortful Swallowing
Amplitude	91.40 ± 43.99	98.02 ± 41.11
Duration	530 ± 210	590 ± 220

Measures of PsEMG: descriptive statistics. Descriptive statistics were calculated to characterize the PsEMG measurements. Means and standard deviations of PsEMG peak amplitudes on 210 trials of each condition are presented in Table 1.

Repeated-measures ANOVA to evaluate for effect of trial of PsEMG amplitudes revealed no significant effect of trial on amplitude within an individual for the effortful, $F(1, 21) = 0.461$, $P = .899$, or the noneffortful, $F(1, 21) = 1.468$, $P = .163$, swallowing conditions. As collection of PsEMG data presented no systematic changes across trial, within-subject data were averaged for all subsequent analyses.

Normal versus effortful swallow at PsEMG. Repeated-measures ANOVA to evaluate for differences between conditions revealed no significant difference between amplitude measures detected by PsEMG for swallowing condition (effortful vs non effortful), $F(1, 21) = 1.545$, $P = .228$, although the average amplitude for effortful swallowing ($M = 97.994$) was greater than that for noneffortful swallowing ($M = 92.491$). This is in contrast to the same analysis performed on manometric pressure measures in the upper pharynx, $F(1, 21) = 6.752$, $P = .017$) and midpharynx, $F(1, 21) = 8.644$, $P = .008$), which surround the PsEMG electrode. For both sensors, significantly greater pharyngeal pressure was identified for the effortful swallowing condition than for the noneffortful swallowing condition.

Significant differences were detected between conditions on measures of duration of PsEMG, $F(1, 21) = 6.766$, $P = .018$, with effortful swallowing ($M = 595$ milliseconds) producing significantly longer measurable PsEMG waveforms than the noneffortful swallowing ($M = 528$ milliseconds) condition. This is consistent with significant differences in duration of manometric pressures at both the upper, $F(1, 21) = 61.037$, $P < .001$, and lower, $F(1, 21) = 9.733$, $P = .006$) sensors.

Relationship between PsEMG, submental sEMG, and pharyngeal pressures. Pearson correlation coefficients were derived to evaluate the relationship between PsEMG measures and other measures across swallowing conditions. For peak amplitude, there was no significant correlation between PsEMG and submental sEMG ($r = 0.166$, $P = .307$). Surprisingly, there was a negative but weak correlation between peak PsEMG and both manometric measures (Mano1: $r = -0.151$, $P = .352$; Mano2: $r = -0.387$, $P = .011$).

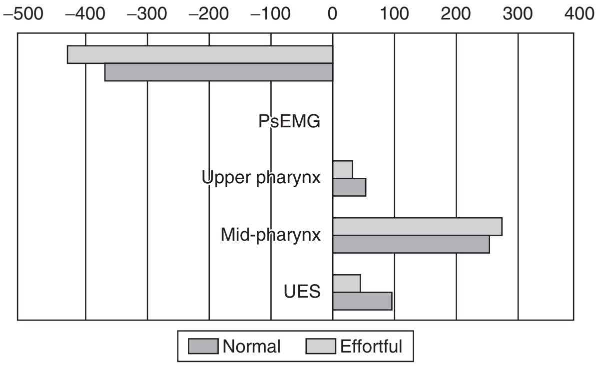

Figure 5. Experiment 2: temporal relationships between pharyngeal surface electromyography (PsEMG), submental surface EMG (SsEMG), and pharyngeal manometric pressures in the upper pharynx, midpharynx, and upper esophageal sphincter (UES). Latency characteristics are illustrated for both normal and effortful swallowing conditions. All data represent averages across research participants and are displayed in milliseconds.

For measures of duration, significant, moderate correlations were identified for PsEMG and submental sEMG ($r = 0.475$, $P = .002$). Nonsignificant and weak correlations were identified for PsEMG duration and duration of manometric pressure (Mano1: $r = 0.289$, $P = .071$; Mano2: $r = 0.082$, $P = .618$).

Temporal relationships between sEMG measures and pharyngeal pressures. A descriptive investigation was undertaken to characterize the overall timing of PsEMG onset in relationship to onsets of other measures. These data, for both noneffortful and effortful swallow, are summarized in Figure 5. Onset of PsEMG was used as a temporal point of reference. As depicted, contraction of the submental muscle group occurred before onset of pharyngeal constrictor activation, while upper pharyngeal pressure generation preceded pressure generation in mid pharynx. UES relaxation occurred slightly after pressure generation in the upper pharynx and before pressure generation in the midpharynx.

Variance components analysis. To clarify patterns of within- and between-subject variance in the amplitude data, variance components estimation was conducted. A between-subjects coefficient of variation (CV) of 42.05 was calculated; within-subject CV was calculated at 33.938. The CV for task was calculated at only 11.879. When taken in the context of overall experimental variance, between-subject variation accounted for 58% of the total variation, whereas variation within subjects

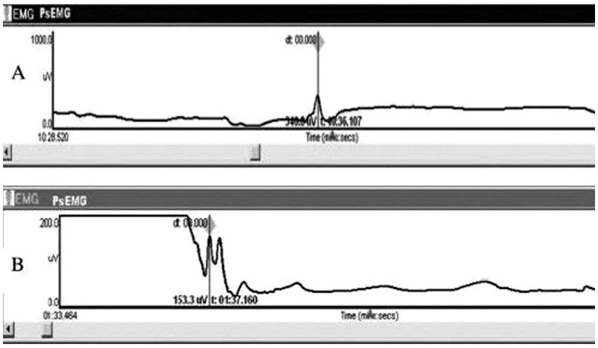

Figure 6. (A) Experiment 2: pharyngeal surface electromyography (PsEMG) unimodal waveform using circumferential electrode; floating baseline suggests detachment of the catheter from the pharyngeal wall. (B) Experiment 3: PsEMG bimodal waveform using adapted unidirectional electrode; floating baseline suggests detachment of the catheter from the pharyngeal wall.

and across trials accounted for 37% of the total variance. Swallowing task-specific variance was measured at only 5% of the total variation.

Summary of Findings

- Effortful swallow did not produce significantly increased PsEMG measures, although the duration was significantly longer. This is in contrast to pharyngeal manometric recordings, which were significantly higher in amplitude and longer in duration for effortful swallow.
- Less than 5% of the variance in circumferential PsEMG amplitude measures is task specific, suggesting that this method of measuring pharyngeal muscle strength is inadequate.
- Very weak correlations between PsEMG and other measures of pharyngeal swallowing biomechanics were identified.
- Finally, the temporal relationship of PsEMG to other measures appears appropriate.

EXPERIMENT 3

Research Aims

Experiment 2 revealed no significant differences in PsEMG peak measures between noneffortful and effortful swallows when using a circumferential electrode and identified enormous within- and between-subject variance. To eliminate the contribution of base of tongue (BOT) to the PsEMG signal and thus refine the consequent measurement, experiment 3 specifically investigated muscle activity of the PPW using a posteriorly oriented unidirectional electrode. It further investigated the correlation between PsEMG measures and manometric pressure measures during swallowing maneuver conditions.

Method

Similar methods to those used in experiment 2 were employed for this project; however, a few adaptations were made to suit the purpose of this experiment. A thin layer of nonconductive rubber paint was applied to the anterior facing 65% of the circumferential electrode used in experiment 2, leaving the posterior 35% exposed to the surface of the PPW. Performance of a tongue-hold maneuver was included in this experiment as it is generally believed to accentuate PPW activity.[34,35] (Based on videofluoroscopic assessment of healthy[35] and dysphagic[34] research participants, Fujiu et al documented that when individuals swallow with the tongue anchored between the front teeth, there was a subsequent increase in anterior movement of the PPW. Thus, this technique has been employed as a rehabilitation exercise for pharyngeal swallowing impairment.)

Data collection. Forty young, healthy research participants performed a set of 5 noneffortful saliva swallows. This was followed by a set of either 5 effortful swallows or 5 tongue-hold swallows, randomized across research participants, before performing the alternate condition.

Data preparation. Although the circumferential electrode used in experiment 2 produced a typical unimodal waveform pattern (Figure 6), the unidirectional electrode used in this experiment resulted in a bimodal PsEMG waveform (Figure 6) on 62.6% of swallows across all participants and conditions. This is followed by a unimodal waveform in 23.6% and no identifiable activity in 13.7% of swallows. Furthermore, the bimodal peak pattern varied within participants and conditions: 5 trials were performed for each condition by each participant; however, not all of these trials displayed a double-peak pattern. Given the variability in measured PsEMG activity and the degree of artifact in the subsequent waveforms, it was necessary to classify and then average measures for statistical analysis. Therefore, when 2 or more trials within 1 condition displayed a double-peak pattern, peak amplitude measures were averaged for subsequent statistical analysis.

In addition, there were not always mean values available for every condition from every participant. To compensate for missing values, research participants were grouped according to distinguishable patterns. Grouping participants according to the PsEMG peak pattern they displayed allowed the largest number of

Table 2. Experiment 3: Means and Standard Deviations of Pharyngeal Surface Electromyography (PsEMG) Amplitude (in microvolts) of All Participants Who Displayed 2 or More Double Peaks in All 3 Swallowing Conditions

	Noneffortful		Effortful		Tongue Hold	
	M	*SD*	*M*	*SD*	*M*	*SD*
PsEMG 1	238.84	233.19	284.68	199.48	265.83	113.43
PsEMG 2	255.88	190.14	288.77	182.44	305.85	215.53

research participants to be included in the data sets. In general, 4 patterns could be identified, and research participants were assigned to 1 or more of these groups according to the pattern they presented. The following groups could be identified:

Group 1: double-peak pattern in all 3 conditions (n = 17)
Group 2: double-peak pattern in noneffortful and effortful swallows (n = 24)
Group 3: double-peak pattern in noneffortful and tongue-hold swallows (n = 22)
Group 4: double-peak pattern in effortful and tongue-hold swallows (n = 25)

For all groups, statistical analyses were performed for each of the PsEMG peaks separately.

In addition to the biomechanical measures described for experiment 2, this project investigated several additional measures. These included measures of peak PsEMG 1, peak PsEMG 2, the latency between peak PsEMG 1 and peak PsEMG 2, the latency between peak PsEMG 1 and peak manometric pressure 1 (upper pharynx), and the latency between peak PsEMG 2 and peak manometric pressure 2 (midpharynx).

Intraclass correlation coefficients were used to evaluate interrater and intrarater reliability. Repeated-measures ANOVAs were used to identify differences between swallowing conditions. A general linear model component of variance analysis was applied to investigate sources of variance within and between conditions (noneffortful vs effortful vs tongue-hold swallows). Pearson correlation coefficients were used to investigate the relationship between PsEMG and other measures of swallowing physiology.

Results

Interrater and intrarater reliability. Moderate to high interrater and intrarater reliability was achieved for manometric peak amplitudes and pressure durations and PsEMG peak measures, with intraclass correlation coefficients ranging from a high of $r = 0.99$ for peak PsEMG 2 measures to a low of $r = 0.59$ for total pharyngeal swallow duration. Poorer reliability overall was identified for durational measures of peak PsEMG to peak manometric pressure, with intraclass correlation coefficients ranging from a high of $r = 0.62$ for peak-to-peak duration and a low of $r = 0.21$ for peak PsEMG 1 to peak manometric pressure 1.

Measures of PsEMG: descriptive statistics (double-peak pattern). Repeated-measures ANOVA conducted on those research participants who displayed a complete set of 5 double peaks in any of the 3 conditions revealed no significant effect of trial, $F = 1.813$, $P = .161$. Thus, as there were no systematic changes across trials, subsequent analyses were performed on averaged data within a subject (Table 2).

Normal vs effortful vs tongue-hold swallow at PsEMG. PsEMG amplitude measures varied quite dramatically within and between both conditions and subjects in both PsEMG peaks. However, although there were apparent differences in means, these were not statistically significant in any group (Table 3). This phenomenon is partially due to the degree of variability in the PsEMG signal. To quantify the sources of variability, variance components for within- and between-subject sources were calculated for peak amplitude measures of PsEMG 1 and PsEMG 2. This analysis revealed for peak PsEMG 1 a CV due to within-subject variation of 47% and a CV for between-subject variation of 42%. Twenty-eight percent of the total variation was due to between-subject variability, 35% to within-subject variability, and only 37% to the swallowing condition. For PsEMG 2, this analysis revealed a CV due to within-subject variability of 41% and a CV for between-subject variability of 40%. Twenty-nine percent of the total variation was due to between-subject variability, 31% to within-subject variability, and 39% to the swallowing condition.

No significant influence of gender was found for either PsEMG peak amplitude (Table 3). Comparison of peak PsEMG 1 and peak PsEMG 2 revealed no significant differences in any of the conditions (noneffortful: $F = 0.428$, $P = .522$; effortful: $F = 0.066$, $P = .800$; tongue hold: $F = 1.189$, $P = .292$).

For durational measures, peak PsEMG 1 to peak PsEMG 2 latency was retrieved from the original data set. On average, the mean peak-to-peak latency was 0.34 seconds ($SD = \pm 0.11$) for noneffortful swallows, 0.30 seconds ($SD = \pm 0.12$) for effortful swallows, and 0.36 seconds ($SD = \pm 0.14$) for tongue-hold swallows. Repeated-measures ANOVA revealed no significant main effect of condition ($F = 1.111$, $P = .342$) on duration. There was also no significant condition by gender effect ($F = 0.508$, $P = .607$).

Table 3. Experiment 3: Results of Repeated-Measures ANOVA for Each of 4 Classified Groups of Data

		PsEMG 1		PsEMG 2	
Group	Parameter	F	Significance	F	Significance
1: All conditions	Condition	0.073	.930	0.179	.752
	Condition × Gender	0.015	.903	0.329	.641
2: Noneffortful versus effortful	Condition	0.001	.981	0.054	.817
	Condition × Gender	0.206	.654	0.106	.747
3: Noneffortful versus tongue hold	Condition	0.048	.829	0.990	.331
	Condition × Gender	0.066	.800	1.945	.178
4: Effortful versus tongue hold	Condition	0.434	.517	0.409	.529
	Condition × Gender	0.345	.563	0.919	.348

No significant main effects were identified for either electrode.

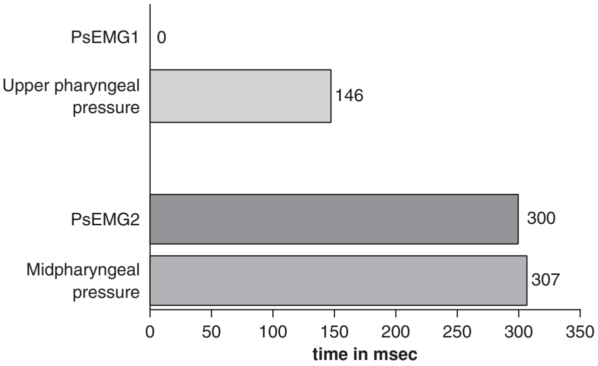

Figure 7. Experiment 3: temporal relationships between the onset of pharyngeal surface electromyography (PsEMG) and the onset of pharyngeal pressure. All data represent averages across subjects and are displayed in milliseconds.

Measures of PsEMG: single-peak pattern. No statistically significant main effects were found between peak amplitudes based on condition (group 1: $F = 0.011$, $P = .921$; group 2: $F = 0.804$, $P = .421$). As both groups represented only 6 subjects each, single-peak swallows were excluded from further analyses due to insufficient data.

Relationship between pharyngeal pressure and PsEMG. Pearson correlation coefficients were derived to investigate whether PsEMG peak amplitudes correlated significantly with pressure amplitudes measured in the upper and middle pharynx. Analyses revealed that peak PsEMG 1 was significantly correlated with peak manometry 1 ($r = 0.293$, $P = .000$), although the correlation was weak. Peak PsEMG 2, however, was not significantly correlated with peak manometry 2 ($r = 0.018$, $P = .735$). Correlating peak PsEMG 1 with peak PsEMG 2 revealed a significant and moderate correlation ($r = 0.634$, $P < .001$).

Temporal relationship between PsEMG and pharyngeal pressures. To investigate the sequencing of pharyngeal physiological and biomechanical events, the latencies between peak PsEMG 1 and peak manometry 1 (upper pharynx) and peak PsEMG 2 and peak manometry 2 (midpharynx) were analyzed. On average, peak PsEMG 1 occurred 0.146 seocnds ($SD = 0.14$) before peak manometry 1, while peak PsEMG2 occurred 0.007 seconds ($SD = 0.09$) before peak manometry 2 (Figure 7).

Summary of Findings

- Use of a unidirectional electrode revealed a unique bimodal PsEMG pattern that might reflect sequential contraction of muscles of the PPW.
- Use of a unidirectional electrode did not reveal significant differences in PPW muscle activity between noneffortful, effortful, or tongue-hold saliva swallows.
- However, when compared to the circumferential electrode, the unidirectional electrode produced overall higher variability but with disproportionately greater task-specific variance.
- These findings suggest that the current catheter design and measurement procedures do not represent a valid measure of pharyngeal muscle activity.

DISCUSSION

This series of exploratory research studies provides preliminary data toward the development of PsEMG in the clinical assessment of swallowing physiology. It evaluates pharyngeal catheter placement and laterality issues and discusses the usefulness of 2 catheter designs, each with a slightly different physiologic focus.

Hamdy and colleagues[26] described the use of PsEMG to measure MEPs in the pharynx. The results of their work suggest that muscles involved in the pharyngeal phase of swallowing are represented bilaterally but asymmetrically. Although these findings have been confirmed with functional magnetic resonance imaging studies,[31] the results from experiment 1 of this study suggest that confirmatory measures for this type of work may indeed be very important. Electrode placement at midline cannot be ensured using this method of catheter placement and thus may have implications for interpretation of MEP data, which evaluates the laterality of cortical representation of swallowing. Electrode placement requires visual confirmation at the time of data collection to reliably assign the collected data to the correct recording site. Alternatively, use of hooked wire electrodes will ensure a more reliable pairing of data and recording site. However, it is acknowledged that there are practical limitations to the use of these electrodes in the pharynx.

Experiments 2 and 3 proposed to explore the applicability and limitations of PsEMG for the measurement of pharyngeal muscle activity using 2 methodological approaches. For both methods, it was of interest to determine if the recording techniques produced differing waveform characteristics and were sensitive to changes in muscle activity involved in several behavioral swallowing maneuvers. In addition, these experiments sought to evaluate both the temporal and amplitude relationships between PsEMG measures and other measures of swallowing physiology and biomechanics. Fundamentally, swallowing is a synergistic response. Central pattern generators within the brain stem distribute similar commands to functionally distinct muscles during the deglutitive process.[36-39] Thus, one would expect a correlation between PsEMG measures and other measures of pharyngeal physiology and biomechanics. These experiments investigated correlations between PsEMG and submental sEMG, pharyngeal manometric pressure, and duration. In addition, temporal relationships between measures were investigated.

When properly positioned in the pharynx, the PsEMG electrode would rest at approximately 4.5 cm above the high-pressure zone of the UES. This placement likely overlies the anatomical convergence of the middle and inferior pharyngeal constrictors. The circumferential electrode used in experiment 2 consistently produced a single-peak waveform that presumably reflected summated motor activity from the pharyngeal walls as they compress laterally and anteriorly around the catheter during pharyngeal pressure generation and the intrinsic lingual musculature (Figure 6A). Sustained approximation of the pharyngeal tongue to the PPW during sequential contraction of the constrictors appears to override any specific measurement of pharyngeal muscles. In contrast, the unidirectional electrode used in experiment 3, which was designed to measure only pharyngeal wall muscle activity, produced a more frequent pattern of a bimodal, double-peaked waveform (Figure 6B). This bimodal signal, with an average interpeak interval of 340 milliseconds, is speculated to represent the sequential contraction of the 2 pharyngeal constrictor muscles. Similar sequential activation has been found in rabbits and dogs.[40] In studies of rabbits, the latency between middle and inferior constrictor activity was found to be about 50 milliseconds. However, total swallowing duration of rabbits at approximately 0.3 seconds is much shorter than the average total swallowing duration of the participants in this study ($M = 1.11$ seconds). It therefore seems justifiable to assume that the first peak measured by the electrode represents activation of the middle pharyngeal constrictor, whereas the second peak results from activation of the inferior pharyngeal constrictor.

Descriptively, the averaged raw data from the effortful swallow appeared to be characterized by higher amplitude and longer duration measures of PsEMG than the data gleaned during noneffortful swallow in both experiments and for both peaks in experiment 3. Surprisingly, the unidirectional electrode revealed higher average peak amplitudes in the second peak only for the tongue-hold swallow, although this maneuver is known to increase the biomechanical movement of the posterior pharyngeal wall. In addition, the temporal relationship of pharyngeal sEMG to other measures appears appropriate. The onset of PsEMG occurs after the onset of submental sEMG and a drop of pressure in the UES and slightly precedes the onset of pressure in the upper pharynx, which is subsequently followed by pressure in the lower pharynx. Experiment 3 allowed for a more detailed analysis of the sequential timing of events in the pharynx. While the first PsEMG peak preceded the onset of manometric pressure in the upper pharynx, the second PsEMG peak followed the onset of pressure in the upper pharynx and preceded the onset of pressure generation in the midpharynx. The greater latency in the upper pharynx may be related to posterior movement of the BOT. It seems likely that peak PsEMG 1 precedes maximum anterior movement of the PPW by a similarly short length of time as peak PsEMG 2 precedes peak manometry 2. In the upper pharynx, however, the maximum posterior movement of the BOT may occur after the PPW has maximally moved anteriorly. Thus, pressure would continue to increase after maximal PPW anterior movement until maximal BOT retraction occurs. In the midpharynx, maximal PPW anterior movement and maximal manometric pressure generation is relatively closer, as PPW is the only substantial pressure generator at this level of the pharynx. Thus, it would appear at first evaluation that the catheter is reflecting pharyngeal activity at a very gross level.

The exploratory data gleaned from both experiments, however, were not robust enough to substantiate task differences through statistical analysis. The circumferential catheter failed to detect significant differences in pharyngeal muscle activity during noneffortful and effortful swallowing techniques, although duration of contraction was significantly longer for effortful swallow. This is in contrast to significantly higher amplitude and longer duration in pharyngeal pressure measures collected during the same swallows. The unidirectional catheter also failed to record significant differences in amplitude or duration based on swallowing maneuver. The inability to achieve statistical significance between the 2 measures reflects the high degree of variability in measurement both within and across participants.

We hypothesized that there would be significant correlations between measures of PsEMG and other measures of pharyngeal biomechanics, namely, submental sEMG and pharyngeal pressure. Curiously, this was not the case. Submental sEMG and PsEMG measures collected in experiment 2 were poorly correlated for peak amplitude. Either differential degrees of contraction were generated during swallowing at the 2 muscle sites or the pharyngeal catheter method is not able to accurately record muscle activity, thus obscuring measurable correlations. Both explanations are quite feasible. Submental sEMG not only measures activity from contraction of floor-of-mouth muscles that contract during the pharyngeal swallow but also reflects the varying contribution of intrinsic lingual muscles that would not be reflected in pharyngeal EMG measurement. There was, however, a moderate correlation between duration of muscle contraction of the 2 measures.

We further hypothesized that there would be substantive correlations between PsEMG measures and pharyngeal pressure generation, as contractions of muscles in the pharynx are ultimately responsible for pressure generation. Surprisingly, this was not the case for either amplitude or duration using the circumferential electrode or for amplitude using the unidirectional electrode. There was, however, a strong correlation between the amplitude of PsEMG measures recorded at both peaks using the unidirectional catheter design.

Limitations of PsEMG and Sources of Variance

Exploratory data from these experiments suggest that although some expected relationships between measures are apparent, these are not robust enough to withstand significance testing and reflect a high degree of variability in PsEMG data. Data from studies using hooked-wire EMG of the superior pharyngeal constrictor have reported high reproducibility of muscle activity patterns within and between subjects.[21] Thus, the current method of PsEMG is not acceptable and will require substantial revision.

Careful evaluation of sources of variance across the 2 electrode designs reveals interesting information. The circumferential electrode produced an unacceptable degree of intrasubject and intersubject variability, with very little variance associated with swallowing maneuver. This electrode measured not only from the pharyngeal constrictors but also from the pharyngeal tongue. Although retraction of the pharyngeal tongue to the posterior pharyngeal wall is considered part of the pharyngeal swallow, control of the lingual tongue may well be considered more amenable to adaptation as it is largely involved in oral, volitional components of swallowing. Huckabee and Steele[41] have recently documented that adaptation of oral tongue movement subsequently influenced generation of pharyngeal pressure, particularly in the upper pharynx, or the region most heavily influenced by pharyngeal tongue. Lingual to palatal compression during swallowing appeared to serve as a type of motor-priming mechanism, thus facilitating adaptation of pharyngeal swallowing dynamics.

Using a more specific measurement offered by a unidirectional electrode, the patterns of variance shift remarkably. There is an increase in variability overall, with larger standard deviations surrounding the means. However, quite interestingly, the percentage of experimental variance attributed to swallowing maneuver increased disproportionately when compared to data derived from the circumferential electrode. Although overall variance increased, the unidirectional electrode better detected differing muscle activity associated with swallowing maneuver.

Sources of intrasubject and intersubject variability are unacceptable and will require careful attention in the further development of techniques for PsEMG. For both sources of variability, the issue of electrode to skin contact is a major design obstacle and indeed will prohibit use of this technique if it cannot be substantially improved. It is a fundamental principle that measurement of surface EMG activity requires contact of the electrode to the tissue overlying the targeted muscle. It would appear that this method of PsEMG violates that principle. Certainly, this is the case for measurement of PsEMG activity at rest. Although not seen in all of our research participants, Figure 3 represents a research participant with the catheter in situ in which the contour of the cervical spine inhibits contact at rest. This configuration changes, however, during swallowing behavior when the pharynx compresses the electrode to the skin surface (Figure 4). Regardless, we cannot ensure consistency of this contact; thus, electrode to skin contact may be variable even during deglutitive behavior.

Movement artifact during swallowing is also likely substantial as the electrode is not secured in the pharynx. Deglutitive behavior requires a considerable shortening of the pharyngeal cavity. In our studies, the catheter was secured to the nares externally, and thus there was some limitation to movement. However, as the pharynx shortens during swallowing, the catheter will not shorten with it. A greater or lesser degree of pharyngeal shortening, as would conceivably be the case during swallowing maneuvers, would thus provide a source of variance as pharyngeal muscle activity will be measured in slightly different locations along the pharyngeal lumen. Circumferential PsEMG again represents a fairly gross measure of summated activity of several muscle groups. Adaptation to the more specific unidirectional electrode produced a substantial increase in overall measured variance. If we presume that this catheter measures the sequential contraction of the middle and then inferior constrictor muscles, as the data may suggest, then variations in location of measurement in this small anatomical region would be likely. This may account for a significant amount of both intrasubject and intersubject variation.

Suggestions for Improvements in PsEMG Validation

The optimal method for validating PsEMG would be to compare EMG activity collected from a surface electrode with that collected from intramuscular electrodes. However, it may be necessary to first improve the PsEMG technique. The primary limitation of PsEMG identified through this research program is an unacceptably low signal-to-noise ratio. The appearance of noise in the recorded signal is likely due to mechanical limitations, that is, insufficient electrode-skin contact and movement artifact. To further develop methods for PsEMG, it will be essential to improve electrode-skin contact and signal-to-noise ratio. Several ideas are proposed:

1. A redeveloped catheter should extend into the proximal esophagus by approximately 10 cm. It can be argued that a longer distance between the most distal sensor and the tip of the catheter will provide increased anchoring/stability of the catheter. This may help to limit motion artifacts during swallowing.
2. Stabilizing the superior aspect of the catheter by adhering it to the PPW with removable biologic glue may be considered a means of limiting movement. This rather unconventional method promises to prevent the catheter from moving away from the PPW in between swallows and thus may inhibit artifact.
3. In addition, monitoring of electrical impedance should be employed. Commonly, minimization of impedance effects is accomplished by abrasion of the skin with an alcohol pad or even puncturing of the skin. These methods are not practical in the pharynx. However, an impedance of 5.000 to 10.000 Ω should not be exceeded for research purposes.[42] Monitoring of impedance would allow researchers to identify contaminated data to consequently exclude them from statistical analysis. Preliminary research studies need to be undertaken to investigate whether the proposed threshold is appropriate for surface electromyographic measures in the pharynx.
4. Our catheter collected PsEMG values from only 1 location in the pharynx; however, sequencing of pharyngeal muscle activity with other measures of pharyngeal biomechanics appeared appropriate. It would be beneficial to create a catheter design that is able to record activation at multiple sites along the PPW. This would allow an investigation of sequencing of muscle activation. Custom-designed unidirectional electrodes should be used, with the most distal sensor being circumferential to best measure UES contraction and relaxation. Individual monitoring of each of the constrictors promises further insight into the sequential activation of the PPW.

CONCLUSION

This exploratory research program provides valuable, however preliminary, information about the usefulness and limitations of pharyngeal sEMG. Use of this assessment tool in clinical practice remains fraught with difficulty and in its current state produces an unacceptable amount of measurement error. If the technical limitations can be resolved through further development, there is potential for improved investigation of neuromuscular pathology in swallowing impairment and subsequently development of more precise rehabilitative intervention.

ACKNOWLEDGMENT

Data represented in this article were accrued through a series of postgraduate research projects that were conceptualized and supervised primarily by Dr Maggie-Lee Huckabee.

REFERENCES

1. Agency for Health Care Policy and Research. *Diagnosis and Treatment of Swallowing Disorders (Dysphagia) in Acute-Care Stroke Patients*. Rockville, Md: Agency for Health Care Policy and Research; 1999.
2. Martin-Harris B, Logemann JA, McMahon S, et al. Clinical utility of the modified barium swallow. *Dysphagia*. 2000;15:136-141.
3. Clark HM, Henson PA, Barber WD, et al. Relationships among subjective and objective measures of tongue strength and oral phase swallowing impairments. *Am J Speech Lang Pathol*. 2003;12:40-50.
4. Dworkin JP, Hartman DE. Progressive speech deterioration and dysphagia in amyotrophic lateral sclerosis: case report. *Arch Phys Med Rehabil*.1979;60:423-425.
5. Swick HM, Werlin SL, Dodds WJ, et al. Pharyngoesophageal motor function in patients with myotonic dystrophy. *Ann Neurol*. 1981;10:454-457.
6. Weijnen FG, Kuks JB, van der Bilt A, et al. Tongue force in patients with myasthenia gravis. *Acta Neurol Scand*. 2002;102;303-308.
7. Borasio GD, Voltz R, Miller RG. Palliative care in amyotrophic lateral sclerosis. *Neurol Clin*. 2001;19:829-847.

8. Francis K, Bach JR, DeLisa JA. Evaluation and rehabilitation of patients with adult motor neuron disease. *Arch Phys Med Rehabil.* 1999;80:951-963.
9. Shaw GY, Searl JP. Botulinum toxin treatment for cricopharyngeal dysfunction. *Dysphagia.* 2001;16:161-167.
10. Murry T, Wasserman T, Carrau RL, et al. Injection of botulinum toxin A for the treatment of dysfunction of the upper esophageal sphincter. *Am J Otolaryngol.* 2005;26:157-162.
11. Moerman M, Callier Y, Dick C, et al. Botulinum toxin for dysphagia due to cricopharyngeal dysfunction. *Eur Arch Otorhinolaryngol.* 2002;259:1-3.
12. Schneider I, Thumfart WF, Pototschnig C, et al. Treatment of dysfunction of the cricopharyngeal muscle with botulinum A toxin: introduction of a new, noninvasive method. *Ann Otol Rhinol Laryngol.* 1994;103:31-35.
13. Kelly JH. Management of upper esophageal sphincter disorders: indications and complications of myotomy. *Am J Med.* 2000; 108:43S-46S.
14. Clark HM. Neuromuscular treatments for speech and swallowing: a tutorial. *Am J Speech Lang Pathol.* 2003;12:400-415.
15. Huckabee ML, Kelly BK. Rehabilitationsmodelle im Management von Dysphagien: Kasuistiken zur Schluckapraxie und zur Spastischen Dysphagie (Models of rehabilitation in dysphagia management: a case for swallowing apraxia and spastic dysphagia). In: Stanschus S, ed. *Rehabilitation von Dysphagien.* Idstein, Germany: Schulz-Kirchner Verlag GmbH; 2006:37-171.
16. Huckabee ML, Pelletier CA. *Management of Adult Neurogenic Dysphagia.* San Diego, Calif: Singular; 1999.
17. Logemann JA. Evaluation and treatment of swallowing disorders. 2nd ed. Austin, Tex: Pro-Ed; 1998.
18. Jaradeh S, Shaker R, Toohill R. Electromyographic recording of the cricopharyngeus muscle in humans. *Am J Med.* 2000;108(4A): 40S-42S.
19. Palmer PM, McCulloch TM, Jaffe D, et al. Effects of a sour bolus on the intramuscular electromyographic (EMG) activity of muscles in the submental region. *Dysphagia.* 2005;20:210-217.
20. Palmer JB, Tanaka E, Siebens AA. Electromyography of the pharyngeal musculature: technical considerations. *Arch Phys Med Rehabil.* 1989;70:283-287.
21. Perlman AL, Palmer PM, McCulloch TM, et al. Electromyographic activity from human laryngeal, pharyngeal, and submental muscles during swallowing. *J Appl Physiol.* 1999;86:1663-1669.
22. Tachimura T, Ojima M, Nohara K, et al. Change in palatoglossus muscle activity in relation to swallowing volume during the transition from the oral phase to the pharyngeal phase. *Dysphagia.* 2005;20:32-39.
23. Elidan J, Shochina M, Gonen B, et al. Electromyography of the inferior constrictor and cricopharyngeus muscles during swallowing. *Ann Otol Rhinol Laryngol.* 1990;99:466-469.
24. Ertekin C, Aydogdu I, Yuceyar N, et al. Effects of bolus volume on oropharyngeal swallowing: an electrophysiologic study in man. *Am J Gastroenterol.* 1997;92:2049-2053.
25. Ertekin C, Tarlaci S, Aydogdu I, et al. Electrophysiological evaluation of pharyngeal phase of swallowing in patients with Parkinson's disease. *Mov Disord.* 2002;17:942-949.
26. Hamdy S, Aziz Q, Rothwell J, et al. The cortical topography of human swallowing musculature in health and disease. *Nat Med.* 1996;2:1217-1224.
27. Hamdy S, Aziz Q, Rothwell J, et al. Explaining oropharyngeal dysphagia after unilateral hemispheric stroke. *Lancet.* 1997;350: 686-692.
28. Fraser C, Rothwell J, Power M, et al. Differential changes in human pharyngoesophageal motor excitability induced by swallowing, pharyngeal stimulation, and anesthesia. *Am J Physiol Gastrointest Liver Physiol.* 2003;285:G137-G144.
29. Fraser C, Power M, Hamdy S, et al. Driving plasticity in human adult motor cortex is associated with improved motor function after brain injury. *Neuron.* 2002;34:831-840.
30. Gow D, Rothwell J, Hobson A, et al. Induction of long-term plasticity in human swallowing motor cortex following repetitive cortical stimulation. *Clin Neurophysiol.* 2004;115:1044-1051.
31. Hamdy S, Mikulis D, Crawley A, et al. Cortical activation of human volitional swallowing: An event-related fMRI study. *Am J Physiol.* 1999;277:G219-G225.
32. Kahrilas PJ, Logemann JA, Krugler C, et al. Volitional augmentation of upper esophageal sphincter opening during swallowing. *Am J Physiol.* 1991;260:G450-G456.
33. Castell JA, Dalton CB, Castell DO. Pharyngeal and upper esophageal manometry in humans. *Am J Physiol.* 1990;258: G173-G178.
34. Fujiu M, Logemann J, Pauloski B. Increased post-operative posterior pharyngeal wall movement in patients with anterior oral cancer: preliminary findings and possible implications for treatment. *Am J Speech Lang Pathol.* 1995;4:24-30.
35. Fujiu M, Logemann J. Effect of a tongue-holding manoeuvre on posterior pharyngeal wall movement during deglutition. *Am J Speech Lang Pathol.* 1996;5:23-30.
36. Blitzer A. Approaches to the patient with aspiration and swallowing disabilities. *Dysphagia.* 1990;5:129-137.
37. Perlmann AL. Electromyography and the study of oropharyngeal swallowing. *Dysphagia.* 1993;8:351-355.
38. Crary MA. A direct intervention program for chronic neurogenic dysphagia secondary to brainstem stroke. *Dysphagia.* 1995; 10:6-18.
39. McKeown MJ, Torpey DC, Gehm WC. Non-invasive monitoring of functionally distinct muscle activations during swallowing. *Clin Neurophysiol.* 2002;113:354-366.
40. Basmajian JV, Dutta CR. Electromyography of pharyngeal constrictors and soft palate in rabbits. *Anat Rec.* 1961;139:443-449.
41. Huckabee ML, Steele CM. An analysis of lingual contribution to submental sEMG measures and pharyngeal pressure during effortful swallow. *Arch Phys Med Rehab.* In press.
42. Cram JR, Kasman GS. *Introduction to Surface Electromyography.* Gaithersburg, Md: Aspen; 1998.