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Research Article

Effects of Submental Surface Electrical Stimulation on Swallowing Kinematics in Healthy Adults: An Error-Based Learning Paradigm

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Purpose: Hyoid bone and laryngeal approximation aid airway protection (laryngeal vestibule closure) while moving toward their peak superior and anterior positions during swallowing. Submental surface electrical stimulation (SES) is a therapeutic technique that targets the muscles that move the hyoid bone during swallowing. It is unknown whether submental SES only increases peak hyoid bone swallowing positions but not peak laryngeal swallowing positions, which could require faster or greater laryngeal movement to achieve adequate laryngeal vestibule closure.
Method: We examined the effects of submental SES on hyo-laryngeal kinematics in 30 healthy adults who swallowed 50 times using an error-based learning paradigm.
Results: Submental SES did not alter any hyo-laryngeal swallowing kinematic. However, submental SES significantly changed the starting position of the hyoid bone just prior to the swallow onset (more anterior; $p = .003$). On average, submental SES immediately prior to swallow onset can position the hyoid approximately 20% closer to its peak swallowing point.
Conclusions: These findings indicate that electrical stimulation of the agonists for hyoid movement might not alter swallowing outcomes tested in this study. However, submental SES could have clinical utility by minimizing swallowing impairments related to reduced hyoid swallowing range of motion in individuals with dysphagia.

Two accepted rehabilitation approaches include (a) restoring function by training new skills to maximize an activity and (b) reducing a disability by training compensatory mechanisms when restoration is not possible (Barnes, 2003). Winstein, Lewthwaite, Blanton, Wolf, and Wishart (2014) suggest that restoring function versus merely reducing the impact of an existing disability might depend upon whether *exercise* is being trained versus *practice* during rehabilitation (Winstein et al., 2014). According to Cross, exercises are repetitions of an already learned act, whereas practice is "more than mere repetition, it is repetition with a purpose" (p. 487; Cross, 1967). To date, several studies have substantiated the theory that acquiring new motor skills to restore function requires "progressive challenge, intensity, problem solving, motivation, and focused attention" (p. 6; Winstein et al., 2014; Barnes, 2003).

In traditional dysphagia rehabilitation, compensatory mechanisms are most commonly prescribed, perhaps suggesting a more risk-averse approach (Lazarus, 2017). However, with the emergence of device-driven swallowing treatments, such as the surface electrical stimulation (SES), it might be possible to include progressive challenge, intensity, and problem-solving by incorporating error-based learning (EBL). EBL occurs when a disruption to a movement goal (perturbation) is introduced, requiring the system to overcome the effects of the perturbation (error) on a trial-by-trial basis (Bastian, 2008; Wolpert, Diedrichsen, & Flanagan, 2011). EBL was evident among healthy adults who swallowed with anterior neck SES, because it targets infra hyoid muscles and significantly limits hyo-laryngeal elevation (Humbert, Christopherson et al., 2012; Humbert et al., 2006; Humbert, Lokhande, Christopherson, German, & Stone, 2012; Humbert, Michou, MacRae, & Crujido, 2012; Ludlow et al., 2007). This occurred in two different ways. First, hyo-laryngeal peaks that were initially reduced gradually approached baseline levels (also known as preperturbation levels) over several trials (Anderson et al.,

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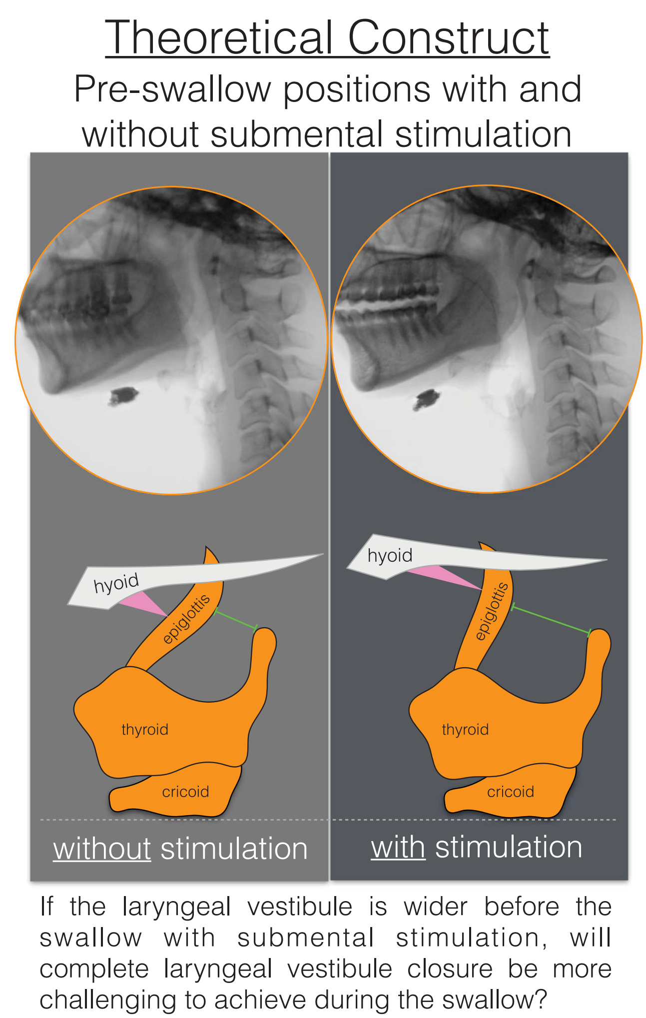
2015; Humbert, Christopherson, & Lokhande, 2015). Second, when SES was unexpectedly removed, hyo-laryngeal peak elevation was higher than baseline levels, which is evidence of aftereffects (Humbert, Christopherson et al., 2012). Aftereffects are exaggerated movements that occur when a motor plan is put in place to overcome a perturbation that is no longer present (Bastian, 2008).

It is important to note that the EBL outcome described above in Humbert et al. (2015) was induced with a continuous SES paradigm. Continuous SES is stimulation that is administered both during the swallow and during the interswallow intervals (time between swallows). Conversely, intermittent SES is a paradigm where stimulation is administered only during the swallow but not during the interswallow intervals. When EBL was examined with intermittent SES to the anterior neck, hyo-laryngeal elevation did not gradually increase to overcome perturbation as with continuous SES. Instead, hyo-laryngeal peaks remained reduced over several swallowing trials (Humbert et al., 2015). Despite the absence of adaptation of hyo-laryngeal peaks with intermittent stimulation, duration of the laryngeal vestibule closure gradually increased across several swallows. To date, these paradigms have only been tested in healthy adults.

These outcomes raise important questions about SES paradigms for swallowing. On one hand, the aforementioned studies indicate that SES on the anterior neck opposes natural movements of the hyoid and larynx and presents a challenge to swallowing (Humbert et al., 2006; Park et al., 2009). On the other hand, it is not clear whether submental SES can challenge any swallowing event because agonist muscles are targeted (anterior belly of the digastrics, mylohyoid, and geniohyoid muscles). To understand this, studies should examine the physiological effects of submental stimulation on hyo-laryngeal movements during swallowing. Currently, published research on the immediate effects of submental SES report little or no change. This includes no pressure changes in the pharynx and upper esophageal sphincter (UES), minimal movement of the hyoid or larynx at rest, and no significant change in labial or lingual force generation (Heck, Doeltgen, & Huckabee, 2012; Humbert, Poletto, Saxon, Kearney, & Ludlow, 2008; Ludlow et al., 2007; Safi, Wright-Harp, Lucker, & Payne, 2017; Suiter, Leder, & Ruark, 2006). One study reported faster laryngeal movements, but no laryngeal imaging was used (electromyography only; Schultheiss, Schauer, Nahrstaedt, Seidl, & Bieler, 2016). Studies of longer term effects in patients with dysphagia report altered hyoid or laryngeal movement but were uncontrolled studies, so it is unclear whether effects were caused by submental stimulation (Nam, Beom, Oh, & Han, 2013; Rofes et al., 2013). Other studies focus on changes in the central nervous system (Doeltgen, Dalrymple-Alford, Ridding, & Huckabee, 2010), but only tested very low sensory thresholds that do not cause submental muscle contractions (Cugy et al., 2016; Verin et al., 2011) or only reported prebolus and postbolus flow outcomes (Beom, Kim, & Han, 2011; Lim, Lee, Lim, & Choi, 2009). Some have investigated submental movement at rest and reported a range of hyoid movement, but concurrent swallowing with submental stimulation was not tested (Burnett, Mann, Cornell, & Ludlow, 2003; Humbert et al., 2006; Kagaya et al., 2018). The literature does not adequately explain how the SES of submental muscles impacts hyo-laryngeal swallowing kinematics. This is important to understand because electrical stimulation, including submental electrode placements, is frequently used to address impaired airway protection in dysphagia rehabilitation (Crary, Carnaby-Mann, & Faunce, 2007).

Submental SES could theoretically present a challenge to laryngeal movements during swallowing in the following way (see visuals in Figure 1). Laryngeal vestibule closure is partially achieved by hyo-laryngeal approximation when both the hyoid bone and larynx elevate during swallowing (Ekberg, 1982, 1986; Ekberg & Sigurjonsson, 1982; Fink & Demarest, 1978; Logemann, Kahrilas, & Cheng, 1992; Vandaele, Perlman, & Cassell, 1995). Given that submental SES targets hyoid elevators, but not laryngeal elevators

Figure 1. Theoretical construct for effects of submental surface electrical stimulation on hyo-laryngeal movements in healthy adults.



(laryngeal elevators are longitudinal pharyngeal muscles and thyrohyoid), it is plausible that, if submental SES increases the extent of hyoid excursion, but not laryngeal excursion, then more laryngeal elevation might be required to achieve adequate hyo-laryngeal approximation for laryngeal vestibule closure. In other words, submental SES could present a challenge to the laryngeal elevators. Thus, the goal of this investigation was to examine the effect of hyo-laryngeal elevation with submental SES using a continuous and intermittent EBL stimulation paradigm in healthy adults.

It is hypothesized that submental SES would cause the following: (1) increased hyoid excursion but not laryngeal excursion, causing initially delayed onset of laryngeal vestibule closure; (2) over several swallows with submental SES, participants would learn to increase the extent of laryngeal excursion, which would gradually reduce laryngeal vestibule closure onset delays; and (3) Hypotheses 1 and 2 would only be present in continuous submental SES but not in intermittent submental SES because learning would be disrupted similarly to outcomes reported by Humbert et al. (2015). Thus, the overall research question of this study overlaps with the hypothesis, including the following: Does submental SES alter hyo-laryngeal kinematics during or immediately after stimulation, and does the stimulation paradigm impact the effects?

Material and Methods

Participants and Ethical Approval

Thirty healthy adults (21 female, 9 male) with no reported history of neurological disease, head and neck surgery, speech or swallowing disorders, or contraindications to SES participated. Participants were aware of the general study procedures (swallowing barium with videofluoroscopy and electrical stimulation); however, the onset and offset times of stimulation were unknown to the participants. An institutional review board approved the study, and all participants provided written consent to participate.

Videofluoroscopy and Surface Electromyography

The swallowing function was imaged and recorded with videofluoroscopy (AIXIOM Sireskop SD40, Siemens). All images were in full resolution, continuous, and recorded at 30 frames-per-second in the lateral plane. The oral cavity, pharynx, larynx, cervical vertebrae, and UES were visible. A timestamp was also used so that each swallow had a unique identifier. Bipolar surface electromyography electrodes (ADInstruments) were placed on the anterior neck approximately to the left and right sides of the thyroid cartilage. The sole purpose of the surface electromyography was to confirm the presence of electrical stimulation throughout the study by observing the stimulation artifact in the signal.

Electrical Stimulation

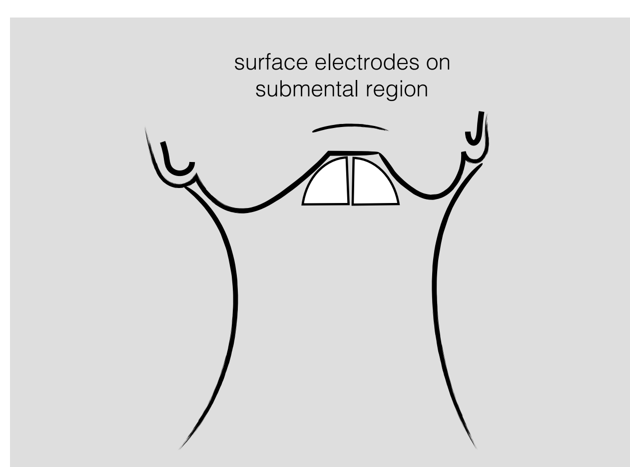
Electrodes were positioned on the submental region (below the mandible and above the hyoid bone) as shown in Figure 2. Electrical stimulation was administered using the Ampcare ESP device and electrodes, a Food and Drug Administration–cleared medical device system, because it was designed only for submental application in dysphagia treatment. The skin in the submental region was cleaned with alcohol (to remove oils) and then wiped with a TENS Clean-Cote Skin Wipe to increase electrodes to skin contact. All male participants were clean-shaven on the submental region to increase electrode adhesion. Similarly to Humbert et al. (2006) and Ludlow et al. (2007), the device was modified to administer stimulation whenever a button was pushed as opposed to the commercially available version that administers stimulation using a set time protocol of 5 s on and 15 s off. This was necessary to test the continuous stimulation paradigm where stimulation was not removed and to customize the “on” and “off” stimulation durations for the intermittent paradigm to each participant.

Stimulation Paradigms

Stimulation Levels

We tested two stimulation levels, including the sensory-only (low stimulation) and sensory–motor (high stimulation) intensity levels. These two stimulation levels were determined individually. First, the sensory-only level was confirmed when participants noted that they felt the prickly sensation on the submental region, but no hyoid movement was observed on videofluoroscopy. Second, the sensory–motor level was obtained by further gradually increasing the amplitude to the highest level that participants could tolerate without pain, leading to hyoid anterior and/or superior movement at rest on videofluoroscopy. When testing the sensory-only and sensory–motor levels at rest with videofluoroscopy, participants were instructed not to move their head or tongue and not to open the jaw. Each stimulation level was recorded for each participant.

Figure 2. Submental surface electrode position used in study.



Study Design

This investigation included two stimulation paradigms: continuous ($N = 15$; mean age: 37.7 ± 18.8) and intermittent ($N = 15$; mean age: 30.7 ± 13.2). The following procedures were the same in both study groups. In both paradigms, there were 50 swallows across three phases: preperturbation (10 swallows), perturbation (30 swallows), and postperturbation (10 swallows). Also, in both stimulation paradigms, the preperturbation and postperturbation periods involved sensory-only level stimulation. The sensory-only level stimulation was used to mask the onset and offset of the high stimulation during the perturbation phase. That means that the primary perceptual change across the three phases was the onset or offset of a feeling of a muscle contraction (motor), whereas the prickly sensation remained throughout the 50 swallows of the study. Masking was used to enhance EBL because it has been previously shown that outcomes, such as aftereffects, are not observed when participants are aware that the perturbation will be removed (Anderson et al., 2015; Humbert et al., 2015). In both stimulation paradigms, the perturbation period involved the administration of the sensory–motor stimulation. All participants swallowed 5 ml of thin liquid barium 50 times. This volume was used in an attempt to standardize swallows without administering too much barium throughout the study to avoid a feeling of excessive fullness prior to the end of the study. A small plastic tube administered the bolus to the oral cavity, and all swallows were verbally cued to coordinate the stimulation and videofluoroscopy. Participants were asked not to suck the tube and to wait for the verbal cue before swallowing.

The two different stimulation paradigms (continuous and intermittent) were tested in the perturbation phase (see Figure 3). With continuous stimulation, the sensory–motor level stimulation was administered both during the swallows and during the 10-s intertrial intervals. On the other hand, during the perturbation phase of the intermittent stimulation, the sensory–motor level stimulation was only applied during swallowing, but the sensory-only level was administered during the 10-s intertrial interval.

Kinematic Analyses

Investigators were blinded to the study group during all of the analyses (SS and KS). The raters had at least 2 years of training and were required to have at least 90% agreement in the measures detailed below prior to working on data in this study.

The following outcome measures were used in this study to identify the effects of submental SES.

Range of motion analysis. Range of motion (peak extent of movement) was marked for the hyoid bone and for the larynx. Peak Motus (Vicon Peak, Version 9.2) system was used for the kinematic analysis of the videofluoroscopic images. The investigator digitized the following points on each frame of the videofluoroscopic images: (a) the superior/posterior aspect of the subglottal air column (y-axis), which represented the position of the larynx; (b) the anterior/inferior-most point of the hyoid bone (x-axis and y-axis); and (c) the anterior/inferior-most point of the lowest vertebra, which can be seen on all swallows (commonly C5 or C6), which represented a stable reference point.

Similar to Humbert, Christopherson, et al. (2012), the hyoid and laryngeal points were compared with the vertebra (reference point) to determine peak changes during the following times:

1. Peak excursion position when sensory–motor stimulation was administered at rest.
2. Baseline position immediately prior to swallow onset (preswallow).
3. Peak excursion position during swallow.

This means that we derived the following range of motion measures:

1. Laryngeal superior peak movement.
2. Hyoid superior peak movement.
3. Hyoid anterior peak movement.
4. Laryngeal baseline position (y-axis).
5. Hyoid baseline position (y-axis).
6. Hyoid baseline position (x-axis).

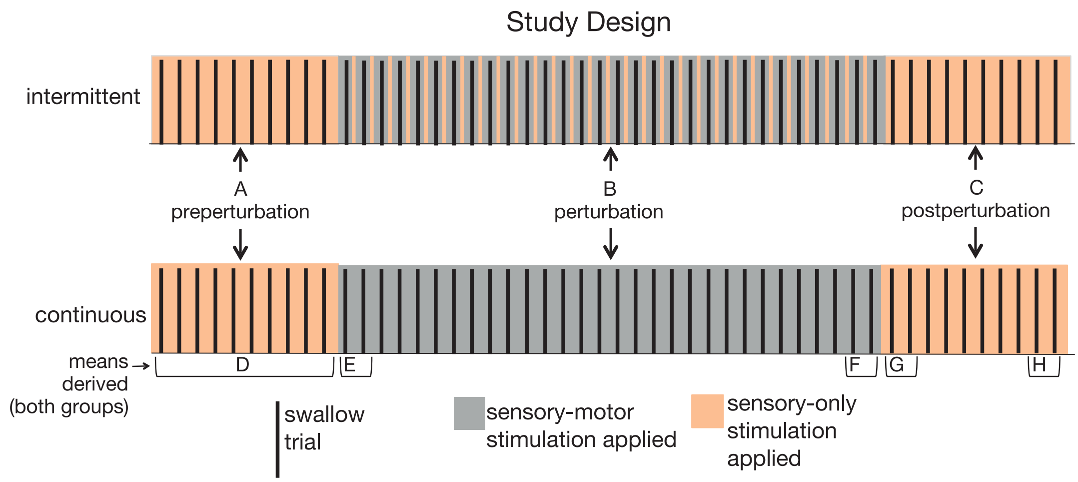
Swallowing timing analysis. Timing measures were taken to determine whether other swallowing-related events were adapting concurrently with our primary outcome variables (hyoid and laryngeal range of motion), given the interconnected nature of range of motion and timing of swallowing physiology. Six timing events of swallowing were included:

- Stage transition duration (*swallow reaction time*): time between when the bolus passes the ramus of the mandible and the first frame of the hyoid bone movement (referred to as *hyoid burst* in this article).
- Duration to maximum hyoid position elevation: time between hyoid burst and arrival at the maximum hyoid elevation.
- Duration to UES opening (hyoid): time between hyoid burst and first frame of the UES opening.
- Duration to UES opening (bolus): time between the bolus passing the ramus of the mandible and first frame of the UES opening.
- Laryngeal vestibule closure duration: time between first frame of the laryngeal vestibule closure until first frame of the laryngeal vestibule opening.
- Laryngeal vestibule closure reaction time: time between hyoid burst and first frame of the laryngeal vestibule closure.

Examining Evidence of EBL (Comparisons)

The effects of submental SES were compared in two different ways in both the intermittent and continuous groups.

Figure 3. Study design showing different stimulation paradigms for intermittent versus continuous submental surface electrical stimulation. Swallowing trials included in comparisons for stimulation phases (A, B, and C), and periods specific to research questions for error-based learning (D–H) are shown.



The first was to test for differences across the three phases of the study, including preperturbation, perturbation, and postperturbation (see A, B, and C of Figure 3). This three-block comparison allowed the examination of overall effects of the perturbation across several swallows. The second set of comparisons were necessary to test the specific research questions related to EBL and involved five comparison periods across the study with fewer swallow trials to answer four research questions (see D to H of Figure 3):

1. Is there an initial perturbation effect when submental surface stimulation is administered at the sensory–motor level? To determine if there is an initial perturbation effect for each measure, we compared the mean of all swallows of the preperturbation period to the mean of the first two swallows of the perturbation period (early perturbation period).
2. Is there a return to preperturbation (baseline) levels during the perturbation period? To test the return to preperturbation levels (overcoming the effect of the perturbation), we compared the mean of the first two perturbation trials (early perturbation period) to the mean of the last two perturbation trials (late perturbation period). Gradual trends across the 30 swallows during the perturbation period were also examined.
3. Are there aftereffects? To determine if aftereffects are present when the perturbation is unexpectedly removed, we compared the mean of the preperturbation swallows to the mean of the first two postperturbation swallows (early postperturbation).
4. Does de-adaptation occur? To determine if aftereffects diminish and return to baseline, we compared the first two swallows of the postperturbation period (early postperturbation) to the last two swallows of the postperturbation period (late postperturbation).

Statistical Analysis

Our statistical analysis included a linear mixed-model analysis (SPSS Version 22). We controlled for heterogeneity among individuals by using subject as a random effect. There were two comparisons. One comparison included the three phases (preperturbation, perturbation, and postperturbation), and the fixed effects included groups (continuous, intermittent) and a covariate of trial to examine linear trends. Another comparison answered the research questions specific to EBL across the five phases (preperturbation, early perturbation, late perturbation, early postperturbation, late postperturbation), and the fixed effects included groups (continuous, intermittent). If significant fixed effects were found, pairwise comparisons were Sidak corrected for multiple comparisons. A paired *t* test was used to compare the stimulation at rest effects of sensory–motor levels (hyoid position during no-stimulation vs. during sensory–motor stimulation). We tested the interrater reliability of our measurements on 10% and the intrarater reliability on 7% of the data with intraclass correlation coefficients. The intraclass correlation coefficient represents the proportion of total variation, including between-subjects variability and measurement variability.

Results

Timing measures were completed on 1,500 swallows, and the range of motion was competed on 1,450 swallows. The range of motion could not be completed on one participant because his vertebrae were out of view. Interrater and intrarater reliability was excellent for all timing measures (see Table 1). For the range of motion, all measures were good to excellent except the interrater reliability for the hyoid anterior peak and the intrarater reliability of the laryngeal baseline position. This might be explained by a well-known statistical phenomenon where less variability in a

Table 1. Interrater and intrarater reliability for range of motion and timing measures.

Range of motion	Interrater ICC	Interrater ICC
Laryngeal superior peak	.70	.92
Hyoid superior movement	.90	.95
Hyoid anterior movement	.97	.50
Laryngeal baseline position (*y*-axis)	.35	.92
Hyoid baseline position (*y*-axis)	.91	.87
Hyoid baseline position (*x*-axis)	.98	.70
Timing		
Bolus passes the ramus of mandible	.97	.99
Hyoid burst	.99	.99
Hyoid at maximum elevation	.99	.99
First frame UES open	.99	.99
Laryngeal vestibule open	.97	.99
Laryngeal vestibule closed	.99	.99

Note. ICC = intraclass correlation; UES = upper esophageal sphincter.

data set will lead to lower correlations (Goodwin & Leech, 2010). Still, outcomes might have been impacted by judgment error in the measurements.

Stimulation Levels

The continuous group had an average sensory-only stimulation of 1.87 mA (range: 1–2 mA) and an average sensory–motor stimulation of 4.6 mA (range: 2–8). In the intermittent group, the average sensory-only stimulation was 2 mA (range: 1–3 mA), and the average sensory–motor stimulation was 4.1 mA (range: 3–6).

Results for Stimulation at Rest

At-rest measures of hyoid and laryngeal movements due to submental sensory–motor level stimulation were calculated. In order to understand the scale of these at-rest measures, they are provided here as a percentage of the peak movement induced during swallowing without sensory–motor stimulation (mean of 10 preperturbation swallows; see Figure 4). On average, at-rest sensory–motor stimulation induced 22.5% (hyoid anterior), 17.5% (hyoid superior), and 6% (laryngeal superior) of the movement measured during the preperturbation swallows. Figure 4 shows induced movement at rest for continuous and intermittent groups independently. Continuous and intermittent group at-rest measures were not different for laryngeal superior movement (p = .378), for hyoid anterior (p = .306), or for superior movement (p = .120).

Range of Motion Outcomes

Range of motion. Fixed effects show that, during the period immediately before the swallow, there was a statistically significant difference in the baseline anterior position of the hyoid in the continuous group (p = .003, F = 5.86; see Figure 5). This was the only statistically significant outcome found in the range of motion. No pairwise comparison or test for linear trends yielded significant outcomes for any research question that was posed in this investigation (see Table 2).

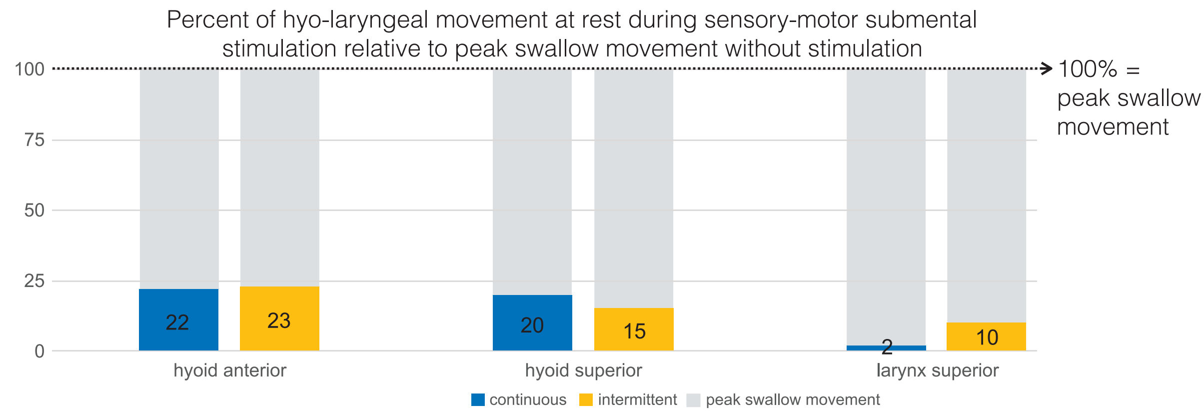
Timing measurements. No statistically significant fixed effect was found.

Discussion

This study aimed to determine if submental SES in healthy adults induces a perturbation that can eventually be overcome by way of EBL. Unlike studies showing EBL due to swallowing with anterior neck stimulation where the hyoid and laryngeal depressors are targeted, this study did not yield any evidence of EBL with submental stimulation. This likely occurred because submental SES did not cause at-rest changes that posed difficulty to swallowing. In fact, at-rest stimulation effects positioned the hyoid (primarily) and larynx closer to its end goal (in the superior and/or anterior direction). Thus, because the agonists for the hyoid anterior and superior excursion are targeted with submental stimulation, no error could be induced to cause a subsequent, measurable error-reduction response among our specific outcome measures. Overall, this finding is supported by other studies on swallowing function (Barkmeier, Bielamowicz, Takeda, & Ludlow, 2002; Burnett, Mann, Stoklosa, & Ludlow, 2005). The only significant effect was in the extent of hyoid anterior positioning during the at-rest period immediately prior to swallow onset in the continuous group. This significant at-rest effect may have only been evident in the continuous group because submental stimulation was ongoing before, during, and after swallowing, unlike the intermittent group.

Our study findings are supported by published research showing little or no change with submental SES on swallowing outcomes among healthy controls (Heck et al., 2012; Humbert et al., 2008; Ludlow et al., 2007; Safi et al., 2017; Suiter et al., 2006) and in patients with dysphagia (Baijens et al., 2013; Lee, Hong, Lee, Shin, & Cho, 2015). Still, other studies have reported improvements in swallowing severity measures where sensory-level submental stimulation appears to have been administered to patients during the treatment phase (Gallas, Marie, Leroi, & Verin, 2010; Verin et al., 2011). Marginal effects with submental electrical stimulation may have occurred in studies of healthy adults because of lower stimulation amplitude tolerance than required to observe robust effects. In several patient studies, neither the hypotheses nor the outcomes were based upon specific swallowing pathophysiologies (i.e., no laryngeal vestibule closure); instead, a diagnosis of dysphagia alone was sufficient for patient study inclusion. This is problematic because of the very wide range of swallowing impairment types (i.e., lingual control vs. UES stricture). To elaborate, it was theorized in the introduction of the current study that it is possible that hyoid elevation without laryngeal elevation could pose a challenge for patients with minimal laryngeal elevation (see Figure 1). However, such an effect would need to be tested in individuals with dysphagia that is primarily due to reduced laryngeal elevation that

Figure 4. Percent of the hyoid bone (superior and anterior) and laryngeal (superior) movement induced with at-rest sensory–motor stimulation is shown relative to peak hyo-laryngeal elevation achieved during the 10 preperturbation swallows.



leads to disordered laryngeal vestibule closure. Although patient selection might be challenging, it is possible that submental SES might have highly specific, not general, effects on swallowing, warranting patient selection by the type of swallowing impairment rather than just the presence of dysphagia.

It is widely accepted in many rehabilitation domains that one primary goal of rehabilitation is to challenge an impairment to restore function and that a secondary goal is to reduce the disability by training compensatory mechanisms. Submental SES might not challenge laryngeal movement; instead, it might facilitate hyoid movement by moving it

Figure 5. The graph demonstrates differences in hyoid anterior position at baseline immediately prior to swallowing across the 50 trials in the three study phases (continuous group only): preperturbation, perturbation, and postperturbation (p = .003). Data are in arbitrary units (peak movement relative to vertebra position – raw data).

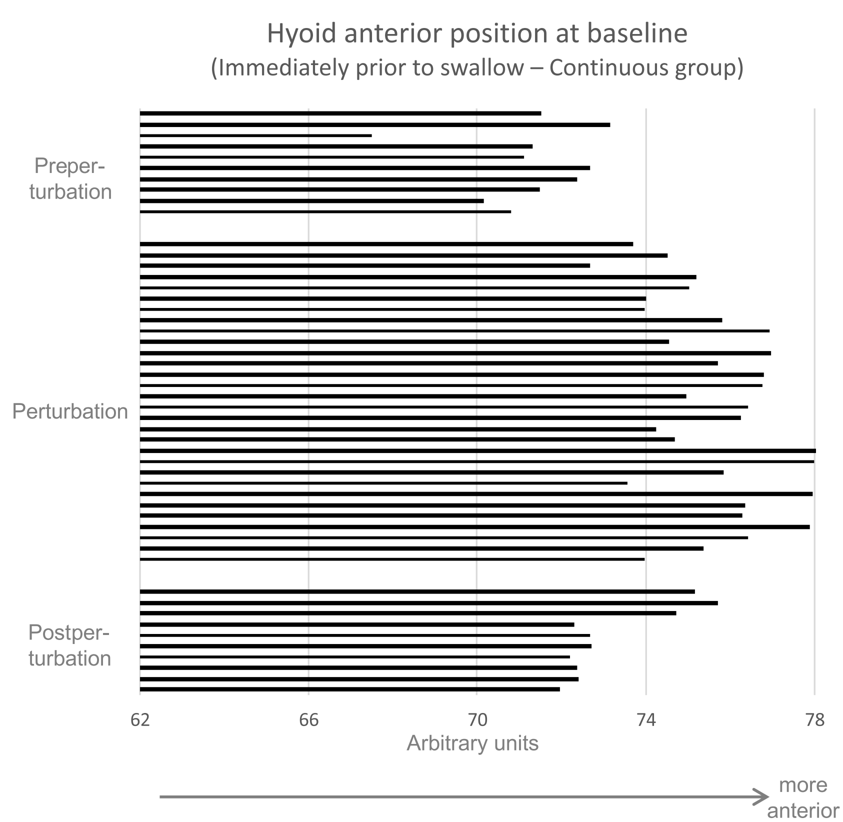


Table 2. Statistical outcome of hyo-laryngeal range of motion for three phases and for five comparison points for both continuous and intermittent groups.

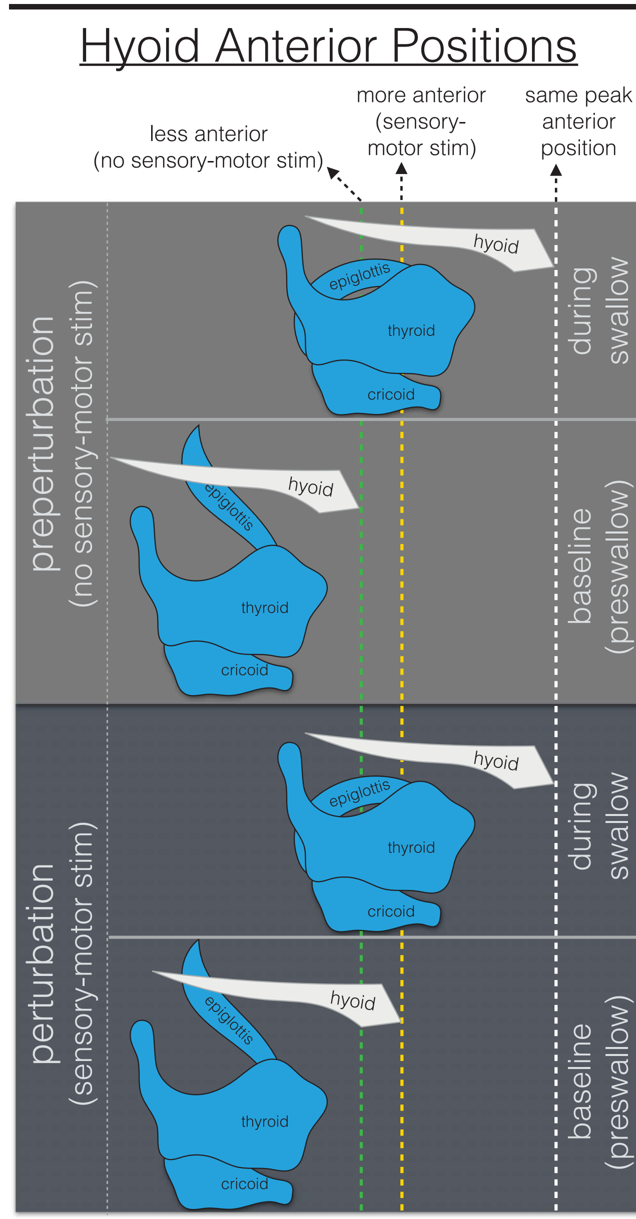
	Preswallow		Peak	
Measure	***p* value**	***F* statistic**	***p* value**	***F* statistic**
Range of motion (3 phases)				
Continuous				
Hyoid superior	.926	0.08	.934	0.07
Hyoid anterior	**.003**	**5.86**	.885	0.12
Laryngeal superior	.733	0.31	.753	0.28
Intermittent				
Hyoid superior	.649	0.43	.599	0.51
Hyoid anterior	.969	0.03	.191	1.66
Laryngeal superior	.72	0.33	.961	0.04
Range of motion (5 comparison periods)				
Continuous				
Hyoid superior	.971	0.13	.997	0.11
Hyoid anterior	.994	0.06	.997	0.03
Laryngeal superior	.994	0.06	.997	0.04
Intermittent				
Hyoid superior	.985	0.09	.745	0.49
Hyoid anterior	.996	0.07	.282	1.271
Laryngeal superior	.996	0.05	.993	0.06

Note. Bold font indicates statistical significance.

closer to its peak excursion just prior to swallowing (see Figure 6). In this study, healthy adults began swallowing with the hyoid at varied positions along the horizontal plane. Submental stimulation might have positioned the hyoid bone approximately 20% closer to its final anterior destination (pairwise comparisons not significant). This effect might be useful in patients with reduced excursion time to maximum hyoid elevation by facilitating speedier hyoid movements along the horizontal plane. We might not have found differences in laryngeal elevation when attempting to approximate the hyoid to achieve laryngeal vestibule closure during the swallow because hyoid peak excursion was not increased with submental stimulation.

The outcomes of this study are significant because SES is a commonly used, but poorly understood, technique in swallowing rehabilitation (Crary & Carnaby, 2014). Furthermore, some stimulation devices geared toward dysphagia management target the submental region differentially from the anterior neck. Electrical stimulation for swallowing remains controversial, despite numerous treatment studies, possibly because of mixed efficacy outcomes (Logemann, 2007). For instance, some studies report improvements in swallowing function with SES treatment, whereas others do not (Humbert, Michou et al., 2012). These conflicting results might exist because most studies of SES do not include physiological outcomes (i.e., swallowing kinematics) but instead report bolus flow and/or functional rehabilitation outcomes (i.e., penetration, aspiration, diet upgrades). Applying EBL principles to understand the physiological bases of rehabilitation techniques requires physiological outcome measures and is widely used in other rehabilitation domains (occupational, physical, visual; Doig, Fleming, Ownsworth, & Fletcher, 2017; Yen, Schmit, &

Figure 6. Hyoid bone more anterior at baseline just prior to swallow onset with sensory–motor stimulation (stim) compared with preperturbation period. However, the same hyoid peaks were achieved during swallowing in both preperturbation and perturbation swallows.



Wu, 2015). EBL strategies could improve our understanding of SES of dysphagia management and lead to better designed long-term therapeutic studies in select patient populations (Humbert & German, 2013). In the current study, we have shown that submental SES does not alter the hyo-laryngeal range of motion and the timing of laryngeal vestibule closure, UES opening, or swallow onset in the healthy adults that we have tested. This could be because the agonists are targeted, which neither facilitated nor disturbed swallowing in healthy adults.

Findings of this study are limited because they were derived from healthy adults who swallowed under highly cued circumstances. Also, the outcomes are based on a short-term experimental paradigm and do not test pharyngeal or lingual outcomes that might have had significant outcomes due to the manipulations applied in this study. Future studies should focus on patients with swallowing impairments that have the potential to be impacted by submental electrical stimulation (i.e., reduced hyoid and/or laryngeal elevation) over longer periods to determine if range of motion facilitation has significant rehabilitation potential for dysphagia management.

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