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Examination of swallowing maneuver training and transfer of practiced behaviors to laryngeal vestibule kinematics in functional swallowing of healthy adults

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HIGHLIGHTS

- First study to describe the occurrence of LVC transfer when comparing pre, during and post-training outcomes.
- Outcomes indicate it is possible to manipulate and hasten swallowing airway protection (LVCrt).
- Outcomes also indicate that manipulation of LVCrt can transfer to natural swallowing.
- LVC reaction time was significantly shorter both during vLVC training period and post-training in 5 ml natural swallows.

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ABSTRACT

Swallowing maneuvers are routinely trained in dysphagia rehabilitation with the assumption that practiced behaviors transfer to functional swallowing, however transfer is rarely examined in the deglutition literature. The goal of this study was to train the volitional laryngeal vestibule closure (vLVC) maneuver, which is a swallowing maneuver that targets prolonged laryngeal vestibule closure (LVC). In two different training experiments, 69 healthy adults underwent Long-hold (hold vLVC as long as possible) or Short-hold vLVC training (hold vLVC for 2 s). Before and after vLVC training, natural swallows (swallowing without a therapeutic technique) were completed. The outcome variables included laryngeal vestibule closure reaction time and the duration of laryngeal vestibule closure. Results indicate that during both Long-hold and Short-hold vLVC trainings, vLVC swallows had faster laryngeal vestibule closure reaction times and longer durations of laryngeal vestibule closure than in pre-training 5 ml liquid swallows. However, only faster laryngeal vestibule closure reaction times transferred to post-training 5 ml liquid swallows (20–24% faster), but not prolonged durations of laryngeal vestibule closure. Our findings suggest that swallowing maneuver training has the potential to induce transfer of what was practiced to functional swallowing behavior, although not all practiced behaviors may generalize. These findings are significant for bolstering the effectiveness of dysphagia management in medical settings and should be tested in individuals with dysphagia.

1. Introduction

Airway protection during normal swallowing is primarily accomplished by laryngeal vestibule closure (LVC), which involves intricate coordination of several oropharyngeal structures. The kinematic events involved in LVC include epiglottic inversion, hyo-laryngeal elevation, aryepiglottic fold bunching, arytenoid adduction and forward pivoting, base of tongue posterior movement, and pharyngeal constriction [10, 12–14,27,36].

Swallowing maneuvers are prescribed in dysphagia therapy to target impaired airway protection, because they involve volitional modifications to the timing and extent of some structures involved in swallowing [26]. They may target prolonging hyo-laryngeal elevation

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during a Mendelsohn maneuver [21] or arytenoid adduction and true vocal fold closure during a supraglottic swallow [5,32]. Swallowing maneuvers are distinct from functional oropharyngeal swallowing, which does not emphasize modification of any particular component of the swallow, but serves simply to move saliva, liquids, or foods into the esophagus. We will refer to functional oropharyngeal swallowing as *natural* swallows throughout this manuscript.

1.1. Transfer of swallowing maneuvers in dysphagia rehabilitation

Despite the known physiological modifications that can be achieved with swallowing maneuvers, the swallowing research literature does not adequately address the important rehabilitation goal of transferring these learned therapeutic gestures to functional, non-therapeutic behaviors (i.e. leg strengthening exercises transfer to walking). Transfer is characterized simply as a trained behavior that affects an untrained behavior [19]. This rehabilitation goal of transference is partially derived from a key principle of motor learning, wherein learning is primarily proven when a practiced behavior transfers to a different task or sensorimotor system [25,42,44]. Transfer has two components including *generalization* (trained behavior is applied to different settings or tasks) and *maintenance* (transference is persistent over time) [3]. Given the gap in knowledge regarding immediate effects of swallowing training, it seems that generalization is a critical first step toward establishing the presence of transfer of swallowing maneuvers to natural swallowing. To test generalization, swallowing scientific experiments should examine behaviors before, during and after a target training. This is needed in order to understand (1) whether the swallowing maneuvers that were trained are different than natural swallowing (pre-training versus training) and (2) to determine if post-training swallowing is affected by training (pre-training versus post-training). However, according to Macrae and Humbert [30] much of the swallowing treatment literature reports data on behaviors observed either (a) during the training period or (b) before and after the training.

1.2. Goal and significance of the current study

The current manuscript describes two experiments that investigate whether training a novel swallowing behavior transfers to natural swallowing immediately post-training. Specifically, we examined transfer when training the volitional laryngeal vestibule closure maneuver (vLVC). The vLVC maneuver begins with a swallow and requires prolonging LVC for at least 2 s, thus LVC prolongation is directly targeted with the vLVC maneuver [2,29]. We aimed to determine whether LVC modifications made during vLVC training transfer to functional swallowing behavior, by comparing LVC timing among pre-vLVC training, vLVC training, and post-vLVC training swallowing in healthy adults. We hypothesized that post-training water swallows would have longer LVC durations than pre-training water swallows, given the focus of LVC prolongation during vLVC training. The outcome of this study is significant because it begins to address a relevant, published concern that dysphagia exercises may not lead to improvement of swallowing function [22,23]. Understanding whether swallowing maneuver training can immediately transfer to natural swallowing behavior post training (generalization) is a critical first step toward improving the efficacy of dysphagia rehabilitation.

2. Methods

2.1. Experiments

Two experiments were conducted to test our hypothesis that transfer can occur in healthy adults who train a swallowing maneuver. Both experiments involved a pre-, during, and post-training phase as well as a timed vLVC performance task. In the *Long-hold vVLC training*, participants were asked to prolong the vLVC swallow for as long as possible. In the *Short-hold vVLC training*, participants were asked to perform a 2-second vLVC swallow. The Long-hold and Short-hold trainings were not designed for direct comparison. Our goal is to report findings from these two different vLVC training protocols to provide a richer understanding of whether and how vLVC training influences the presence or type of transfer to functional swallowing.

2.2. Participants

This study included 69 healthy adult participants in total, including 34 individuals who participated in the Long-hold vLVC training (mean age 27 yrs ± 11) and 35 who participated in the Short-hold vLVC training (mean age 35 yrs ± 14). The subjects had no history of speech, respiratory, or swallowing problems and data from 51 of these participants were previously reported to test a different hypothesis in Macrae et al. [29] and Azola et al. [2]. The local Institutional Review Board (IRB) approved the study and all participants provided written informed consent prior to participation.

2.3. Procedures prior to training for both experiments

All participants were required to demonstrate their first accurate performance of the vLVC swallowing maneuver in order to participate in any vLVC swallow training. The vLVC swallow maneuver began with a saliva swallow, followed by volitional prolongation of LVC duration for at least 2 s (view vLVC maneuver here: https://www.youtube.com/watch?v=hiPbGsnNj8s). Two seconds is the threshold for accurate vLVC performance because it is approximately three times longer than the duration of LVC in a natural swallow of healthy adults [34], indicating that volition was needed to prolong closure. Participants were taught to perform the vLVC for the first time with instructions to swallow saliva and palpate the thyroid notch (aka Adam's apple) to detect its upward movement. Then, they were instructed to swallow again and hold the thyroid notch up as high and long as possible. In addition, participants were told that they should not be able to breathe during this short period. These instructions were followed by videofluoroscopic recordings of vLVC swallow maneuver attempts to allow the investigator to confirm the first accurate performance. Participants were only advanced to vLVC training if they performed the vLVC maneuver accurately within 5 attempts. In previous studies, most participants needed <5 attempts to achieve the vLVC maneuver [2,29]. Five attempts allowed adequate trials to demonstrate the maneuver without using gratuitous videofluoroscopy time, which was limited for participants' safety and to ensure adequate time to record the remaining trials of the study. All swallows in all phases were recorded with videofluoroscopy and verbally cued by the investigator to synchronize the onset of videofluoroscopic recording with swallowing. Each vLVC trial was performed with saliva rather than a bolus, although participants were permitted 1 ml water boluses during the inter-trial intervals trials to maintain enough oral moisture to initiate a swallow. The inter-trial intervals were approximately 30 s throughout both trainings.

2.4. Procedures for the Long-hold vLVC swallow training

Prior to Long-hold training, five participants could not achieve the vLVC maneuver and were excluded from vLVC training. These individuals, who we refer to as "Learners", were permitted to continue to attempt to achieve the vLVC maneuver for a total of 15 trials instead of vLVC training. The remaining 29 participants completed the Long-hold training. The Long-hold vLVC training included three phases in the following order: (1) pre-vLVC training natural swallows (water), (2) vLVC training swallows (saliva), and (3) post-vLVC training natural swallows (water). The study designs for Long-hold and Short-hold experiments are shown in Fig. 1.

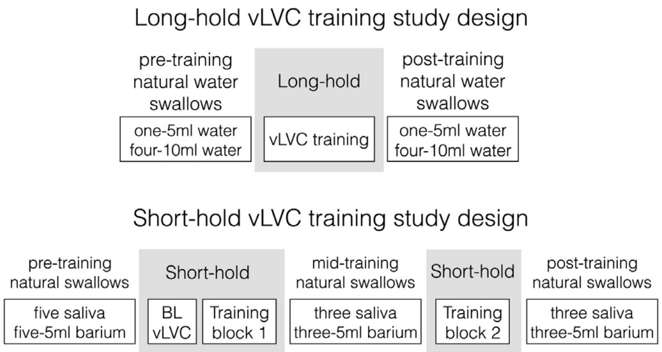

Fig. 1. Study design for Long-hold and Short-hold vLVC swallowing training.

2.4.1. Pre- and post-training natural water swallows

All pre- and post-training natural swallows were water boluses for this experiment to examine transfer to a more familiar and realistic bolus that is regularly consumed and can be better generalized to real world swallowing (as compared to barium). The pre- and post-training phases each included one-5 ml water swallow followed by four-10 ml water swallows. The rationale for 5 ml and 10 ml water boluses is that LVC kinematics vary depending on the volume of a bolus (review: [33]). Thus, testing two different volumes in pre- and post-Long-hold vLVC training allowed us to determine whether vLVC swallowing training transfers to post-training LVC kinematics differently depending on bolus volume. In particular, 5 ml and 10 ml volumes were tested because larger volumes (~14 ml or greater) can induce double or "piecemeal" swallowing, which would prevent confirmation of the volume of water swallowed in the study [11]. A greater number of 10 ml swallows were tested because 10 ml is closer to the volume that healthy people typically sip in less restricted circumstances [20]. When post-training water swallows began, participants were instructed to discontinue performance of the vLVC maneuver and to swallow naturally.

2.4.2. Long-hold vLVC training swallows

Long-hold vLVC training involved simply performing 6 vLVC trials where participants were required to prolong dLVC for as long as possible. Thus, in the Long-hold training, participants completed 7 vLVC maneuver swallows (first accurate demonstration plus 6 training trials). Although 7 trials are fewer than the number of repetitions that would be trained in a rehabilitation setting, the current study was limited by videofluoroscopy time so 7 trials was the maximum possible within our time frame. Videofluoroscopy time was a limiting factor for the Long-hold training because several participants could prolong LVC durations for 10 s or greater, similarly to the data that were published in Macrae et al. [28,29].

2.5. Procedures for Short-hold vLVC swallow training study design

The Short-hold vLVC training included six phases in the following order: (1) pre-training natural swallows (5-saliva; 5-thin liquid barium), (2) 5 baseline vLVC swallows, (3) 10 vLVC training swallows (block 1), (4) mid-training natural swallows (3-saliva; 3-thin liquid barium), (5) 10 vLVC training swallows (block 2), and (6) post-training natural swallows (3-saliva; 3-thin liquid barium).

2.5.1. Pre-, Mid-, and Post-training natural swallows

Saliva and 5 ml thin liquid barium were tested because they differ in many ways, including volume, texture, and taste of the bolus. Similar to the Long-hold vLVC swallow training, testing different types of boluses enables us to detect any differentiation of transfer, which could elucidate involvement of sensory-motor integration in this process. Mid-training swallows were included to determine whether the number of training trials impact transfer (i.e. after 10 training trials versus after 20 training). Immediately prior to the mid- and post-training natural swallows, participants were instructed to discontinue performing the vLVC maneuver and to swallow naturally.

2.5.2. Short-hold vLVC baseline swallows

The 2-second baseline vLVC swallows were used to establish vLVC swallowing behavior prior to the two training blocks.

2.5.3. Short-hold vLVC training swallows

Short-hold vLVC training involved performing a 2-second vLVC swallow ten times in two-different, ten-trial training blocks.

2.6. Videofluoroscopy and data analysis

All swallows were acquired in the sagittal plane (continuous 30 frames/s). The field of view included the oral cavity, pharynx, larynx, trachea, upper esophageal sphincter, and cervical vertebrae. Each swallow was cropped into a single video clip with no identifying information and labelled with a random number to facilitate blinded analyses. Since the vLVC maneuver focuses on laryngeal vestibule closure, we included the two LVC kinematic measures that have been published in the research literature, including laryngeal vestibule closure reaction time (LVCrt) and the duration of laryngeal vestibule closure (dLVC). LVCrt (also known as duration to laryngeal vestibule closure or DTLVC) is the time interval between (a) swallow onset (marked by "hyoid burst", which is the first superior and/or anterior rapid motion of the hyoid bone) and (b) the first frame when the laryngeal vestibule is closed and no airspace can be seen through the hyo-laryngeal structures [1,7,16,45]. dLVC is the time interval between (a) the first frame when the laryngeal vestibule is closed until (b) the first frame when the laryngeal vestibule reopens and airspace can be visualized as the epiglottis begins its return to rest position [35].

2.7. Statistical analyses

This study used a linear mixed models analysis (SPSS version 24) [15]. The random effect was "subject" to control for heterogeneity among participants. For fixed effects in the Long-hold training experiment, 5 factors were included: pre-training 5 ml water, pre-training 10 ml water, vLVC swallows, post-training 5 ml water, and post-training 10 ml water. For fixed effects in the Short-hold experiment, 9 factors were included: pre-training saliva swallows, pre-training barium swallows, baseline vLVC swallows, training block 1 vLVC swallows, mid-training saliva swallows, mid-training barium swallows, training block 2 vLVC swallows, post-training saliva swallows, and post-training barium swallows. When fixed-effects were significant, pairwise comparisons were Bonferroni corrected to manage multiple comparisons. Pairwise comparisons of interest corresponded to the study design which tested LVC kinematics before, during, and after training.

2.8. Comparisons

To test transfer, we examined LVC kinematics before, during and immediately after vLVC training. Our first comparison was made to understand whether vLVC swallows were different than baseline natural swallows, thus we compared pre-training natural swallows to vLVC swallows. This was needed to identify the kinematics that were actually practiced during training and could potentially be transferred. Specifically, in the Long-hold training, we compared pre-training water swallows (5 ml and 10 ml) to the vLVC swallows. In the Short-hold training, we compared among the pre-training saliva and barium swallows to vLVC swallows. To correct for multiple comparisons (Bonferroni), pairwise comparisons were significant at the ≤0.025 alpha value (0.05/2) for Long-hold vLVC training. To correct for multiple comparisons in the Short-hold training, pairwise comparisons were significant at the ≤0.008 alpha value (0.05/6) for Short-hold vLVC training.

Our second comparison was made to examine the presence of transfer immediately post-training, thus we compared pre-training natural swallows to post-training natural swallows. Specifically, for the Long-hold training, we compared pre-training natural water swallows (5 ml and 10 ml) to the corresponding post-training water swallows (5 ml and 10 ml). For the Short-hold training, we compared among the pre-, mid- and post-training natural swallows (saliva and barium). To correct for multiple comparisons (Bonferroni), pairwise comparisons were significant at the ≤0.025 alpha value (0.05/2) for Long-hold vLVC training. To correct for multiple comparisons in the Short-hold training, pairwise comparisons were significant at the ≤0.008 alpha value (0.05/6) for Short-hold vLVC training.

2.9. Reliability

We tested the reliability of our timing measurements on 20% of the data (inter- and intra-rater) by computing intraclass correlation coefficients (ICC). The ICC indicates variability in measurement outcomes. Values near 1 suggest valid biological differences, whereas values near 0 indicate measurement errors.

3. Results

Inter-and intra-rater reliability were excellent (ICC ≥ 0.98) for both LVCrt and dLVC.

3.1. Fixed effects

3.1.1. dLVC

Significant fixed effects were found for both Long-hold vLVC (p = 0.001; F = 55.84) and Short-hold vLVC training (p ≤ 0.001; F = 254.94) showing that dLVC was significantly different across all tasks that were compared (Fig. 2).

3.1.2. LVCrt

Significant fixed effects were found for both Long-hold vLVC (p = 0.022; F = 2.90) and Short-hold vLVC training (p ≤ 0.001; F = 8.17), showing that LVCrt was significantly different across all tasks that were compared.

3.2. Pairwise comparisons

3.2.1. Are LVC kinematics during vLVC maneuver training different than pre-LVC training natural swallows? (Tables 1 and 2).

3.2.1.1. dLVC. In Long-hold vLVC training, 5 ml pre-training natural water swallows (0.41 s ± 1.2 SD) and 10 ml pre-training natural water swallows (0.52 s ± 2.4 SD) had significantly shorter dLVC times than vLVC maneuver swallows (9.3 s ± 9.6 SD). Short-hold vLVC training outcomes were similar, where dLVC was significantly shorter in both saliva pre-training water swallows (0.48 s) and 5 ml barium pre-training swallows (0.42 s) compared to the vLVC maneuver swallows (Baseline vLVC = 2.8 s; vLVC training block 1 = 2.5 s; vLVC training block 2 = 2.7 s) (Fig. 2).

3.2.1.2. LVCrt. In Long-hold vLVC training, LVCrt was longer in pre-training 5 ml water swallows (0.21 s) compared to vLVC maneuver swallows (0.16 s) (p = 0.01), a 24% decrease in reaction time. However, LVCrt of 10 ml pre-training water swallows (0.16 s) was not different than vLVC training swallows (p = 0.931). Likewise, Short-hold vLVC training also revealed longer LVCrt in pre-training barium swallows (0.21 s) compared to vLVC maneuver swallows (baseline = 0.16 s; training block 1 = 0.17 s; training block 2 = 0.16 s). However, LVCrt of pre-training saliva swallows (0.15 s) was not different than vLVC maneuver swallows.

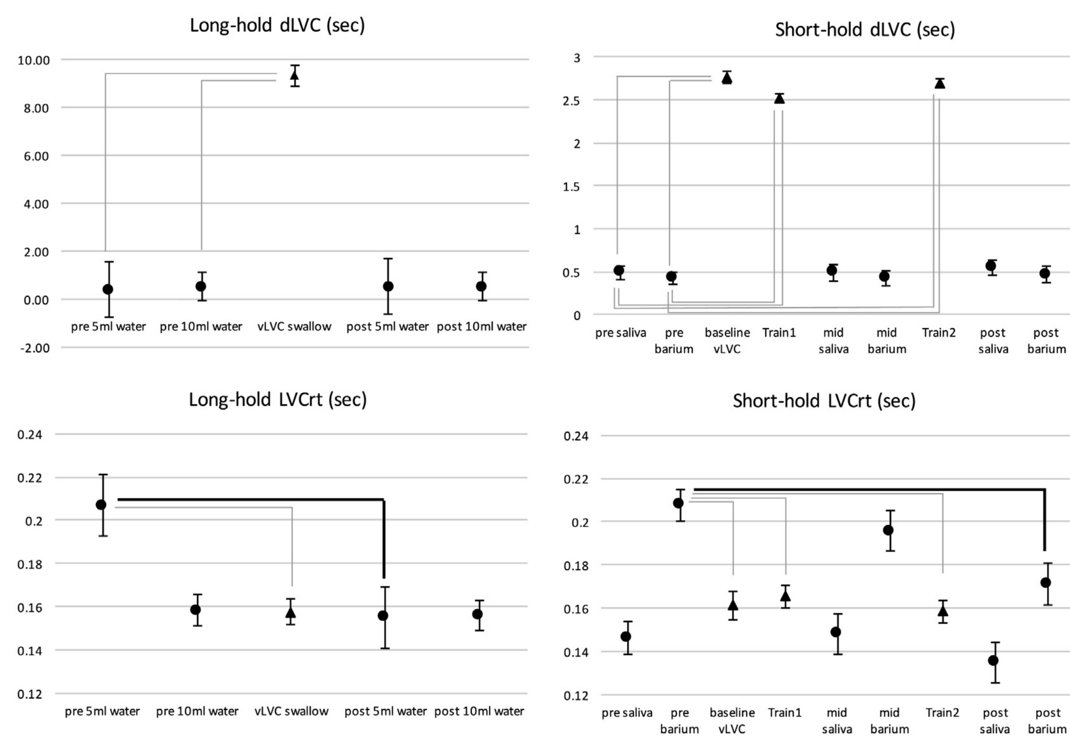

Fig. 2. Graphed outcomes for dLVC and LVCrt in seconds for both Long-hold and Short-hold training. Significant differences in Question 1 (Are vLVC swallows different than pre-training natural swallows) are indicated with a thin grey line. Significant differences in Question 2 (Is transfer evident by differences between pre- and post-natural swallows) are indicated with a thick black line.

Table 1
Means, std. error, and confidence intervals for dLVC and LVCrt.

Long-hold (df 444)	dLVC mean	Std. error	95% CI lower	95% CI upper
Pre 5 ml water	0.41	1.16	−1.87	2.69
Pre 10 ml water	0.51	0.59	−0.64	1.68
vLVC training	9.32	0.45	8.42	10.21
Post 5 ml water	0.52	1.16	−1.81	2.75
Post 10 ml water	0.51	0.60	−0.67	1.70
Long-hold (df 462)	LVCrt mean	Std. error	95% CI lower	95% CI upper
Pre 5 ml water	0.21	0.014	0.18	0.23
Pre 10 ml water	0.16	0.007	0.14	0.17
vLVC training	0.16	0.006	0.15	0.17
Post 5 ml water	0.16	0.014	0.13	0.18
Post 10 ml water	0.16	0.007	0.14	0.17
Short-hold (df 1312)	dLVC mean	Std. error	95% CI lower	95% CI upper
Pre saliva	0.49	0.08	0.34	0.64
Pre 5 ml barium	0.42	0.08	0.28	0.57
Baseline vLVC swallows	2.76	0.07	2.63	2.89
vLVC training block 1	2.52	0.05	2.42	2.63
Mid saliva	0.49	0.09	0.30	0.67
Mid 5 ml barium	0.42	0.09	0.24	0.61
vLVC training block 2	2.69	0.05	2.59	2.80
Post saliva	0.55	0.09	0.36	0.73
Post 5 ml barium	0.46	0.10	0.27	0.65
Short-hold (df 1309)	LVCrt mean	Std. error	95% CI lower	95% CI upper
Pre saliva	0.15	0.007	0.13	0.16
Pre 5 ml barium	0.21	0.008	0.19	0.22
Baseline vLVC swallows	0.16	0.007	0.15	0.17
vLVC training block 1	0.17	0.005	0.16	0.18
Mid saliva	0.15	0.009	0.13	0.17
Mid 5 ml barium	0.20	0.009	0.18	0.21
vLVC training block 2	0.16	0.005	0.15	0.17
Post saliva	0.14	0.009	0.12	0.15
Post 5 ml barium	0.17	0.010	0.15	0.19

Table displays means, standard deviations, and 95% confidence intervals for all trials in the Long-hold and Short-hold trainings in seconds. Degrees of freedom are expressed as df.

3.2.2. Do the LVC kinematics practiced during vLVC maneuver training transfer to mid- or post-training natural swallows? (Table 2)

3.2.2.1. dLVC. The prolonged dLVC that was practiced during vLVC maneuver training did not transfer to post-vLVC training water swallows in the Long-hold training or in the Short-hold vLVC training (means, p-values in Table 2).

3.2.2.2. LVCrt. In Long-hold vLVC training, transfer was evident only in 5 ml water swallows after vLVC training, wherein LVCrt was reduced to from 0.21 s (pre-training) to 0.16 s (post training) ($p = 0.01$), which is a 24% decrease in LVCrt. However, no differences were found between the pre- and post-training 10 ml water swallows (both 0.16 s) ($p = 0.809$). In Short-hold vLVC training, transfer was also only evident in 5 ml thin liquid barium swallows after vLVC training. The LVCrt of post-training barium swallows (0.17 s) were significantly shorter than pre-training barium swallows (0.21 s; $p = 0.003$). Pre- and mid-training barium swallows were not different. No saliva swallow comparison was different among the pre- (0.15 s), mid- (0.15 s), or post-training (0.14 s) periods (p-values listed in Table 2).

3.3. Learners

No Learner achieved one accurate vLVC maneuver swallow. After the 15 attempts, they were asked to complete the same post-training natural saliva and barium swallows (3 saliva, 3–5 ml thin liquid barium). The Learners demonstrated similar LVCrt outcomes across the pre-saliva pre-5 ml water (0.13 s $\underline{+}$ 0.02), pre-10 ml water (0.16 s $\underline{+}$ 0.02), and vLVC attempts (0.11 s $\underline{+}$ 0.03).

4. Discussion

The main outcome of this study is that 2 different vLVC swallow training protocols revealed that training a swallowing maneuver that focuses on airway protection has the potential to transfer to natural swallowing occurring immediately after training. In particular, compared to pre-training 5 ml swallows, reductions in laryngeal vestibule closure reaction time (LVCrt) were found both during vLVC swallows (training period) and after training in 5 ml natural swallows in both experiments (24% shorter in Long-hold and 20% shorter on Short-hold). These outcomes imply the following: First, it may be possible to

Table 2
Pairwise comparisons.

Comparisons	dLVC		LVCrt	
	p-value	Cohen's D	p-value	Cohen's D
Question 1: Are LVC kinematics during vLVC maneuver training different than pre-vLVC training natural swallows?				
Long-hold training				
Pre-5 ml water vs vLVC swallow	<**0.001**	−1.31	**0.001**	0.65
Pre-10 ml water vs vLVC swallow	<**0.001**	−1.30	0.931	0.04
Short-hold training				
Pre-saliva vs baseline vLVC swallows	<**0.001**	−2.27	0.133	−0.19
Pre-saliva vs vLVC train block 1	<**0.001**	−2.40	0.037	−0.22
Pre-saliva vs vLVC train block 2	<**0.001**	−2.96	0.182	−0.15
Pre-5 ml barium vs baseline vLVC swallows	<**0.001**	−2.38	<**0.001**	0.51
Pre-5 ml barium vs vLVC train block 1	<**0.001**	−2.55	<**0.001**	0.43
Pre-5 ml barium vs vLVC train block 2	<**0.001**	−3.16	<**0.001**	0.53
Question 2: Do the kinematics practiced during vLVC maneuver training transfer to mid- or post-training natural swallows?				
Long-hold training				
Pre 5 ml water vs post 5 ml water	1.000	−0.48	**0.01**	0.72
Pre 10 ml water vs post 10 ml water	1.000	0.02	0.809	0.04
Short-hold training				
Pre-saliva vs mid-saliva	0.981	0.01	0.877	−0.20
Pre-saliva vs post-saliva	0.635	−0.16	0.346	0.15
Pre-5 ml barium vs mid-5 ml barium	1.000	0.00	0.320	0.13
Pre-5 ml barium vs post-5 ml barium	0.780	−0.24	**0.003**	0.39

Table displays p-values and Cohen's D (effect size) for dLVC and LVCrt for Long- and Short-hold trainings. Outcomes are categorized by research question and comparison. Bold text indicates statistically significant differences.

manipulate and hasten swallowing airway protection (LVCrt). Second, under certain training circumstances, manipulation of LVCrt might transfer to natural swallowing. Although these effects are small, it is important to note that LVCrt is a swallowing event that is typically very short in duration (~198–363 ms in normal swallows), likely to aid in the protection of aspiration at an early point in the swallow. Thus, slightly earlier airway protection might have some clinical significance. Cabib et al. [6] has shown that delayed laryngeal vestibule closure is a significant cause for aspiration, yet no traditional swallowing maneuver directly targets onset of laryngeal vestibule closure. Hastening laryngeal vestibule closure by 20–24% (as demonstrated in our current study) could be clinically significant in patients who aspirate due to delayed LVC onset.

4.1. Importance of laryngeal vestibule closure during swallowing

According to Cabib et al. [6], delayed LVC is one of the most characteristic aspiration-related parameters in dysphagic patients post-stroke [6]. Starmer et al. [41] reported that patients with post-radiated submental muscles who penetrated and aspirated also had decreased dLVC [41]. These, and many other studies that link disordered LVC to aspiration, highlight the complexity of LVC mechanics and its pathophysiology [24,37,38]. To our knowledge, the vLVC swallowing maneuver is the only treatment option that requires individuals to focus on modifying LVC gestures alone during a swallow. This justifies training the swallowing maneuvers that target LVC kinematics in dysphagia rehabilitation.

4.2. vLVC training impacts LVC reaction time (LVCrt), not duration of LVC (dLVC)

Wong et al. [43] introduced the notion that the structures involved in LVC predict their distance from one another prior to swallowing to plan appropriate movements to close the airway during the swallow. This theory could explain our findings where LVCrt was faster, but dLVC was unchanged in natural swallows after vLVC training, which was a surprising outcome [43]. We hypothesized that successful prolongation of dLVC during training would transfer to dLVC during post-training saliva and bolus swallows. However, an alternate finding could be explained by the possibility that vLVC swallows may actually have two phases, including 1) the swallow (reflexive, but modifiable) and 2) the volitional prolongation of dLVC after the swallow is complete. It is possible that planning for the volitional part of the vLVC (LVC prolongation after swallow) likely occurs prior to swallow onset and manifests by controlling LVC in two ways: hastening LVCrt during the swallow and prolongation of volitional LVC post swallow. Thus, prolonged LVC during the second phase of the vLVC maneuver, might only be an appended, non-swallow volitional behavior. Therefore, since the only swallow-related modification was LVCrt during vLVC training, then only LVCrt could be transferred to post-training natural swallowing.

Participants were not asked to attend to LVCrt at any point during the trainings. Furthermore, investigators cannot distinguish between 0.16 and 0.21 s in real time, so neither the participant nor the investigator was aware of LVCrt kinematics during the investigation. A faster LVCrt might be an important part of the motor planning needed to perform the vLVC maneuver swallow accurately. Earlier LVC onset indicates that participants were able to identify the particular swallowing event that required modification prior to swallowing onset. Perhaps this outcome is supported by theories presented by Wong et al. [43], where achieving target behaviors of LVC mechanics occur prior to the swallow. It is also supported by theories of implicit learning and reflexive learning [4,8], wherein what was learned cannot be explicitly verbalized or is largely unknown, but has been shown to lead to after-effects in swallowing airway protection kinematics in healthy adults [1,7,16–18].

Further explanation of the importance of LVCrt in performing the vLVC swallowing maneuver accurately is derived from data from the "Learners" who could never demonstrate an accurate vLVC swallow. Among Learners, LVCrt of natural swallows were similar before and after their 15 vLVC attempts. These outcomes indicate that Learners may not have employed appropriate motor planning techniques to manipulate LVC mechanics prior to swallowing, leading to unchanged LVCrt and dLVC. Given the short duration of the Learners' pre-5 ml water swallow, it is also possible that these participants could not achieve an accurate vLVC maneuver swallow because a faster vLVCrt is required and they appeared to have naturally very fast LVC reaction times, leading to a ceiling effect that prevented accurate vLVC performance.

It is notable that the LVC event that was not explicitly practiced transferred to swallowing (LVCrt), rather than the targeted therapeutic behavior (dLVC). In patients, this particular outcome of faster LVCrt could be beneficial. However, it raises concerns that studies in individuals with dysphagia that also do not conduct detailed kinematic analyses of behaviors before, during and after training might have unintentional and undiscovered benefits beyond the primary goal of the treatment. Of course, there could also be detrimental outcomes that are both unintentional and undiscovered.

4.3. vLVC training altered LVCrt in only 5 ml swallows in both experiments

Outcomes from both experiments led to faster LVCrt in only the 5 ml swallows (water and barium), but not saliva or 10 ml water swallows. During pre-training swallowing, LVCrt was longer in 5 ml water swallows (0.21 s) than 10 ml water swallows (0.16 s) in participants in the Long-hold training and longer in 5 ml barium swallows (0.21 s) than saliva swallows (0.15 s) among participants in the Short-hold experiment. Previous studies of healthy adults report LVCrt ranges of approximately 0.19 s to 0.36 s in 5 ml water or thin liquid barium swallows [1,16,28]. The saliva and 10 ml swallows had particularly fast LVCrt. Thus, it is possible that LVCrt training effects differentially transferred to 5 ml swallows because the hastening of the LVCrt was physiologically possible whereas as a "ceiling effect" may have prevented transfer in saliva and 10 ml water swallows. It is unknown why two different types of 5 ml boluses (water, thin liquid barium) have longer LVCrt durations than saliva and 10 ml water swallows, however this warrants future studies into bolus type effects on airway protection reaction time. It is also possible that since some patients have delayed LVCrt that impacts swallowing safety [6,39], bolus type effects on transfer may be a smaller concern, as these patients may have much more for room for improvement.

4.4. Limitations and conclusions

The outcomes of this study are limited because they were conducted on healthy adults and results may not be immediately generalizable to individuals with swallowing impairments. Furthermore, the Long-hold training had fewer training trials than a typical rehabilitation swallowing training circumstance. It has been shown that modifying a motor plan might require an interval of at least 24 h to consolidation of underlying motor skills [31,40]. This study is also limited because both experiments were designed to test the immediate effects of vLVC training. Overall, we report small but consistent effects on LVCrt. Because LVCrt is a very short swallowing event, a 1–2 frame reduction is approximately 20–24% earlier airway closure, which can be enough time to prevent aspiration. Still, increased clinical significance might be demonstrated in future studies with longer periods of vLVC training, especially among patients who have prolonged LVCrt and greater improvements to be gained. Future studies should employ long-term study designs to determine whether swallowing behavioral trainings can have long-lasting effects on functional swallowing in patients.

We have shown initial evidence that training a LVC-focused swallowing maneuver can lead to transfer of practiced behaviors to functional swallowing during the post-training period. This is an important first step, given concerns that dysphagia therapies have minimal effects on swallowing behaviors [9]. Future studies on vLVC training and other swallowing maneuvers should conduct detailed swallowing kinematic analyses of swallowing function before, during, and after training to identify training effects that were expected and unexpected, as well as beneficial and detrimental. This will help to bolster the importance of dysphagia management in medical settings.

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