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Human hyo-laryngeal movements show adaptive motor learning during swallowing

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Abstract

The hyoid bone and larynx elevate to protect the airway during swallowing. However, it is unknown whether hyo-laryngeal movements during swallowing can adjust and adapt to predict the presence of a persistent perturbation in a feed-forward manner (adaptive motor learning). We investigated adaptive motor learning in nine healthy adults. Electrical stimulation was administered to the anterior neck to reduce hyo-laryngeal elevation, requiring more strength to swallow during the perturbation period of this study. We assessed peak hyoid bone and laryngeal movements using videofluoroscopy across 35 5ml-water swallows. Evidence of adaptive motor learning of hyo-laryngeal movements was found when: (1) participants showed systematic, gradual increases in elevation against the force of electrical stimulation, and; (2) hyo-laryngeal elevation overshoot the baseline (pre-perturbation) range of motion, showing behavioral after-effects, when the perturbation was unexpectedly removed. Hyolaryngeal kinematics demonstrate adaptive, error-reducing movements in the presence of changing and unexpected demands. This is significant because individuals with dysphagia often aspirate due to disordered hyo-laryngeal movements. Thus, if rapid motor learning is accessible during swallowing in healthy adults, patients may be taught to predict the presence of perturbations and reduce errors in swallowing before they occur.

Keywords

deglutition; adaptation; larynx; deglutition disorders

INTRODUCTION

One of the principal biological functions of the hyoid bone and larynx (hyo-larynx) is to protect the airway during swallowing. These structures elevate with precise timing to avoid aspiration (ingested material in the airway below the vocal folds)[1]. The initiation, duration and extent of hyo-laryngeal elevation depend heavily upon the properties of the bolus that is

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being swallowed[2]. However, it is not clear how learning can occur in swallowing based on perturbations that are not bolus-dependent in adults.

Adaptation learning is a form of motor learning that takes place in a short time scale (i.e. minutes to hours) and involves adjusting movements through a trial-and-error manner in the presence of new demands. During adaptation, the brain makes gradual, but quick, calibrations to predict the consequences of movements to prevent or reduce errors before they occur[3].

An example of adaptation learning, also known as error-based learning, is described in Figure 1. In this example the task requires a subject to lift a barbell to shoulder-height over several trials where new demands in the weight of the barbell are introduced throughout three consecutive phases, including (1) pre-perturbation (5lb); (2) perturbation (15lb) with an unexpected catch trial (5lb), and; (3) post-perturbation (5lb).

During the pre-perturbation phase, the subject would establish a baseline by lifting a 5lb weight to shoulder-height with accuracy over several trials. Then, for the perturbation phase, the barbell weight would be unexpectedly increased to 15lb, causing the subject to undershoot the target at the start of the perturbation phase. However, the subject should overcome the perturbation effect overtime with trial-by-trial increases in strength to reach the shoulder-height target with the 15lb weight. In other words, we would expect to see the subject make gradual gains to systematically reduce errors and reach the target (attempt to return toward baseline) over several trials. After these systematic gains have been made and maintained, they are tested with a catch trial by unexpectedly reducing the weight to 5lb for one trial in the midst of the perturbation phase. As a result of this catch trial, we would anticipate that the subject would overshoot the shoulder-height target (after-effect showing feed-forward adaptation), and thus the baseline pre-perturbation level, since they were planning to lift a 15lb weight. Finally, the post-perturbation phase would involve an unexpected shift in barbell weight back to 5lb. Since the subject was not expecting this weight decrease, we would expect that the barbell would again be lifted beyond the shoulder height as in the catch trial.

Thus, adaptation learning is evident during consistent perturbation by making gradual gains over several trials to overcome the effects of the perturbation by attempting to reach the baseline level. Adaptation learning is also evident in after-effects when unexpected perturbation removal occurs during the catch trial and the post-perturbation period, demonstrated by overshooting the baseline or target. In both cases, subjects are engaged in learning as they attempt to predict and overcome movement errors before they occur. This type of error-based learning is a robust, well studied phenomenon seen in different motor behaviors with the cerebellum as one of the critical neural substrates[4–8].

Error-based learning during swallowing has not been investigated, despite its potential to elucidate the mechanisms that healthy adults use to overcome occasional aspiration, penetration or other errors in swallowing. If it is determined that error-based learning is possible during some aspect of normal swallowing, this new knowledge can be applied to dysphagic individuals who might be able to re-gain these error-avoiding skills that were present before dysphagia began. Thus, the goal of this investigation was to determine whether hyo-laryngeal movements have the ability to undergo similar error-based, adaptive motor learning during swallowing, which has not previously been shown. We hypothesized that hyo-laryngeal movements would show evidence of adaptation in two ways, including: (1) the presence of systematic error reduction to attempt to return toward baseline performance over the perturbation phase, shown by gradually increasing hyo-laryngeal elevation, and; (2) the presence of after-effects that overshoot the baseline when the

perturbation is unexpectedly removed during catch trials or the post-perturbation period. Understanding this basic form of motor learning is significant for swallowing because swallowing impairment (dysphagia) can result from abnormalities of hyo-laryngeal movements and lead to aspiration, malnutrition, dehydration, or death.

MATERIALS AND METHODS

Ethical Approval and Participants

This study included 9 healthy adults (mean age 24.1; 4 females) with no history of neurological disease, speech or swallowing impairment, chronic medical condition, or contraindications to surface electrical stimulation or ingestion of barium. All participants signed written informed consents to participate in the study, which was approved by the Institutional Review Board.

Procedures

Videofluoroscopy—We used videofluoroscopy to image hyo-laryngeal movement, a radiographic technique that allows imaging and analysis of swallowing kinematics. We obtained full resolution fluoroscopic digital images in real time (30 frames per second) in the lateral plane. The image intensifier was focused on the oral cavity, the posterior pharyngeal wall, and just below the upper esophageal sphincter in the lateral plane. A time-stamp was superimposed onto images as a unique identifier of each frame.

Electrical stimulation—Previous studies have shown that surface electrical stimulation reduces peak hyo-laryngeal elevation when applied to the anterior neck at an intensity that causes muscle contractions (sensory-motor level), lending itself well to the perturbation of these hyo-laryngeal movements[9, 10]. In this study, surface electrical stimulation (Ministim®, Life-Tech Inc.) was administered to the anterior neck on the skin overlying the infrahyoid muscles (omohyoid, sternohyoid, sternothyroid, and thyrohyoid) to either depress the hyoid bone and larynx (sensorymotor stimulation) or to stimulate the cutaneous afferents in this area (sensory-only stimulation) (Figure 2A). When stimulating with surface electrodes, the electrical current is strongest in superficial tissues near the electrodes and weakest in deeper tissues. This means that lower intensities can stimulate the sensory nerves of the skin in isolation (sensory-only), but higher levels will stimulate both skin and muscle (sensory-motor). We manipulate these levels of stimulation in our study design in an attempt to diminish distinctions between the presence and absence of the perturbing force of electrical stimulation at the sensory-motor level throughout the study.

Thus, *no perturbation* is defined as swallows with low, sensory-only stimulation that does not resist hyo-laryngeal elevation, while *perturbation* is defined as swallows with high, sensory-motor stimulation that resists hyo-laryngeal elevation. This means that participants will experience the tingly sensation of electrical stimulation throughout the examination during both the no-perturbation and perturbation periods.

To confirm the presence of stimulation during the study, EMG artifact recording from muscles under the chin were monitored for each swallow. Using EMG, we could also differentiate between higher (sensory-motor) and lower (sensory-only) stimulation levels for post data analysis. The sensory-motor and sensory-only intensity levels were determined on a subject-by-subject basis. The sensory-motor level was obtained by gradually increasing the amplitude to the highest level that could be tolerated without pain, inducing hyo-laryngeal depression seen with videofluoroscopic imaging during simulation at rest. The sensory-only level was determined by stimulating at a low level where the participant reported a tingly sensation, but no feeling of muscle contraction was reported. This sensory-only level was

subsequently confirmed when no hyo-laryngeal movement was observed with stimulation at rest during videofluoroscopy.

Study design (Figure 2B)

We characterized adaptation by determining: (a) gradual increases in hyo-laryngeal elevation during the presence of a consistent perturbation showing systematic error-reduction, and; (b) the presence of after-effects when the perturbation is unexpectedly removed, resulting in hyo-laryngeal elevation that overshoots the baseline levels. Each session included 35, verbally cued swallows. The inter-swallow intervals were approximately 10 seconds in duration across the whole study and all participants were naive to the study design. To elicit and standardize volitional swallowing, 5ml of water was infused to the front of each participant's mouth with a small plastic tube that did not interfere with oropharyngeal swallowing. This study included three phases, which were preperturbation (5 swallows), perturbation (26 swallows) and post-perturbation (5 swallows).

Pre-perturbation—The 5 swallows of the pre-perturbation period had concurrent sensory-only stimulation. The sensory-only stimulation was necessary to keep the sensory cues constant throughout the various phases of the examination. This way, when the perturbation period began, at the higher sensory-motor level, it was detectable only due to sudden resistance to hyo-laryngeal elevation and not because of the tingly sensation of the cutaneous afferents that precedes muscle contraction.

Perturbation—The perturbation phase immediately followed and included 26 swallows in the following sequence: 18 perturbed swallows with sensory-motor stimulation (perturbation block 1), 1 catch trial with sensory-only stimulation (no perturbation), then 7 additional perturbed swallows with sensory-motor stimulation (perturbation block 2).

Post-perturbation—In the post-perturbation phase, participants performed another 5 swallows with an unexpected return to sensory-only stimulation (no perturbation).

Kinematic Analysis

The investigators performing the kinematic analyses were blinded to the perturbation type. Data analysis included peak extent of movement of the hyoid bone and the larynx independently. All videofluoroscopic recordings were digitized using Peak Motus (ViconPeak, Centennial, CO 80112) version 9 for kinematic analysis. The following points were located on each frame: the superior/posterior aspect of the subglottal air column (y-axis) to measure the position of the larynx and the anterior/inferior most point of the hyoid bone (y-axis) (Figure 2C). First, peak vertical hyoid movements (HY) and laryngeal vertical movements (LY) were determined relative to the C5 vertebrae, which served as a stable reference point[10]. Therefore, the peak hyo-laryngeal measures in this study were described as elevation relative to the C5 level in mm. Then, all peak measures derived were scaled, ranging from 0 (lowest among 35 swallows) to 1 (highest among 35 swallows) individually for each participant. This was needed to adjust for individual differences in range of hyolaryngeal movement during swallowing that might exacerbate the variance. The fifth cervical vertebra was also used to adjust for any whole body movement during swallowing.

Data Analysis

In this study we aimed to determine whether hyo-laryngeal movements adapt to perturbations in two ways. First, we determined whether adaptation occurred during the perturbation phase (perturbation block 1), demonstrated by a systematic increase in peak

hyo-laryngeal movements to overcome the perturbation effect and attempt to return toward pre-perturbation or baseline levels. Second, feed-forward adaptation was defined as the presence of an after-effect in the catch trial and post-perturbation period.

Statistical Analysis—Statistical testing was done using a repeated measures mixed model ANOVA (repeated variable – subject; fixed variable – swallow phase, i.e. pre-perturbation, perturbation, catch trial, post-perturbation) for peak range of motion of the larynx and hyoid (LY and HY). When swallow phase differences were significant, to test our two main hypotheses, post hoc comparisons of the mean changes between different swallows were conducted with a two-sample t-test assuming unequal variances, including a Bonferroni corrected alpha threshold of $p=0.025$ to adjust for multiple comparisons.

Comparisons (Figure 2B)—To test whether adaptation occurred within perturbation block 1, we compared the peak range of motion between the mean of the first three and last three swallows. To test for after-effects, we compared the mean peak range of motion of the 5 pre-perturbation (baseline) swallows to the catch trial and to the first swallow of the post-perturbation period, independently. If the peak ROM was significantly higher than the pre-perturbation mean, then feed-forward adaptive motor learning was assumed[3].

One additional two-sample t-test was conducted to test the perturbation effect of sensory-motor electrical stimulation on hyo-laryngeal elevation for a significant reduction in peak elevation in swallows at the start of the perturbation block. So, we compared the mean of the pre-perturbation swallows to the first two swallows in perturbation block 1.

To test the reliability of our peak range of motion measurements, intra-class correlation coefficients (ICC) were computed on 10% of the data. The ICC represents the proportion of total variation (between-subject variability and measurement variability) that may be attributed to between-subject variability. Values near 1 suggest nearly all variability is essentially biological, whereas values near 0 indicate that variability is primarily a result of measurement problems.

RESULTS

All participants tolerated the procedures well. There were no dropouts or adverse events. ICC for the peak ROM measures was excellent at 0.99.

Perturbation effect

The presence of surface electrical stimulation at the sensory-motor intensity level resulted in clearly perturbed hyo-laryngeal movements. This was evident by significantly reduced peak hyoid and laryngeal elevation (HY and LY $p<0.0001$) at the onset of perturbation block 1 (Figure 3).

Evidence of adaptation learning

There was a significant difference among the phases of the experiment for hyoid bone and laryngeal elevation (ANOVA_{RM}: HY and LY $p<0.0001$, $df=47$). During the perturbation period, a systematic return toward the pre-perturbation (baseline) peak range of motion levels was evident (Figure 3) within perturbation block 1. This was seen by significantly lower peak elevation at the start compared to the end of perturbation block 1 (HY $p<0.0002$ and LY $p<0.003$). Also, significant adaptation after-effects were found, where peak elevation for the catch trial was significantly higher than the pre-perturbation baseline means (catch trial overshooting the pre-perturbation period), revealing the presence of error-based, feed-forward adaptive movements (HY $p=0.025$; LY $p=0.018$). No after-effects were found

for the first swallow of the post-perturbation period for hyoid elevation ($p=0.24$) and marginal after-effects were found with laryngeal overshoot ($p=0.079$). This likely occurred because there were fewer perturbed swallows during perturbation block 2 (before the post-perturbation swallows) allowing less time to maintain the same level of resistance against the perturbation before it was unexpectedly removed.

DISCUSSION

This study shows evidence, for the first time, of adaptive motor learning of hyoid bone and laryngeal movements in healthy adults during swallowing.

Adaptive motor learning occurs when a perturbation interferes with successful completion of a task resulting in movements that attempt to compensate for the effect of the perturbation[11]. In other words, adaptation occurs when perturbed movements attempt to return toward baseline performance levels during a period of consistent perturbation. This is also evident by the presence of after-effects, such as movements in the opposite direction of the perturbation when the demand is suddenly removed[12]. In adaptation learning, new demands require gradual adjustments in a short time scale.

In our experimental paradigm, healthy participants swallowed against continuous hyo-laryngeal resistance and their performance gradually moved toward baseline. This shows that in the presence of stable, predictable demands, it is possible to gradually and quickly calibrate hyo-laryngeal movements to overcome errors. Although some adaptation gains were temporarily lost in the initial trials in perturbation block two, immediately after the catch trial, this is a common phenomenon in motor adaptation studies[8, 11, 13].

Participants in our study demonstrated an after-effect with higher peak range of motion compared to their pre-perturbation performances during the catch trials. This occurred because they were trying to compensate for the expected resistance to laryngeal-elevation that, in reality, was not present. No significant after-effects were found for the first swallow of the post-perturbation period for either hyoid or laryngeal peak elevation. This suggests that the number of perturbation trials or the temporal duration of the perturbation might impact the magnitude of the after-effect in our study. Perturbation periods are known to affect catch trials in some cases [14–18], but not others [19] and may be a function of the type of perturbation, the motor task, and whether the task tends to be fast- or slow-adapting in nature.

To our knowledge, only one previous study has investigated the effects of non-bolus related perturbations on learning for hyo-laryngeal movement. Burnett et al (2005) instructed healthy participants to self-trigger electrical stimulation of the hyoid and laryngeal elevator muscles during volitional swallowing. After 9 to 13 successfully self-stimulated swallows, the final attempt was an unexpected sham trial where the participants attempted to self-trigger, but no current was delivered (foil). In the Burnett study, no after-effects of hyo-laryngeal movement were observed with the foil swallow, as pointed out by the authors, possibly because the self-triggered, stimulated swallows did not induce errors during swallowing[20].

Adaptation learning is known to occur in other areas of oropharyngeal function besides swallowing, such as speech. In speech, adaptation learning can occur following the placement of an orthodontic appliance or oral dental plate [21]. The device that is inserted into the oral cavity lowers the palate. In response, tongue movements are initially not accurate for speech. Adaptation learning occurs when individuals quickly adjust tongue movements so that speech perception returns to normal. Following removal of the device, however, tongue movements are no longer sufficient because the participants have learned

to accommodate to the oral device. De-adaptation quickly occurs so that speech is again accurate without the device in place. Speech relies on the same anatomical substrates as swallowing [22–24], yet differences in central neurological processing are likely considerable [24]. Therefore, understanding motor control for swallowing, in particular, is important.

Conclusions

Our study shows evidence of adaptive motor learning of hyo-laryngeal movements during swallowing. Our data are limited to hyo-laryngeal peak elevation with surface electrical stimulation perturbations. Other studies are needed to determine whether other structures (i.e. tongue, pharynx) can show similar behaviors with other forms of perturbations. However, our findings are important because the pharyngeal phase of swallowing involves a stereotypical cascade of events with the overall goal of moving ingested material into the esophagus without invading the airway. We have shown that this rapid form of motor learning is accessible during events of the pharyngeal swallow in healthy adults, therefore patients may be taught (implicitly or explicitly) to predict the presence of perturbations (i.e. weakness or fatigue) so that they may reduce biomechanical errors that lead to penetration or aspiration. As such, exploiting training protocols that follow motor learning principles may be useful for treating dysphagia.

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Adaptation learning example

Figure 1.

Adaptive learning example showing a typical study design used to explore evidence of adaptation in a resistance task of lifting a barbell to a shoulder-height target level in the presence of ongoing perturbations. Participants are not expecting the onset of the perturbation, the catch trial, or the onset of the post-perturbation swallows. (image: <http://fitnessanddefense.com/upright-rows/>)

A. Electrode Placement

B. Study Design and Comparisons

C. Kinematic Measures

Comparisons

To test gains during perturbation: B versus C

To test after-effects: A versus D; A versus E

Figure 2.

(A) Schematic of the electrode placement on the anterior neck relative the hyoid bone (h.b.) and larynx (t.c. - thyroid cartilage; c.c - cricoid cartilage) that was used to elicit hyo-laryngeal descent. The horizontal arrow indicates the direction of the stimulating current between the surface electrodes. (B) Schematic of study design over 35 5ml-water swallows. Shaded regions denote stimulation intensities: sensory-only (light gray) and sensory-motor (dark gray), that was continuously administered over the course of the study. Comparisons used to test our two hypotheses are shown visually. (C) Schematic of kinematic measures showing the points on hyoid bone (h.b.) and laryngeal structures for range of motion measures as well as the cervical vertebra as the reference point.

Figure 3.

These data show group means of peak elevation of the hyoid bone (HY) and larynx (LY) across swallows in the pre-perturbation phase (mean of 5 swallows shown), perturbation block 1, catch trial (CT), perturbation block 2, then post-perturbation phase (X-axis). Y-axis: scaled ROM derived from raw mm data, scaled from lowest peak measure (zero) to highest peak measure (1).