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Effect of biofeedback and exercise type on neural swallowing control

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Effect of Biofeedback and Exercise Type on Neural Swallowing Control

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EFFECT OF BIOFEEDBACK AND EXERCISE TYPE ON SWALLOWING

Effect of Biofeedback and Exercise Type on Neural Swallowing Control

An Honors Program Project Presented to
the Faculty of the Undergraduate
College of Health and Behavioral Studies
James Madison University

By: Rachel Joy Rinehart

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Accepted by the faculty of the Department of Communication Sciences and Disorders, James Madison University, in partial fulfillment of the requirements for the Honors Program.

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PUBLIC PRESENTATION

This work is accepted for presentation, in part or in full, at the JMU Honors Symposium on December 2, 2016.

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Abstract

The clinical efficacy of swallowing exercises is well established in swallowing literature, and biofeedback has been shown to augment cortical hemodynamic response (HDR) during normal swallowing. This study compared HDR during swallowing exercises with and without biofeedback to HDR during normal swallows with and without biofeedback. Healthy adult participants ($n=6$, mean age=50.83 male=2) were recruited and trained on the following conditions: normal swallowing, swallowing exercise in which a specific physiological target was given (skilled), and swallowing exercises in which no specific physiological target had to be achieved (unskilled). Biofeedback consisted of submental surface electromyography (sEMG) signals displayed visually. HDR were recorded using functional near infrared spectroscopy (fNIRS). Significantly increased early HDR amplitude in the biofeedback conditions was observed only in the cortical sensory areas ($p<.01$). Early response HDR amplitude in the premotor and motor regions were not significantly greater in the biofeedback conditions ($p=.07$ and $p=.61$, respectively). There was a significant difference between the HDR of normal swallows and skilled swallow exercises ($p<.05$), while the HDR difference between normal swallows and unskilled swallow exercises only approached significance ($p=.07$). However, there was not a significant difference between the two exercise types, ($p=.72$). Our findings indicate that visual biofeedback and skilled swallowing exercises increase the cortical HDR compared to normal swallowing.

Literature Review

Swallowing, or deglutition, is a complex process with four stages, each of which includes the involvement of all hierarchical levels of control in the brain, and the complementary function of many anatomical components of the respiratory, phonatory, articulatory, and alimentary systems. In their textbook, *Anatomy and Physiology for Speech, Language, and Hearing*, Seikel, King, and Drumright (2010) reviewed four stages that are commonly used to describe the normal swallowing process. The oral preparatory stage is the first stage, when the bolus, or food/liquid, is brought into the oral cavity and the enzymes in saliva work together with mastication to prepare the bolus for swallowing (Seikel et al, 2010). Labial closure and posterior elevation of the tongue are crucial during this stage to prevent premature bolus spillage. In the oral stage, the tongue transports the bolus posteriorly toward the pharynx through a process called oral transit (Seikel et al, 2010).

The pharyngeal stage of swallowing begins with the initiation of the pre-patterned swallow sequence. Sensory information coming from the afferent nerves in the tongue, lips, palate, velum, cheeks, and pharynx is continually incorporated into the motor plan so that the swallow sequence will be the most appropriate for the given bolus and adjusted for its texture, temperature, and size. During the swallow response, the hyolaryngeal complex is pulled up and forward in the neck, a process called excursion, and the bolus is propelled through the pharyngeal cavity and into the esophagus through the upper esophageal sphincter (UES). Excursion of the hyolaryngeal complex is a very important component of the swallow sequence because it facilitates closure of the airway and UES opening (Seikel et al, 2010). After bolus entrance into the esophagus, esophageal peristalsis squeezes the bolus down into the stomach,

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completing the esophageal stage (Seikel et al, 2010). The normal swallow is a complex process and is subject to compromise at any stage.

Disordered deglutition is called dysphagia. Groher and Crary (2010) refer to the umbrella term “dysphagia” as “a swallowing disorder that involves any one of the three stages of swallowing: oral, pharyngeal, or esophageal” (p. 2). More pointedly, several subcategories exist including oropharyngeal dysphagia, which refers to simultaneously disordered oral and pharyngeal stages and is the most common subgroup treated clinically by speech-language pathologists (Groher & Crary, 2010). There are two factors that are often used to help judge the efficiency of a swallow and determine whether it is dysphagic or not: speed/power of bolus propulsion and the bolus path. Both are directly affected by the movement of the anatomical components in the oral and pharyngeal cavities. In other words, changes in the movement pattern of pharyngeal and laryngeal anatomical components are responsible for changes in bolus flow. Reduced hyolaryngeal excursion, for example, results in limited airway closure and restricted UES opening, inhibiting the bolus from entering the esophagus and increasing the risk of it entering the larynx instead (Seikel et al, 2010).

Dysphagia is a secondary diagnosis as it is always a symptom resulting from an underlying condition. Diseases and disorders that affect the nervous and muscular systems, such as stroke, neurological disease, and head and neck cancer, can cause dysphagia. Stroke has a particularly high incidence of dysphagia, especially in the acute stage (Groher & Crary, 2010). A large number of these patients will go on to recover a normal swallow without intervention, but many would continue to have long-term dysphagia. Smithard et al (1996) found that of a group of 121 untreated stroke patients, 51% were determined to be at risk for aspiration directly

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after the stroke. This group was reduced to 27% at risk of aspiration after a week post-stroke, and further reduced to 6% at six months post-stroke. Early detection and rehabilitation are vital for maximizing swallow safety as dysphagia and the resulting aspiration puts patients at risk for aspiration pneumonia. Dysphagia can lead to malnutrition and dehydration as well as potentially reducing psychological and social well-being (Groher & Crary, 2010).

Rehabilitation of a dysphagic swallow is paramount both for the patients' safety and for their quality of life. Motor learning techniques have effectively been used in both sports medicine and occupational therapy contexts to improve patient performance (Breslin, 1996; Koegh & Hume, 2012). Although swallowing is typically a patterned sequence, conditions can be added that require not only modified motor output, but also greater attention and focus on the task. For example, a condition may call for alterations in swallow strength or length. According to Bastian (2008), the main idea of motor learning therapy is that when a particular condition is introduced and removed on a routine basis, two different motor schemas are formed. The condition can be either extrinsic or intrinsic, and when the condition is present, the motor plan alters the motor output based on the desired outcome. However, when the condition is absent, the motor plan defaults to its baseline normal schema. In this way, the brain does not have to engage in motor adaptation each time the condition is removed or replaced (Bastian, 2008). Often, the goal of the condition is to engage targeted muscles in repetitive work, thus increasing their strength. Improvements in muscle strength lead to greater motor output with less effort. Once the condition is removed and the baseline schema is again functioning, increased motor output will still be achieved because muscle strength improved.

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With swallowing, motor learning exercises like the Mendelsohn Maneuver or the effortful swallow are commonly used in therapy (Kahrilas et al, 1991). A new direction in swallowing rehabilitation research that has recently emerged is that of skill training. As Athukorala et al (2014) have noted, motor learning techniques can sometimes involve “a challenge component [which] requires an individual to problem-solve the movement during practice rather than memorizing the sequences of muscle/joint contractions” (p. 1375). Skill training is motor learning with these challenge components incorporated and, while it is relatively new to dysphagia research, skill training has been preliminarily linked with positive outcomes in swallowing literature (Athukorala et al, 2014; Crary, 1995). In contrast to unskilled motor learning exercises, skill training requires the patient to not only employ increased strength during exercise, but to plan and alter the precision and timing of motor movements.

Biofeedback is a tool that is used during skill training and swallowing treatment to help improve a dysphagic swallow, and it has a broad background of use in the medical setting. Frank et al (2010) have defined biofeedback as “a self-regulation technique through which patients learn to voluntarily control what were once thought to be involuntary body processes” adding that this is “for the purpose of improving physical, mental, emotional, and spiritual health” (p. 85). It provides information to individuals about what is going on in their bodies allowing their neural networks to alter the way in which their bodies behave. There are many different types of biofeedback including those of the visual, auditory, and tactile nature. Visual biofeedback, which is most commonly used, allows the patient to visualize what is going on physiologically within the body. An example of visual biofeedback is the graphical representation of heart rate (Frank et al, 2010). Often, visual biofeedback of what is happening with the patient in real time is paired with a sample of what would ideally be happening with the

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patient. By comparing the two illustrations side by side, patients can consciously alter their behavior to match the example more closely. An example of what this could look like is found in Figure 1. All four graphs in the figure measure the same factor, but the two on the right are labeled “bad” and the two on the left are labeled “good”. The former correspond to what an impaired output would be, and the latter correspond with the targets the individual receiving rehabilitation would be told to aim to make their output match.

With swallowing therapy, biofeedback often takes the form of surface electromyography (sEMG) that represents the movement of the hyolaryngeal complex during swallowing based on input coming from electrodes placed on the submental region. Figure 2 illustrates submental electrode placement that will allow the patient to visualize the muscle activity responsible for hyolaryngeal excursion. In this manner, the patient can visualize how much muscle contraction they are using to elevate their larynx during swallowing and compare it to a target. Figure 3 represents submental sEMG during swallowing with different skill-based targets, such as duration of muscle contraction and strength of muscle contraction. Much like with the use of biofeedback in other settings, patients can use the information presented to them visually to volitionally adjust these components of the swallow, as required by skill-based dysphagia exercises. Humbert (2012) has shown that use of biofeedback is indeed effective in developing better swallowing outcomes.

Research Aims

A relatively new area of research in the field is demonstrating and defining changes in swallow-related neural activity associated with the rehabilitation process. To date, no research has been published examining the effect of visual biofeedback on neural activity during swallowing maneuvers. The purpose of this study was to determine if visual swallowing biofeedback alters the cortical hemodynamic response (HDR) to swallowing in healthy participants. Participants were taught swallowing exercises in which a specific physiological target had to be achieved (skilled) and swallowing exercises in which no specific target was given, but the participant was asked to execute at “maximum strength” (unskilled). All exercises were presented both with and without visual biofeedback and compared to normal swallows with and without biofeedback (control). Simultaneous functional near infrared spectroscopy (fNIRS) allowed for continuous monitoring of cortical blood flow in regions of interest (ROI) that represents neural activity during the task. We hypothesized that the cortical activity during swallowing, or HDR, in healthy participants would be affected by the presence of visual biofeedback in that the amount of oxygenated blood would increase during the presence of biofeedback, indicating increased neural activity. Information gathered from this study may prove useful in determining best practices for therapy with the goal of improving swallowing outcomes for patients with dysphagia.

The following aims were addressed:

Determine how visual biofeedback alters the amplitude and timing of the cortical HDR to swallowing compared to no biofeedback as recorded by fNIRS channels.

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Hypothesis: fNIRS signals will indicate increased levels of blood oxygenation as well as an early peak time in visual biofeedback conditions compared to no biofeedback conditions because the biofeedback will elicit greater cortical control of the swallow.

Determine how skill level of swallowing exercises alters the amplitude of the cortical HDR to swallowing as recorded by fNIRS channels.

Hypothesis: fNIRS signals will indicate increased levels of blood oxygenation during swallowing exercises that require more skill because they require greater cortical control of the swallow compared to exercises that do not require skill.

Method

This study was approved by the James Madison University Internal Review Board (#16-0574). Healthy community members over the age of 20 were recruited for participation in this study through one or more of the following means: paper flyers, James Madison University bulk email, and word of mouth. Inclusion criteria mandated that the participants report no prior history of

- swallowing complaints or problems,
- brain injury or neurological disorders (including stroke),
- previous neck injury requiring treatment by a physician,
- head and neck cancer,
- chronic obstructive pulmonary disease, asthma or other respiratory disease,
- psychiatric disorder other than medically managed depression, or
- progressive neurodegenerative disorders, such as dementia, Parkinson's disease, multiple sclerosis, peripheral neuropathy, and amyotrophic lateral sclerosis.

Participants must also have had a score below 20 on the Reflux Symptom Index (RSI) to participate since a score of 20 or above may be indicative of reflux disease. Each participant was screened with the Mini-Mental State Exam (MMSE) and was required to score at least 26 to determine that the participant would have the ability to understand and follow directions involved in the study. Additionally, participants could not have open sores on the scalp near where fNIRS probes would be placed, nor could they have highly pigmented skin as such interferes with the wavelength transmission process in fNIRS. Vision impairment inhibiting ability to see a computer screen at 2-3 feet distance was also exclusionary. The Edinburgh

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Handedness Survey (EHS) was administered as part of the intake battery to provide additional context in case brain lateralization were to affect findings.

The instrumentation for the study included fNIRS using a TechEn Inc. CW6 model with a 50 Hz continuous sampling rate (Milford, MA). fNIRS is a non-invasive tool by which a series of laser emitters (much like a laser pointer) and detectors are secured to the scalp at strategic placements over ROIs, including premotor, motor, and sensory areas for swallowing bilaterally as seen in Figure 4. Scalp placement of the fNIRS probes was determined using Brainsight 2.0 software that allowed the investigators to map brain regions from the scalp based on retrofitting the participant's head to a stock brain MRI. In order to eliminate any risk of laser lights shining in anyone's eyes, they were not turned on until after they are attached to the scalp, and were turned off again before removal.

Respiratory inductive plethysmography (Ambulatory Monitoring, Inc., Ardsley, NY, model 10.9000) was used to record participant respiratory patterns throughout the experiment. This consists of stretchy mesh bands wrapped around the ribcage and abdomen that measure expansion/contraction of those areas associated with respiration to identify respiratory apneas, which often indicate swallow onset. Using medical tape, a piezoelectric accelerometer (Kistler Instrument Corporation, Amherst, NY, Model 8778A599) and sEMG electrodes (Teca electrodes; Nicolet Viking IV P) were fastened to the anterior of the participant's neck (level of the thyroid notch) and submental area respectively for the purpose of determining the patient's anatomical movements associated with swallowing. These signals were digitized and recorded with PowerLab 16/30 SP unit (AD Instruments, Colorado Springs, CO, model ML 880). The submental sEMG displayed on the computer monitor simultaneously and functioned as visual

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biofeedback of the swallow for the participant. A webcam captured video of the participant's neck for better visualization of the swallowing process, but did not include the participant's entire face. Finally, a water pump delivered 5 mL boluses of distilled water to the participant's mouth at a slow constant drip over 40 second periods.

The participants were trained to complete two swallowing maneuvers with visual biofeedback, the effortful swallow and Mendelsohn Maneuver both with specific and differing sEMG targets (skilled) and without specific targets (unskilled). Once the participant had executed the target maneuver correctly three to five times in a row, the biofeedback was removed and the participant was asked to again complete the maneuver three to five times correctly without visual biofeedback. Training of each maneuver was complete once the participant was able to execute three to five correct maneuvers in a row without the aid of biofeedback. Training of the average participant took an estimated 30 minutes total, and each condition was trained separately. Next, the participant would begin a series of recorded trials randomized for presence and absence of visual biofeedback and counterbalanced for swallow task. Therefore, there were three counter-balanced conditions: 1. Normal swallow with and without visual biofeedback; 2. Skilled exercises with and without visual biofeedback; 3. Unskilled exercises with and without visual biofeedback. Half of the swallows in each condition were paired with visual biofeedback and the other half were not, and the order in which they were presented was randomized. Specific visual cues indicating when the participant was to swallow and the swallow target were provided on a large computer screen placed directly in front of the participant. While the participant sat in a chair with head and neck supports, boluses of 5 mL were delivered to the participant's mouth using a water pump with tubing to reduce motion artifact caused by excessive head movement, as might happen during cup drinking. The participant then executed

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either one of the motor learning exercise they had previously been taught by the investigators or a normal swallow, depending on the protocol per trial. A detailed trial timeline can be found in Figure 5. There were 30 normal swallow trials, 60 skilled swallow exercise trials, and 60 unskilled swallow exercise trials. Trials were divided into five runs of 20 minutes and bathroom and rest breaks were offered between runs to help control for fatigue. Participants completed the study in the James Madison University Neural Bases of Communication and Swallowing Laboratory at the Department of Communication Sciences and Disorders, and the time commitment for the participant was about 3.5-4 hours and varied slightly for each participant depending on frequency and length of breaks.

Analysis

All swallowing physiological data and the webcam were recorded and analyzed within Labchart software (AD Instruments, Inc.), and fNIRS signals were recorded within the Homer2 software (D. Boas, Harvard). The swallow times were marked within Labchart based on the context provided by webcam, Respiratory inductive plethysmography, accelerometer, and sEMG signals. Swallow times in Labchart were time synchronized with the hemodynamic signal in Homer2. The raw fNIRS signal was high pass filtered at .01 μM and low pass filtered at .5 μM , then corrected for motion artifact using a correlation based algorithm filter (Cui et al, 2010). Post-processing, the investigators visually inspected the hemodynamic signals to manually eliminate signal times with significant motion artifact. Signals were averaged across -5 to 35 seconds from swallow onset for each condition and analyzed for early response amplitudes/times (2-10 seconds post-swallow) and late response amplitudes/times (10-30 seconds post-swallow). Statistical analysis was completed with Statistical Package for Social Sciences (SPSS, v.23). The hemodynamic signals were analyzed for peak amplitude and time of peak amplitude. Paired *t* tests were used to examine differences in peak amplitude between normal swallowing, skilled and unskilled exercise conditions. Paired *t* tests were also used to compare peak HDR amplitudes and time of amplitudes in biofeedback conditions with the no biofeedback conditions both within and across ROIs.

Results

Six participants were included in this study (mean age=50.83 male=2). As previously stated, we hypothesized that increased levels of blood oxygenation would be indicated by greater HDR amplitude in fNIRS signals during visual biofeedback conditions compared to no biofeedback conditions. Confirming our hypothesis, significantly larger HDR amplitude peaks were observed in swallows with visual biofeedback compared to swallows with no biofeedback in the early initial HDR peak ($t(5)=2.65, p<.05$). This difference was not seen in the late HDR response ($t(5)=1.9, p=.11$) though. Figure 6 features the mean change in oxygenated hemoglobin over time for biofeedback swallows and non-biofeedback swallows, and the relationship between the two. Post-hoc tests indicate the increased early HDR amplitude in the biofeedback conditions are only significant in the cortical sensory regions ($t(5)=4.05, p<.01$). Early response in the premotor and motor regions were not significantly greater in the biofeedback conditions ($t(5)= 2.21, p=.07$ and $t(5)=.55, p=.61$, respectively). Figure 7 illustrates this relationship between the amplitude of the HDR to swallowing with biofeedback and no biofeedback in the different cortical regions. Time to peak between biofeedback and no biofeedback conditions was not statistically significant ($t(5)=-1.5, p=.19$). The second hypothesis that fNIRS signals would indicate increased levels of blood oxygenation with swallowing exercises was also partially supported by our findings. There was a significant difference between the HDR of normal swallows and skilled swallow exercises ($t(5)=-2.9, p<.05$), but there was no difference between the HDR of normal swallows and unskilled swallow exercises ($t(5)=-2.31, p=0.07$) nor between the two exercise types ($t(5)=-.38, p=0.72$) as can be seen in Figure 8.

Discussion

As the results indicate, some of the findings match the stated hypotheses and others were a bit more surprising. Visual biofeedback did alter the amplitude of the early HDR, possibly because biofeedback elicited greater cortical control of the swallow, although this effect was not seen in the late HDR. It was not anticipated that the cortical sensory regions would be primarily responsible for this increase in cortical response. This result is of particular interest when considering that cortical sensory areas examined in this study do not process visual stimuli, but rather somatosensory information from the oropharyngeal structures. As the visual cortex is located in the occipital lobe in the posterior brain region, it is distal to regions from which we recorded. Any increase in the amplitude of the HDR in the sensory regions, as was observed in the early biofeedback conditions, would be reflective of greater sensory input from the afferent neurons in the mouth, tongue, pharynx and larynx. Consequently, these findings may suggest that visual biofeedback was responsible for increasing the cortical processing of sensation occurring in the participants' mouths and throats during the swallows.

sEMG visual representation of the muscle activity may have caused the participants to mentally focus more on the sensation of swallowing. However, since sensory feedback is an integral component of the motor act of swallowing, it would be logical to expect an increase in motor HDR as well. Any number of factors, including the small participant pool, could have contributed to the nonsignificant findings in premotor and motor regions for the biofeedback effect. It is also possible that participants' exposure to the visual biofeedback was too randomized, and the cortex may not have had the opportunity to fully adapt to it. There is the

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potential that with longer exposure to continuous biofeedback, we would have been able to detect an increase in motor and premotor HDR amplitude.

When examining exercise type, it was hypothesized that HDR amplitude during skilled swallowing exercises would be increased from that of normal swallows and unskilled swallow exercises. Our results indicated that skilled exercises did increase cortical response compared to normal swallows, while unskilled exercises approached significance when compared to normal swallows, possibly indicating that any swallowing exercise will improve cortical response over a normal swallow. Although giving clinical patients skilled swallow targets is not yet fully integrated into evidence-based practice, some preliminary research (Athukorala et al, 2014) indicates it may be beneficial in some patients. No significance was found for time to peak of HDR in relation to skill level. Similar to the biofeedback findings, these results could likely be attributed, at least in part, to the small sample size.

Conclusion

In conclusion, this study supported the efficacy of biofeedback as an effective swallowing therapy technique as it improves cortical HDR amplitude in sensory regions. This is a pilot project with a small sample size that calls for more research about biofeedback's effect on motor and premotor ROIs. The role of swallowing exercises in increasing the amplitude of HDR across sensory, motor, and premotor ROIs was confirmed by this study, but it failed to show any difference between skilled and unskilled swallow exercise types. Additional studies are needed to explore the neural and physiological benefits of various motor learning paradigms, especially the element of skill training. As the field of dysphagia research learns more about this emerging area of study, we will be able to continue refining our knowledge base and, consequently, make improvements to clinical practice and patient quality of care.

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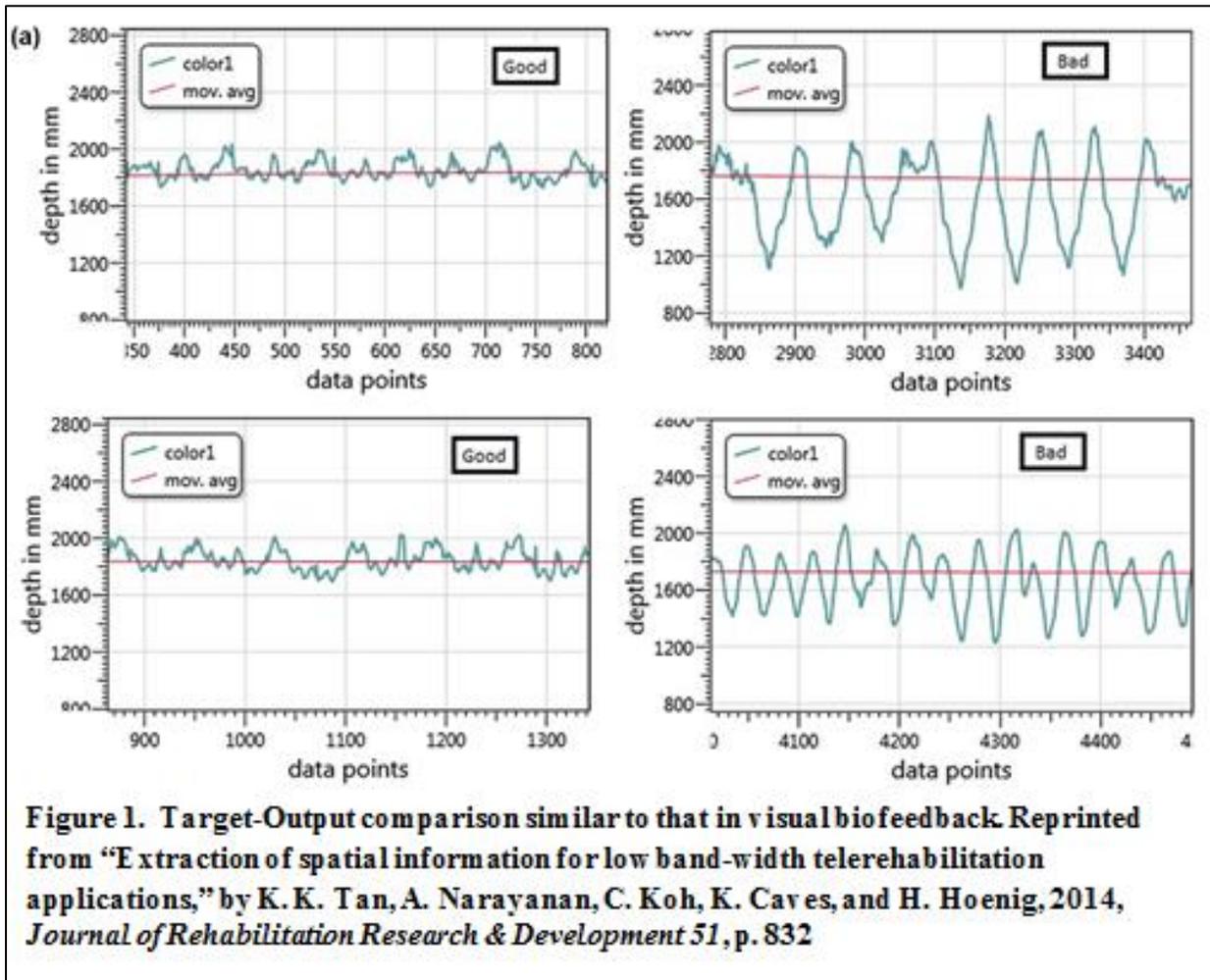
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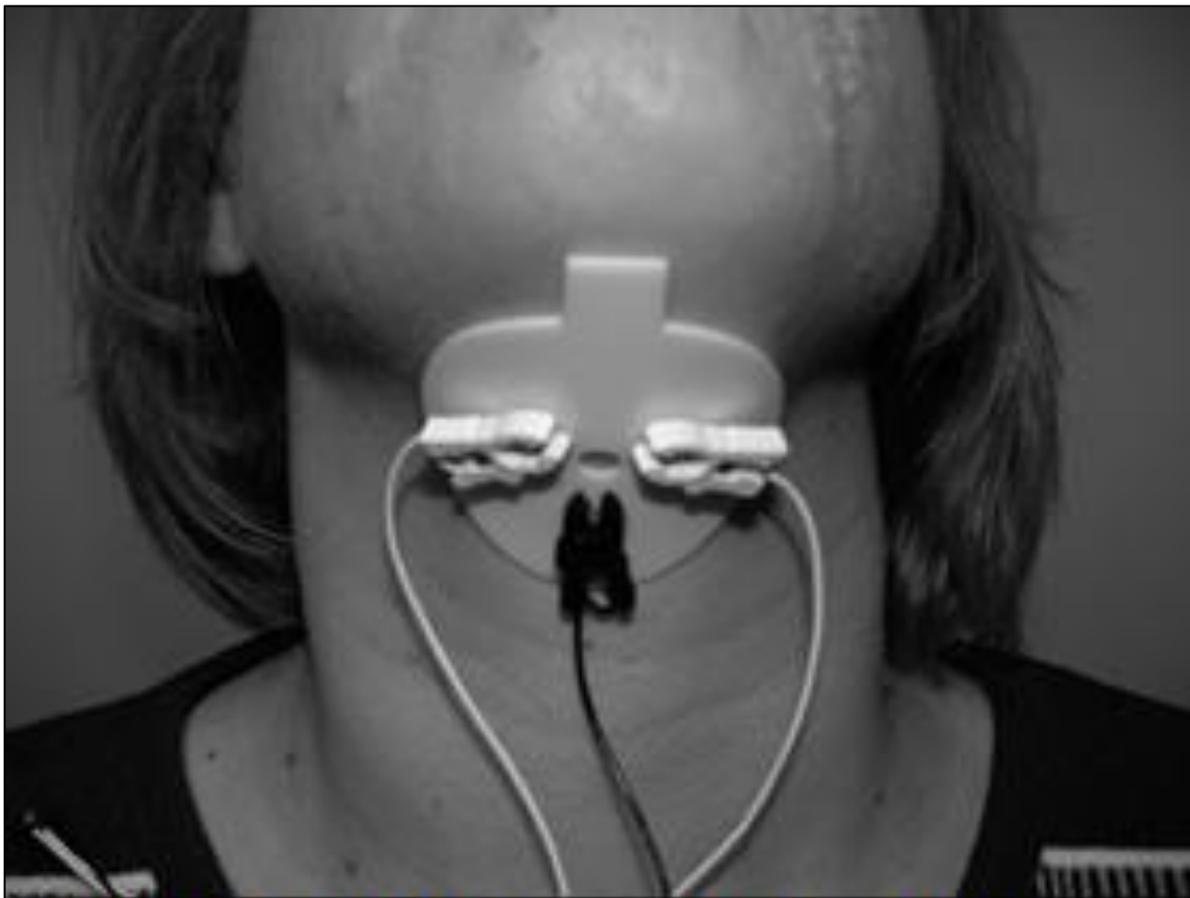
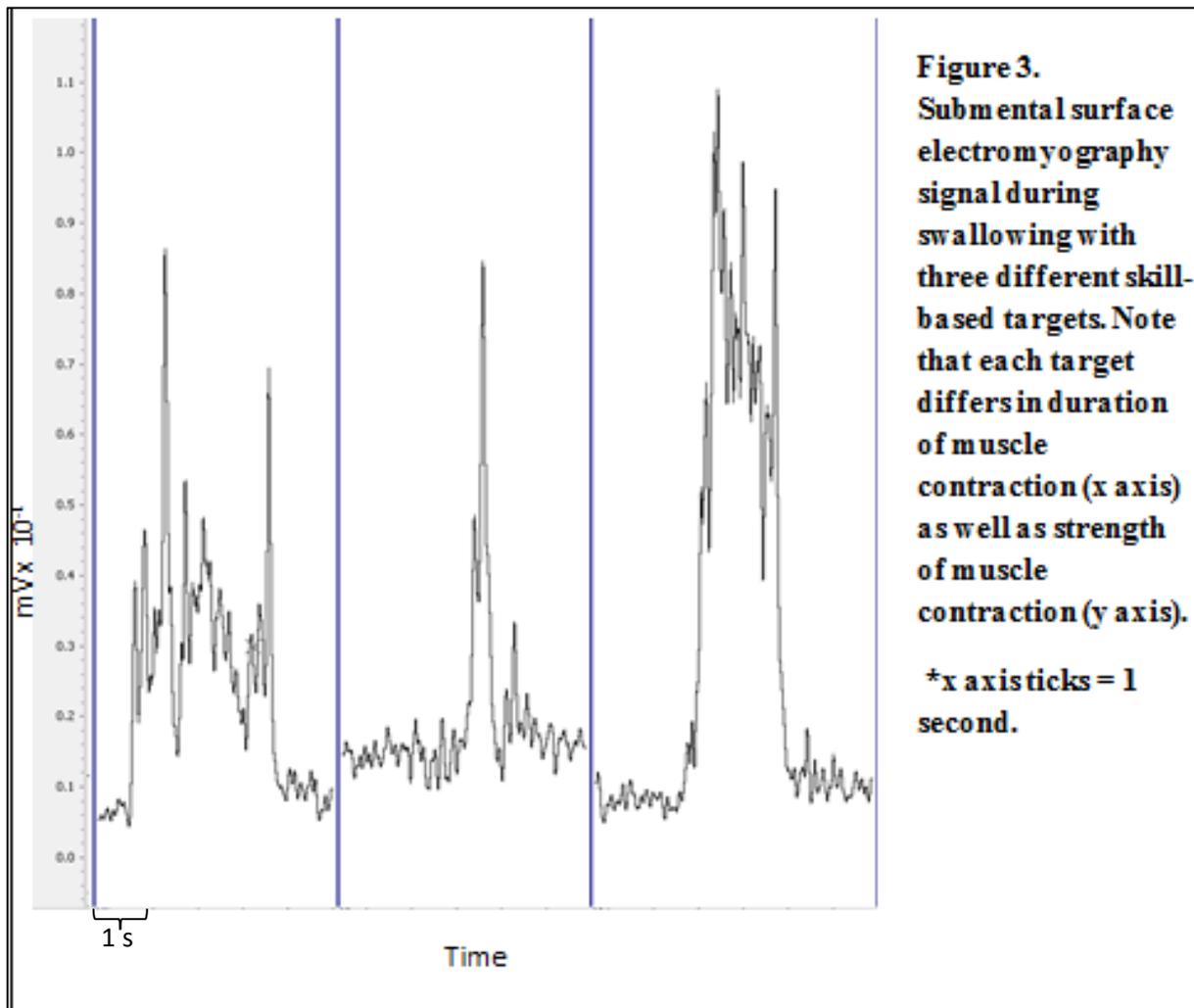
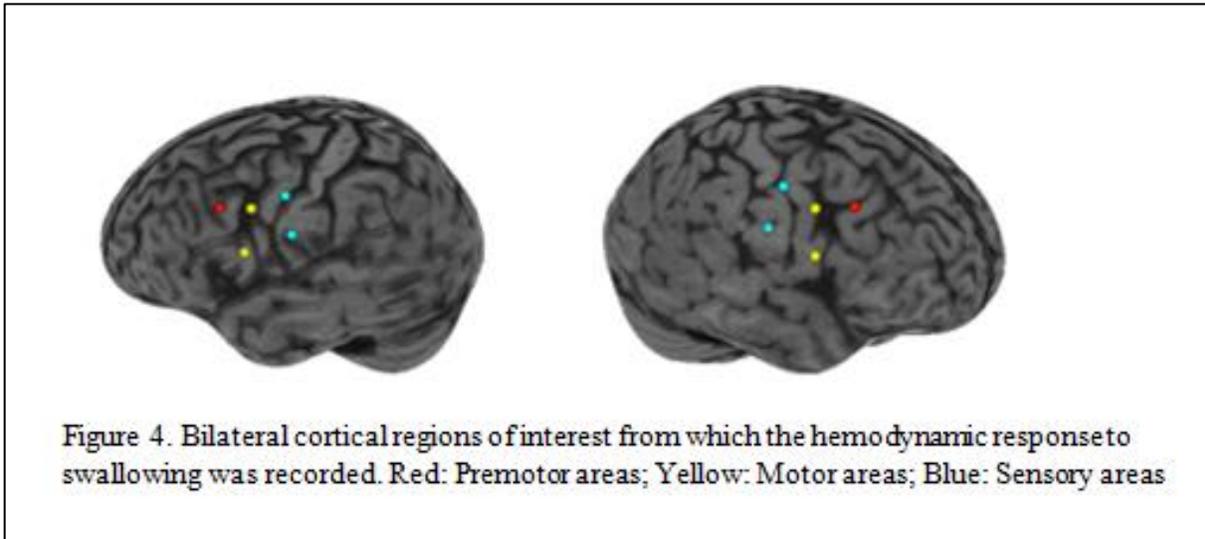


Figure 2. Submental electrode placement.
Reprinted from “Biomedical correlates of surface electromyography signals obtained during swallowing by healthy adults,” by M. A. Crary, G. D. Carnaby Mann, and M. E. Groher, 2006, *Journal of Speech, Language, and Hearing Research* 49, p. 189

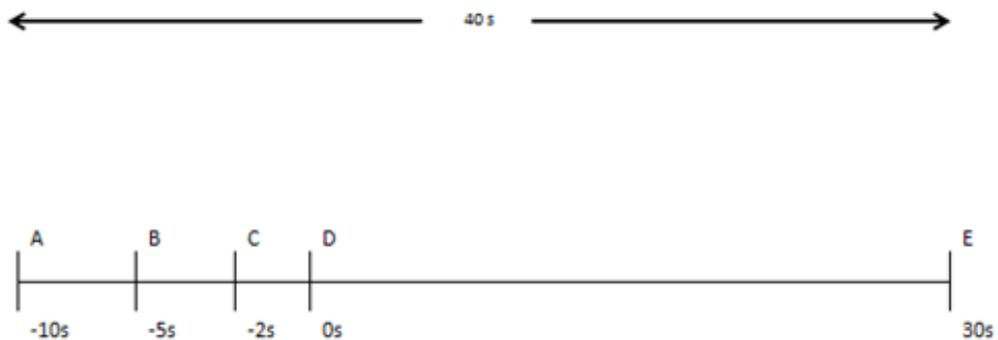


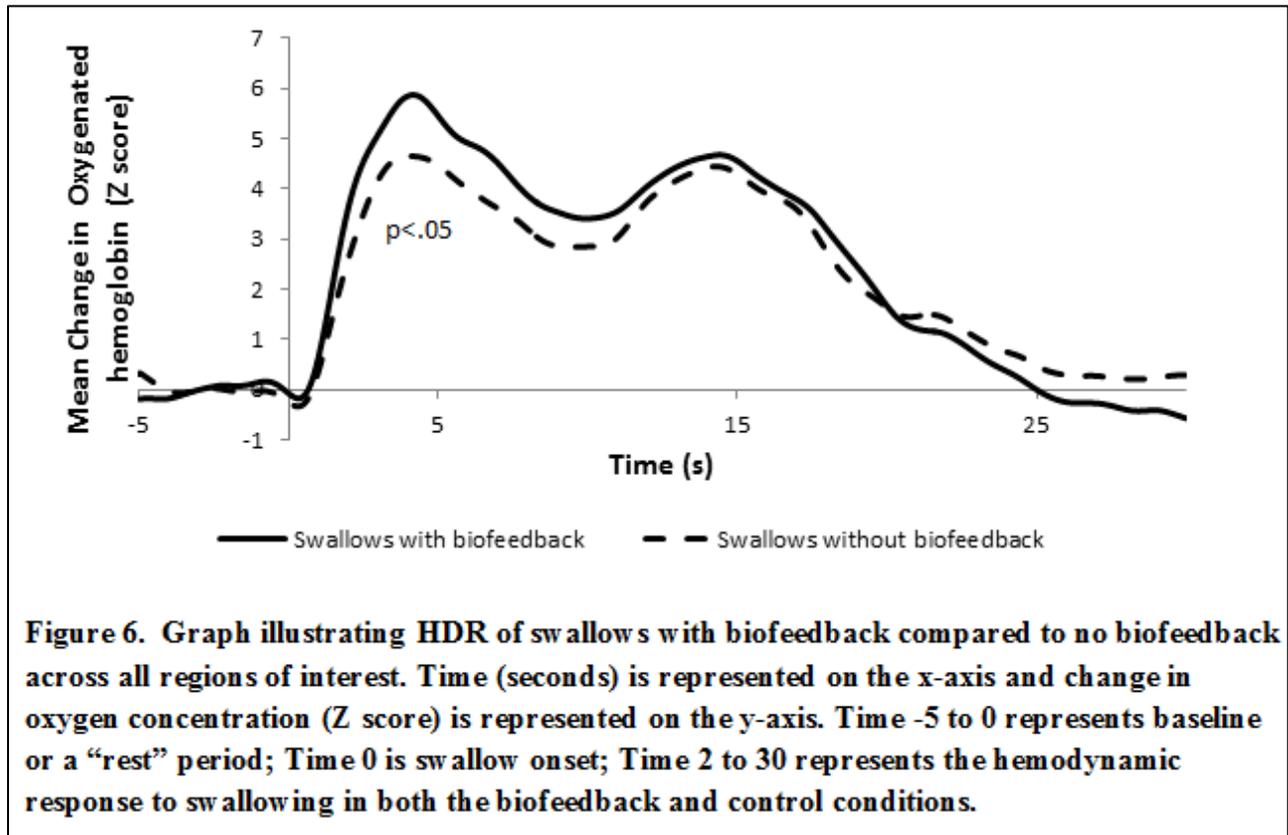


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Figure 5.

- Time A: Trial begins with the participant sitting still and fNIRS recording.
- Time A-Time B: Hemodynamic baseline is observed.
- Time B-Time C: Bolus introduction
- Time C-Time D: Participant swallows
- Time D-Time E: Hemodynamic activity is observed and compared to hemodynamic baseline. A peak is expected to occur sometime around 3-7 seconds after Time D. Subsequent hemodynamic activity is observed and recorded as it nears baseline again.
- Time E: Hemodynamic response returns to baseline and trial concludes with participant sitting still and fNIRS recording. Sequence begins again at Time A.





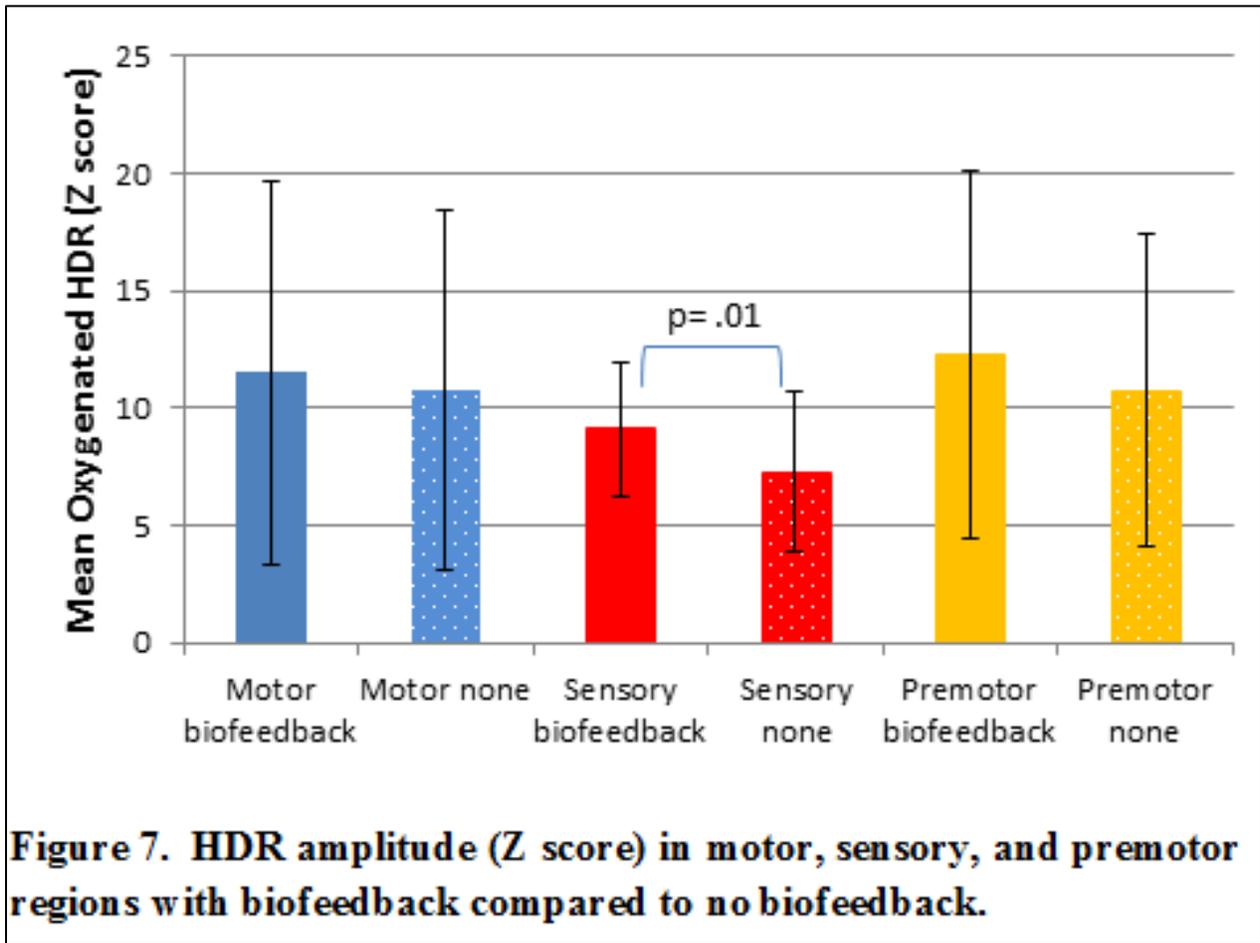


Figure 7. HDR amplitude (Z score) in motor, sensory, and premotor regions with biofeedback compared to no biofeedback.

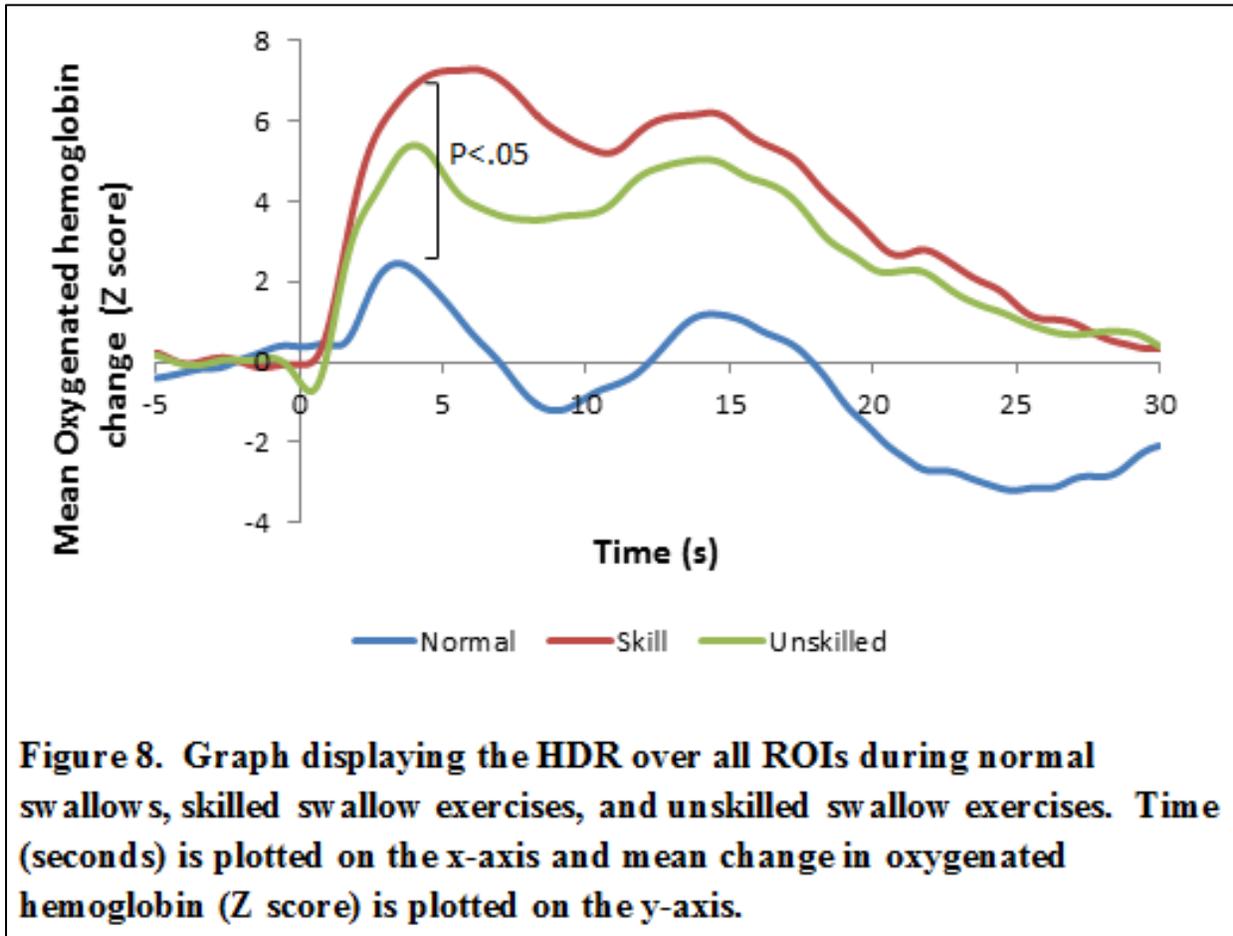


Figure 8. Graph displaying the HDR over all ROIs during normal swallows, skilled swallow exercises, and unskilled swallow exercises. Time (seconds) is plotted on the x-axis and mean change in oxygenated hemoglobin (Z score) is plotted on the y-axis.