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Feasibility of game-based electromyographic biofeedback for dysphagia rehabilitation

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Abstract—**Dysphagia (abnormal swallowing) is widely prevalent in the neurologically impaired and can result from both motor weakness and degraded sensory feedback. We present a system to pair augmentative sensory feedback through surface electromyography biofeedback with video game play for dysphagia rehabilitation. This system was employed with an individual with dysphagia as a result of brainstem stroke and compared against 6 unimpaired individuals. Initial results indicate high usability of the system and identify two objective measures with potential for differentiating control participants from the individual with dysphagia. Both gaming performance and the neck intermuscular beta coherence were decreased for the individual with dysphagia relative to control participants. Performance during gameplay is an estimate of the ability to voluntarily modulate neck muscle activity, whereas intermuscular coherence in the beta band may be representative of transmission from the primary motor cortex to muscle.**

I. INTRODUCTION

The inability to safely swallow (dysphagia) is a serious condition, frequently resulting in increased risk of pneumonia, death, malnutrition, and dehydration, as well as decreased quality of life. Current treatments require intensive intervention with a healthcare professional, and are not always efficacious. Dysphagia is often the consequence of neurologic disease [1]. For example, stroke affects ~5% of individuals over the age of 55, and dysphagia affects 27 – 50% of acute stroke patients [e.g., 2]. Of acute stroke patients with dysphagia, the half that do not die or recover spontaneously within the first 2 weeks have reduced quality of life due to chronic swallowing dysfunction [2]. Improved methods for swallowing rehabilitation could dramatically change the morbidity rate and quality of life for those suffering from chronic dysphagia.

The neural control of swallowing has classically been regarded as reflexive, such that rehabilitation efforts have focused on compensation to increase function and decrease risk [3]. However, recent evidence has shown that the integrated volitional and reflexive aspects of swallowing may be amenable to behavioral modification [3]. Further, although swallowing dysfunction is often due to impaired muscle control and weakness, degraded ***sensory*** information also impedes the cortical control of swallowing [4]. In fact, pharyngeal sensory deficits in post-stroke dysphagic individuals are an indicator of future aspiration and morbidity [5]. Supplying augmented biofeedback to these individuals could improve swallowing function.

An impediment to swallowing rehabilitation is the lack of direct access to the involved muscles. However, anterior neck muscles activate during swallow [6], and are easily accessible through surface electromyography (sEMG). sEMG biofeedback has been explored as an adjunct to traditional swallowing therapy [e.g., 7, 8], but the specific effects have not yet been studied. Striatal dopamine release during video game play may facilitate brain plasticity after perceptual learning [9, 10], and the use of entertaining games for practicing sensorimotor skill may increase patient compliance. Thus, combining sEMG biofeedback with video game environments may effect faster and more widespread learning during swallowing rehabilitation.

We describe a system to pair sEMG biofeedback with videogaming for dysphagia rehabilitation and provide an initial feasibility study of the technique. Six unimpaired individuals interacted with the system to provide baseline performance characteristics, and 1 individual with dysphagia was studied longitudinally over 6 visits of interaction with the system. The goal was to determine if individuals would be able to successfully interact with the system, and to provide preliminary characterization of the physiological effects of the rehabilitation environment in an individual with dysphagia, with unimpaired data for comparison. We explored two potential performance variables to characterize control of neck musculature during gameplay: performance in playing the videogame (number of targets acquired) and the neck intermuscular beta (15-35 Hz) coherence. Our

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findings indicate that the application of videogaming-based biofeedback methods has the potential to radically change the expected outcomes of dysphagia rehabilitation.

II. DEVELOPMENT OF THE REHABILITATION SYSTEM

A. *Overall Concept*

The user self-identifies with a character that can be moved vertically based on sEMG of the user (orange fish in Fig. 1). The character appears on the left side of the screen, and moves up during increased activation, and down during decreased activation at the biofeedback sEMG electrode.

This character is presented with "swallow targets," and the goal of the game is to "eat" as many of the targets as possible. The targets appear at the right of the screen at varying vertical positions, and move with a constant velocity toward the left of the screen. To "swallow" the targets, the character must reach the vertical position of the target, and stay at that position for the appropriate length of time.

B. *sEMG Recording, Processing, and Normalization*

The system provides real-time biofeedback through a laptop computer that is placed in front of the participant. This provides the mobility necessary to use the system in in-patient (bedside) settings and at home (tele-rehabilitation) in addition to outpatient therapy settings. The system can acquire and record up to 4 channels of data at 8000 Hz using a data acquisition card and MATLAB® (Mathworks Inc., Natick, MA). The sEMG signals are expected to be differential signals pre-conditioned via band pass filter to remove potential motion artifacts and to prevent aliasing.

Feedback is provided using the root-mean-squared (RMS) signal from only one sEMG electrode. The RMS values of sEMG collected are computed in real-time in 300ms windows with no overlap, and the biofeedback presented is the weighted moving average (WMA) of the real-time RMS sEMG. If the RMS sEMG signal is a time-series x(t), the WMA is calculated as

$$WMA_t = \left(\tfrac{1}{2}\right)x_t + \left(\tfrac{1}{3}\right)x_{t-1} + \left(\tfrac{1}{6}\right)x_{t-2}. \qquad \text{Eq. 1}$$

The voltage measured at the skin surface can vary widely between individuals due to differences in muscle activation, electrode contact, and subdermal fat. In order to provide a standard protocol for gameplay, biofeedback is presented in terms of normalized sEMG. At the start of each session, participants are asked to produce maximally long and hard dry swallows without biofeedback. The maximum RMS collected during these swallows is used to normalize presentation of biofeedback during gameplay.

C. *Feedback*

Feedback is presented in the context of a virtual rehabilitation environment using custom software written in MATLAB®. To play the game, the participant is asked to move their avatar (an orange fish) up and down to "swallow" targets at varying locations on the screen (see Figure 1). Targets are located at 33%, 66%, and 100% of the participants maximal activation during dry swallows at the beginning of the session, and are of 3 differing 'lengths' corresponding to lengths of activation of 2.8 s, 3.5 s, and 4.7 s. In order to successfully acquire the target, the participant's character must remain within +/- 15% (relative to the participant's maximal dry swallow activation) for the entire length of the target. Text at the top of the biofeedback screen kept track of the number of fish eaten during each trial (out of a total of 7). After a fish was successfully eaten, the highlighted text "You ate the fish!" briefly appeared as a visual reward.

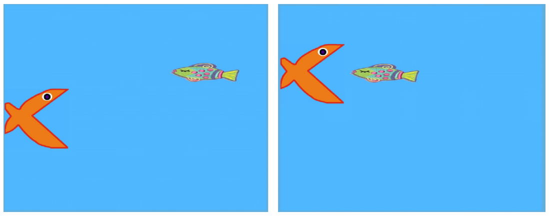

Figure 1: Two screenshots of the biofeedback given by the rehabilitation system. The orange fish moves up and down based on activity measured by the sEMG biofeedback electrode. The smaller fish is a swallow target. It appears on the right of the screen and swims left toward the orange fish at a constant velocity and constant vertical position.

III. FEASIBILITY STUDY METHODOLOGY

A. *Participants*

As a case study, an individual with dysphagia participated in 6 visits. The first 3 visits occurred over a single week, there was a week break, and then three more visits occurred in week 3. The participant with dysphagia was female, age 18, six years post brainstem stroke owing to a ruptured posterior fossa arteriovenous malformation. Her recovery had recently been complicated by development of a syrinx and subsequent ventriculoperitoneal shunt placement. At the time of data collection, her physical function was limited by ataxia and muscle weakness and her speech was dysarthric. She had a small, capped, cuffless tracheostomy tube. Her cognitive skills were functionally intact. She had severe oropharyngeal dysphagia, characterized by tongue and laryngeal weakness (greater on the left side), high aspiration risk and the need for routine oral suctioning to manage secretions. She was receiving regular (weekly) therapy from a certified speech language pathologist, which was arrested during her participation in this study.

Control participants were 6 unimpaired individuals (3 female, 3 male; mean age 30.8 years (SD = 9.5) with no previous history of swallowing disorder. All unimpaired participants presented with no current complaints in their swallowing, and participated in a single visit.

B. *Experimental Protocol*

Gameplay consisted of 10 trials, each lasting 2 minutes. During each trial, a total of 7 fish were presented. Participants were required to take 1 – 2 minute breaks between trials, and a longer (> 5 minutes) break between trials 5 and 6. Muscle activation during biofeedback was not required to be performed as part of the act of swallowing. Participants were allowed to attempt to control their muscle activity in any way they are able. In addition to the visual reward of the text "You ate the fish!", participants were also given auditory positive reinforcement by the investigator.

C. *Recording Procedures*

During visits, anterior neck sEMG was recorded using a 2-channel Bagnoli system (Delsys™ Inc, Boston, Massachusetts) with 2 Delsys™ 2.1 differential surface electrodes placed on the neck surface, referred to as EMG1 and EMG2. Electrodes were placed bilaterally, centered approximately 1.5 cm lateral to the neck midline, with the superior aspect of the sensor approximately 1 cm posterior from the submental surface. This position is intended to measure activations of the thyrohyoid, sternohyoid, and possibly omohyoid muscles. EMG1 was the biofeedback electrode, and was placed on the participant's left neck. EMG2 was placed symmetrically on the right neck. A ground electrode was placed on the superior aspect of the participant's right shoulder. The sEMG recordings were pre-amplified and filtered using the Delsys™ Bagnoli system set to a gain of 1000, with a band-pass filter with roll-off frequencies of 20 and 450 Hz.

D. *Outcome Measures*

In order to characterize control of neck musculature during gameplay, two potential performance variables were explored: the number of targets acquired (fish eaten) and the neck intermuscular beta (15-35 Hz) coherence during interaction. The number of fish eaten is an estimate of individuals' ability to modulate neck muscle activity during biofeedback. Coherence is a frequency domain measure of the linear dependency or strength of coupling between two processes, and intermuscular coherence in the beta band may be representative of transmission from the primary motor cortex to spinal motoneurons [11].

Qualitatively, patient and therapist perceptions of function were also considered in the case of the participant with dysphagia.

IV. FEASIBILITY STUDY RESULTS AND DISCUSSION

A. *Feasibility*

The goal of this feasibility study was to determine whether individuals were able to interface with this system to play the game. All unimpaired participants learned to modulate their neck musculature in response to the biofeedback to play the game. In addition, despite the severe swallowing disorder of the impaired participant, she was also able to play the game. As a marker of her ability to do so without significant frustration, she chose to continue to participate through a full 6 sessions. This ability of this participant to play the game without frustration is likely a function of the self-normalization feature of the system, which allows each individual to play the game using their own available range of sEMG activity. Self-normalization accounts for both inter- and intra-subject variability in electrode placement and electrode impedance as well as actual differences in muscle activation ability to provide usability for a large range of individuals. The participant with dysphagia had a very severe swallowing disorder, so we see high potential for individuals across the spectrum of dysphagia severity to be able to interact with this system. However, the current results are limited to this case study. Future work will examine the usability of this system in individuals with a variety of dysphagia severities and etiologies.

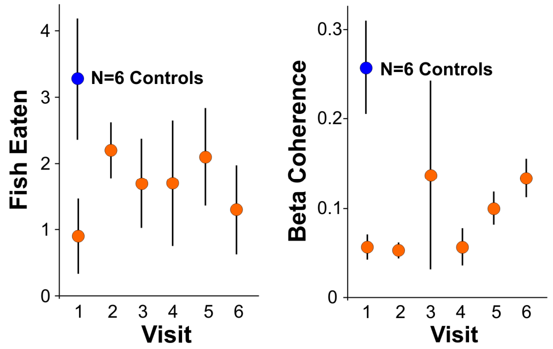

Figure 2: Initial results of feasibility study. Orange markers on the left panel show the average number of fish eaten as a function of visit. Orange markers on the right panel show the average intermuscular beta coherence as a function of visit. The blue markers show the mean values for control participants at their first and only visit. Error bars indicate +/- 1 standard deviation.

B. *Differences between the impaired participant and control participants*

Another goal of this study was to find potential differences between unimpaired individuals and individuals with dysphagia. Figure 2 shows that although the self-normalization feature of the system allowed all individuals to play the game, that the number of fish eaten by the individual with dysphagia was reduced when compared with the six control individuals, and that the average number of fish eaten during interaction increased with the number of visits. The control participants were able to acquire an average of 3.3 fish targets (STD=0.9) during their single visit (out of 7).

Conversely, the participant with dysphagia was able to acquire an average of 0.9 targets (STD=0.6) at her initial visit. Her average for her final 5 visits doubled to 1.8 targets (STD=0.4). Likewise, the average beta band intermuscular coherence of unimpaired individuals was higher than the individual with dysphagia, and that individual saw increases in beta coherence as a function of visit. The average beta coherence of control participants was 0.26 (STD=0.03). The participant with dysphagia had an average coherence of 0.06 (STD=0.01) at visit 1, but showed increases as a function of visit, with her final visit average at 0.14 (STD=0.02).

Although intermuscular beta coherence may be correlated with cortical control of musculature, the most obvious measure of voluntary muscle control would be success at playing the game. However, the number of fish eaten may not be the most reliable outcome measure of muscle control. Due to the self-normalization of sEMG activity, everyone "plays the game" using their own available range of sEMG activity. Although this built-in feature provides usability for a large range of individuals, it also means that potential improvements in the range of activations produced may be missed. Specifically, as individuals continue to play the game after multiple visits, they may increase control of the musculature such that their activations during normalization increase, thus increasing the difficulty of the game.

However, the range of sEMG is not the only factor contributing to an individual's ability to play the game successfully. If this were the case, one would expect equal performance of all participants, regardless of their health status. In fact, although all individuals were able to play the game, unimpaired participants consistently outperformed the participant with dysphagia. Thus, although the needed range of activations can modulate game difficulty, the *control and timing* of muscle activations is still essential to task performance. For this reason, the number of fish eaten is a reasonable surrogate for the ability to voluntarily control neck muscle activity.

C. *Potential for dysphagia rehabilitation*

After six visits of interaction, the participant with dysphagia reported a decrease in the amount of suctioning necessary to manage secretions, particularly at nighttime. In addition, the therapist noted (qualitatively) an increase in the speed of voluntarily initiated laryngeal elevation.

These qualitative clinical outcomes were also mirrored in the two potential outcome measures as a function of visit (see Figure 2). The average number of fish eaten increases after visit 1 for the individual with dysphagia, although no further increases were seen with time. On the other hand, the beta band intermuscular coherence seems to increase after the third visit. Increases in intermuscular beta coherence have been previously shown to accompany locomotor recovery after incomplete spinal cord injury [12], thus these increases as a result of intervention are promising for future study in a larger population.

V. SUMMARY

A new system was developed to pair video gaming with augmentative sEMG biofeedback for dysphagia rehabilitation. A feasibility study of the system in an individual with dysphagia and 6 unimpaired individuals indicated that all individuals studied were able to use the system. Initial data indicates that the number of fish eaten during game play and neck intermuscular beta coherence may have potential as objective measures to differentiate control participants from individuals with dysphagia. Future work is necessary to quantify differences in performance between individuals with dysphagia and control participants as a function of age and etiology of their swallowing disorder. Important further work will determine the efficacy of this system as a tool for swallowing rehabilitation.

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