Using Muscle Synergy to Evaluate the Neck Muscular Activities during Normal Swallowing

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***Abstract* —Swallowing is an extremely complex motion controlled by multiple muscles on the front neck region. Normal swallowing is dependent on orderly activation and co-coordination of the associated neck muscles, known as muscle synergy. However, evidence for muscle synergy during normal swallowing is rarely investigated. In this study, we studied the muscle synergy associated with swallowing saliva based on high-density (HD) surface electromyography (sEMG) signals acquired from four healthy subjects. The non-negative matrix factorization algorithm was applied to reconstruct the muscle activation patterns, and the values of variance accounted for (VAF) coefficients were computed to determine the number of muscle synergies. The results showed that the VAF values raised with the increase in the number of synergies on both the left and right sides of the neck. And the variation tendency of the VAF values was almost similar between the left and right area with a significant correlation (r=0.9902±0.0046, p<0.05). Furthermore, it was observed that an average of 5 muscle synergies was the minimum number required to sufficiently reconstruct the spatial characteristics of the synergism between both sides of the neck. These results suggest that the muscle synergy approach could serve as a promising candidate to evaluate the muscular co-contractions during swallowing, and it might be a useful method for dysphagia monitoring and diagnoses.**

I. Introduction

Swallowing is an important function for human beings, and each person averagely swallow almost 2000 times per day [1]. Swallowing is a neuromuscular process controlled by a complex and coordinated activation of stomatognathic, pharyngeal, and laryngeal muscles. During swallowing, the neck muscles help maintain stabilization of the cranium on the thorax, keeping the propulsive forces stable with respect to the tongue, pharynx, and larynx [2]. Thousands of motor unit action potentials are generated simultaneously by the central nervous system (CNS) which leads to the activation and coordination of the neck muscles [3]. In contrast, physical disorder of the neck muscles could lead to difficulty in swallowing, often called dysphagia. Dysphagia is considered as a critical disease that negatively affects an individual's overall health condition in terms of nutritional status and psychosocial well-being, leading to low quality of life or even death by aspiration. Before assessing swallowing disorder, it is important to understand the coordination mechanism of the neck muscular activities during normal swallowing.

Normal swallowing is triggered by groups of co-activated muscles or muscle synergies, rather than individual muscles. Muscle synergy is defined as a vector stating a pattern of relative muscle activation, and the absolute activation of each synergy is supposed to be a modularization of a single neural command signal [4]. In previous studies, surface electromyography (sEMG) recordings were utilized to extract and explore muscle synergies during different motor tasks. This is because sEMG is noninvasive, simple to acquire, and could reflect the physiological response of muscle contractions in real-time. For example, the sEMG was recorded to analyze the muscular functions of the leg in human during walking at two different speeds, and it was observed that muscle synergies could be recruited voluntarily and reactively by different neural pathways including the central pattern generator for walking [5]. In another study, the number of muscle synergies during movement in stroke survivors were found to be lower compared to the synergies in the healthy controls [6]. In addition, an average of four muscle synergies was extracted from sEMG signals recorded from 32 muscles involved in healthy subjects during forward walking, and these synergies were considered to be sufficient to explain the changes in muscle activation patterns across various speeds [7]. In the interim, these studies provided some information about the muscle synergies among different motions by using sEMG, however the evidence for muscle synergy during normal swallowing is rare. Therefore, it is important to provide an effective means of examining the synergism in the neck muscles responsible for swallowing.

In this study, high-density (HD) sEMG signals with more spatial information were acquired and used to investigate the

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muscular synergism on both the left and right sides of the front neck muscles during swallowing. The number of muscle synergies were determined by using non-negative matrix factorization (NNMF) algorithm [8] and the variance accounted for (VAF) coefficient [9]. Meanwhile, the correlation coefficient and Bland-Altman plots were used to analyze the muscle co-contractions associated with the left and right sides of the neck muscles during the swallowing activities. The finding of this study may provide a new method for effective assessment and diagnoses of dysphagia.

II. METHODOLOGY

A. Subjects

In this pilot study, four healthy male volunteers (mean age =24±2 years) were recruited. None of subject have either history of dysphagia or any medical problems based on medical examination reports. Before the experiment began, all the subjects received a complete explanation of the purpose, risks, and procedures of the investigation, and gave written informed consent as well as permission for publicizing their photographs in science and education. The protocol of this study was approved by the Institutional Review Board of the Shenzhen Institutes of Advanced Technology, China.

B. HD sEMG Signal Measurement

The HD sEMG signals were acquired by using the REFA 128-model system (TMSi, REFA, the Netherlands) from all the recruited volunteers during saliva swallowing tasks with a sampling rate of 1024 Hz. In order to acquire HD sEMG signals from the front neck muscles, a total of 80 electrodes were placed in a 2-dimensional array format consisting of 16 columns and 5 rows as shown in Fig. 1. Prior to the experiments, the HD sEMG electrodes' contact surfaces and the front neck region where the electrodes were to be placed, were carefully cleaned with alcohol swabs to maintain high quality recordings. Then each electrode was coated with a conductive gel to ensure good adhesiveness and conductivity between the electrode and the skin. Finally, all of the 80 electrodes were evenly placed on the front of the neck muscles with 15mm distance between center of any two consecutive electrodes (Fig. 1). During the swallowing test, all subjects were asked to swallow saliva for three times under the instruction of the experimenter.

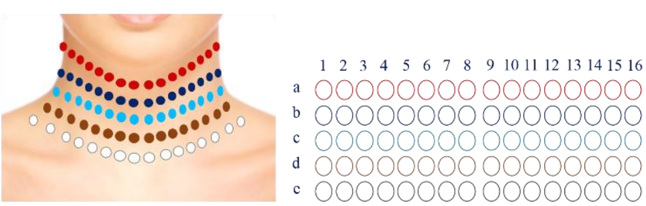

Figure 1. 2D Electrode array placement on the front neck of a subject.

C. Determining Number of Muscle Synergies

The HD sEMG signals acquired from all the recruited subjects during swallowing were properly filtered by using digital filters to reduce the impacts of ECG artifacts picked up by the electrodes and other baseline variations caused by accidental body movements of the subjects. Then the NNMF was used to calculate the muscle synergies on both the left and right sides of the neck muscles by using Equation 1 as follows [10].

$$V_r^{m\times n} = W^{m\times s} C^{s\times n} \tag{1}$$

where V_r is the muscle activation pattern combined by an $m\times n$ matrix, m is the number of channels and n is the number of samples. And W is $m\times s$ the matrix with s synergies and C is the $s\times n$ matrix of synergy activation coefficients.

The NNMF algorithm supposes that a linear combination of a few muscle synergies comprise a muscle activation pattern (V_r). Each column of W represents the weights of each muscle for one synergy. And each row of C represents how the synergy is modulated over time and how much each synergy is activated. The number of synergies, s, is a function of the quality of synergy decompositions. The similarity between the original sEMG (V_o) and the reconstructed sEMG (V_r) is investigated by using the VAF (range from 0 to 1) coefficient of each synergy decomposition based on Equation 2.

$$VAF = 1 - \frac{\sum_{i=1}^{m}\sum_{j=1}^{n}(V_r - V_o)}{\sum_{i=1}^{m}\sum_{j=1}^{n}(V_o)} \tag{2}$$

The VAF values was computed between V_o and V_r for each number of synergies, while the number of the muscle synergies, s, was firstly set to 1 and then increased sequentially to 15 for extraction of muscle synergy. Afterwards the muscle synergy matrices of one side (left or right side) were averaged across all tests for every subjects. To determine the minimum number of muscle synergies that sufficiently reconstructed the spatial characteristics of the sEMG signals, we utilized the mean value of VAFs that were larger than 0.95 (student's t-test at a significant level of $p< 0.05$.). The whole process for determining the synergy numbers was show in Figure2.

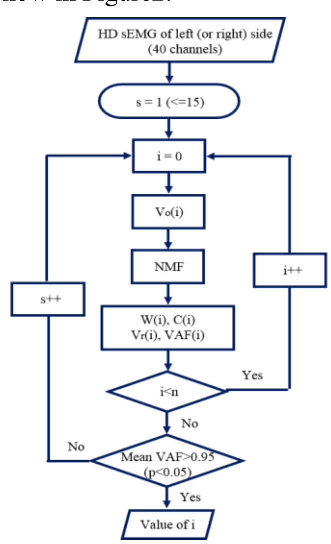

Figure 2. Flow chart of muscle synergy number determination.

In addition, the correlation of VAF values between the left and right sides of the front neck muscles was quantified by Pearson's correlation coefficient while the number of synergies were varied from 1 to 15, in order to evaluate the similarity of muscle synergies on both sides. Furthermore, the degree of agreement between both areas was estimated by using Bland-Altman method that was shown by using the mean and standard deviation of the VAF values.

III. Results

A. The Variation in VAF Values on the Left and Right Sides

In this study, the HD sEMG signals were recorded on both left and right sides of the front neck muscles during swallowing saliva across four normal subjects. A noticeable rise in the VAF values was observed while the number of synergies increased from 1 to 5 (Fig. 3). When the number of synergy increased from 6 to 10, the trend in the VAF values also increased steadily in the range of 0.95 to 0.99. Meanwhile, when the number of synergies raised from 11 to 15, the VAF values fluctuated a little. Additionally, the variation tendency of the VAF values were similar on both the left and right sides of the front neck muscles among all subjects as shown in Fig 3. By using Pearson's correlation coefficient, a significant correlation ($r=0.9902\pm0.0046$, $p<0.05$) was obtained between the VAF values of right and left neck muscles. In the graph, the red lines signify the VAF values of the left side while the blue lines represent the VAF values of the right side over the front neck.

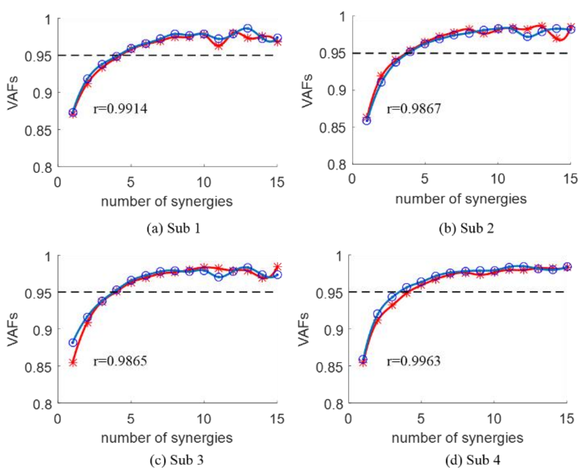

Figure 3. The variation trend in VAF values of both left and right sides of the front neck muscles while the number of synergies increases from 1 to 15 among four subjects. Horizontal dashed black line stands for the threshold of VAF=0.95.

B. Degree of Agreement of VAF Values between the Left and Right Sides

As shown in Fig. 3, the Pearson correlation coefficients between the muscles on the left and right sides were all greater than 0.98 for every subjects, which showed that there was high correlation and similarity in the VAF values between the left and right sides of the front neck muscles. For further evaluating the similarity of both sides, the Bland-Altman method was used to describe the degree of agreement on VAF values. In Fig. 4, the Bland-Altman analysis showed that the bias of the VAF values between the left and right sides was around zero and the limits of agreement was less than 0.03 across all four subjects. And with the Bland-Altman plots, the difference in the VAF values of left and right sides exhibited showed that more than 95% of the data points fell within the limits of agreement for all subjects.

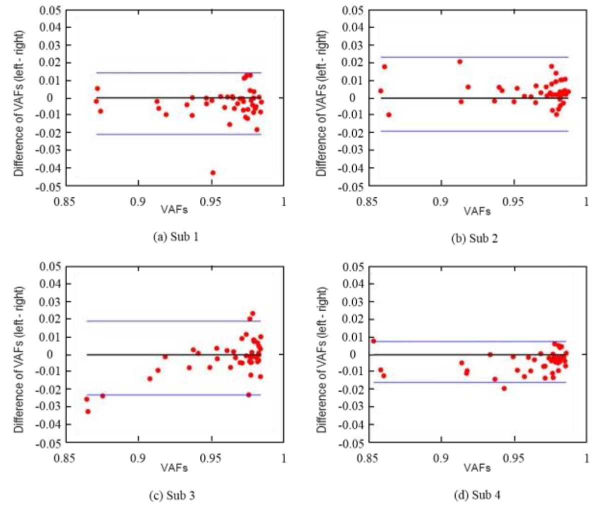

Figure 4. Bland-Altman plots of VAFs difference between the left and right sides of neck muscles.

C. Analysis of dimensionality by using 4 and 5 synergies

The dimensionality of the swallowing motor was analyzed by using the VAF values based on 4 and 5 synergies. As shown in Fig. 5, when the HD sEMG signals were reconstructed by using 4 synergies (Fig. 5(a)), the mean VAF value on both the left and right sides were lower than 0.95 in subject 1, while it was higher than 0.95 in subject 2 and subject 3. Especially, for subject 4 the average VAF value of the left side was a little lower than 0.95 whereas it was a bit higher than 0.95 on the right side. However, the HD sEMG signals were reconstructed with a mean VAF value higher than 0.95 on both the left and right sides of the front neck muscles for all subjects by using 5 synergies (Fig. 5(b)).

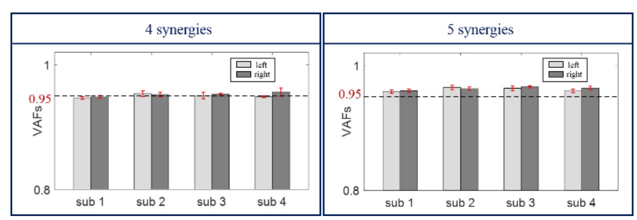

Figure 5. Mean VAF values of the left area and the right area of the neck using 4 (a) and 5 synergies (b). Red vertical lines represent standard deviations from the mean values. Horizontal dashed black line stands for the threshold of VAF=0.95.

IV. Discussion

The act of swallowing is an extremely complex movement that maintains both the physical and mental health of humans. Normal swallowing depends on orderly synergic movements of multiple muscles known as muscle synergism. This study investigated the spatial characteristics of muscle synergies between the left and right sides of the front neck muscles during normal swallowing of saliva based on HD sEMG signals collected from four healthy subjects.

The synergy analysis was considered as synergy selection issue, because different synergy decompositions were based on different number of extracted synergies [11]. And the number of synergies was found to correlate with the metrics of normal swallowing functions. In this study, the number of muscles synergies was determined by using the NNMF algorithm and VAF coefficient. The VAF values could provide information on how well the actual muscle patterns can be matched with a given set of synergies [11]. The variations in VAF values indicated that increasing the number of synergies can improve the reconstruction accuracy of the HD sEMG signals acquired from swallowing of saliva.

Meanwhile, the statistical results of VAF values shown that there was a significant correlation between the left and right sides of the front neck muscles when the subjects swallowed saliva. That is to say, the number of synergies on the left side was increased and decreased with those on right side synchronously. This thereby suggested that there were high symmetric properties between both sides that could be a result of the two-sided coordination of activities of the front neck muscles during normal swallowing. Furthermore, the Bland-Altman plots revealed that there was a high degree of agreement of VAF values between the left and right sides muscles while varying the number of synergies during normal swallowing, which corresponded to the physiological features associated with swallowing. When the saliva was propelled from the mouth through the pharynx into the esophagus, the muscles on both sides had an obviously similarity properties due to bilateral symmetry structure of the human neck. The results demonstrated that the left and right muscle on the front neck had high co-contractions while swallowing the saliva. In addition, the outcomes of similarity between the left and right sides were consistent with those of previous studies [12, 13].

The similarity of the original and reconstructed HD sEMG on both the left and right sides was measured by using the VAF values. Also, the VAF values were applied to identify the sufficient reconstruction of sEMG signals recorded from the neck muscles while using 4 or 5 synergies. The results showed that among all subjects, the VAF values of both the left and right muscles were higher than 0.95 using an equal number of synergies (5), while they were hovered at 0.95 based on 4 synergies. So 5 synergies were carried out as a muscle activation pattern that could sufficiently represent biomechanical characteristics of the swallowing activity. This result revealed that highly complex swallowing movements could be reduced to coordinative patterns of low dimensionality that correspond to biomechanical functions for balancing the muscles associated with swallowing. These results indicate that the evaluation of the muscle synergies based on HD sEMG technique could be useful to assess muscle patterns during swallowing.

It is important to note that he HD sEMG data used to investigate the muscle synergism mechanism was obtained from only four normal subjects in this pilot study. To further validate our hypothesis, more subjects as well as dysphagia patients would be included in our future study. In addition, apart from saliva swallowing data used in this study, we hope to consider more swallowing tasks like water-swallowing and paste-swallowing to have better understanding about the muscular activities during swallowing.

V. Conclusion

In summary, swallowing is an essential part of eating and drinking that involves complex coordination of muscular activities, known as muscle synergies. In this study, significant correlations and high degree of agreement of VAF values between the left and right sides of the front neck muscles were observed during normal swallowing of saliva. These results simply show an orderly activation and co-coordination of the front neck muscles on both sides. Our findings indicate that muscle synergy approach could serve as a potential method to evaluate the muscular co-contractions during swallowing, and it could provide useful information for dysphagia diagnosis.

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