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Spectral analysis of surface electromyography (EMG) of upper esophageal sphincter-opening muscles during head lift exercise

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Abstract—Although recent studies have shown enhancement of deglutitive upper esophageal sphincter opening in healthy elderly patients performing an isometric/isotonic head lift exercise (HLE), the muscle groups affected by this process are not known. A shift in the spectral analysis of surface EMG activity seen with muscle fatigue can be used to identify muscles affected by an exercise. The objective of this study was to use spectral analysis to evaluate surface EMG activitites in the suprahyoid (SHM), infrahyoid (IHM), and sternocleidomastoid (SCM) muscle groups during the HLE. Surface EMG signals were recorded continuously on a TECA Premiere II during two phases of the HLE protocol in eleven control subjects. In the first phase of the protocol, surface EMG signals were recorded simultaneously from the three muscle groups for a period of 20 s. In the second phase, a 60 s recording was obtained for each of three successive trials with individual muscle groups. The mean frequency (MNF), median frequency (MDF), root mean square (RMS), and average rectified value (ARV) were used as spectral variables to assess the fatigue of the three muscle groups during the exercise. Least squares regression lines were fitted to each variable data set. Our findings suggest that during the HLE the SHM, IHM, and SCM muscle groups all show signs of fatigue; however, the SCM muscle group fatigued faster than the SHM and IHM muscle groups. Because of its higher fatigue rate, the SCM muscle group may play a limiting role in the HLE.

Key Words: *dysphagia, electromyography, exercise, muscle fatigue*

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INTRODUCTION

Swallowing is a complicated process that involves many neck muscles, including the suprahyoids. During swallowing, this group of muscles, consisting of the mylohyoid, geniohyoid, and digastric muscles, contract and cause the opening of the crycopharyngeal sphincter or upper esophageal sphincter (UES) to permit food passage into the esophagus. The UES is normally in a state of tonic contraction which prevents air passing from the pharynx to the esophagus. The crycopharyngeus muscle is the main component of UES. Recent studies have shown that the cross-sectional area of the UES opening in healthy elderly persons is significantly smaller compared to the young (1–3). Multiple factors, such as relaxation and distensibility of the crycopharyngeus muscle, as well as the distraction forces imparted on the crycopharyngeus muscle by the UES-opening muscles of the suprahyoid muscle group, may be responsible for this difference.

In a placebo-controlled study, Shaker et al. evaluated the effects of an isotonic/isometric head raising exer-

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cise aimed at strengthening the UES-opening muscles (2). This study showed that the anteroposterior diameter and cross-sectional area of the deglutitive UES opening increased significantly in all elderly volunteers following 6 wk of therapy using the isotonic/isometric exercise (2). Therefore, the head lift exercise (HLE) may be helpful in some patients with disorders of the UES opening. In a subsequent study, patients with swallowing disorders due to abnormal UES opening and dependent on tube feedings were able to eat a modified diet following 6 wk of the Shaker exercise (4).

Although the effectiveness of this exercise in increasing the UES opening during swallowing has been demonstrated by fluoroscopic and manometric studies, what is not known is which muscle groups are affected by the exercise. Because there is a shift in the spectral analysis of surface electromyography (EMG) activity seen with muscle fatigue, the EMG technique allows the evaluation of which muscles are most affected by an exercise (5–9). In our preliminary studies, we showed the ability to measure fatigue of the UES-opening muscles during the Shaker HLE using spectral analysis (5,8,9).

The objective of this study was to use spectral analysis to evaluate and quantify the activities of the suprahyoid (SHM), infrahyoid (IHM), and sternocleidomastoid (SCM) muscle groups in control adult subjects during the HLE.

METHODS

Surface EMG signals were recorded from the SHM, IHM, and SCM muscle groups during the HLE. Spectral analysis, including mean frequency (MNF), median frequency (NDF), root mean square (RMS), and average rectified value (ARV), was performed on the EMG data to determine the fatigue process of each muscle group.

Study Subjects

Five male and six female healthy subjects (average age=32.36±8.32 y; average weight=146.82±26.34 lb; average height=5 ft 7 in±3 in) participated in this study. All subjects were screened to have no history of head injury, neurological dysfunction, neuropathy, myopathy, generalized weakness, neck radiation or surgery or swallowing difficulties. All subjects gave written, informed consent before participating in the study.

Exercise Protocol

During the HLE, the subjects were placed flat on an examining table in a supine position and asked to raise only the head off the table, flexing their necks (**Figure 1**). The intent of the exercise was to have the subject look at their feet, keeping the shoulders flat on the table, with the thoracic muscles relaxed. Only the isometric portion of the HLE was considered in this study. Thus, the adopted exercise protocol consists of two phases that allow two surface EMG recording configurations. In the first phase of the protocol, three surface EMG channel recordings were made simultaneously for a 20-s interval, one channel for each muscle group. A 60-s rest period was allowed prior to commencing the second phase. In the second phase, three 60-s one-surface EMG channel recordings were taken successively for each individual muscle group (SHM, IHM or SCM). A rest period of 5 min was allowed between testing of individual muscle groups.

Figure 1.
A typical healthy subject performing the isometric head lift exercise.

Recording and Instrumentation

Surface EMG signals were detected by a shallow, capped silver-silver chloride disc, 1 cm in diameter. Three active recording disc electrodes (G1s) were placed unilaterally over the left SHM, IHM, and SCM muscle groups. The G1 over the SHM was placed two-thirds of the distance from the mental protuberance to the hyoid bone, proximally, and 1 cm lateral to the midline. On the IHM, the G1 was placed two-thirds of the distance between the jugular notch of the manubrium sterni. The third G1 was placed in the middle of the SCM. The reference electrode (G2) was placed over the left ear lobe. The ground electrode was placed over the left ventral aspect of the wrist. The presence of electrical activity shown by all muscle groups during the HLE was noted.

A dedicated EMG machine, the TECA Premiere II (Oxford Instruments, Pleasantville, NY) with four channels, was used to record surface EMG data. The low filter was set at 1 Hz, and the high filter was set at 1 KHz. The 60 Hz notch filter was turned on to reduce noise interference. Recording sweep speed was set to 1 s. This machine stores up to 1000 points per sweep, resulting in 0.5 Hz frequency resolution. The surface EMG data were recorded and stored for off-line data analysis.

Data Analysis

To evaluate the effectiveness of the HLE protocol, surface EMG is used to investigate the fatigue process of SHM, IHM, and SCM muscle groups. The power spectrum of EMG signals undergoes frequency compression during sustained muscle contraction, long before the muscle becomes unable to sustain a desired force. Traditionally, the mean frequency (MNF) and the median frequency (MDF) are used as appropriate indicators of spectral shift, due to muscular fatigue. Additional variables such as the root mean square (RMS) and the average rectified value (ARV) are used to describe the amplitude variations. The RMS represents the mean power of the EMG signal, whereas the ARV is related to the area under the curve of the rectified EMG signal.

Prior to analysis, the EMG signals were extracted from the EMG machine and converted from binary to ASCII format and saved into files for off-line analysis. The signals were then filtered (with a dual pass to remove phase shift) with a fourth-order Chebyshev band pass filter with a 0.5 ripple factor and cutoff frequencies set at 1 and 500 Hz. Spectral and amplitude variables were then computed with numerical algorithms (time and frequency analysis) using the MatLab software package (The Mathworks, Inc., Natick, MA). These variables were calculated for each 1-s epoch duration throughout the exercise protocol. MNF, MDF, RMS, and ARV variables were plotted as functions of time with a 1-s increment. Using visual and graphical inspections most of these variables showed linear behavior. Thus, a linear model ($y=b_1x+b_0$) is adopted for each variable, to perform statistical processing. A least squares regression line was fitted to each data set using the SPSS statistical package (SPSS, Inc., Chicago, IL). The slope of the linear model, b_1, is then considered the measure of fatigue (rate) in this study, whereas the intercept, b_0, indicates the initial value of the outcome variable.

RESULTS

The time domain of the surface EMG signal samples from the SHM, IHM, and SCM muscle groups of a typical subject are shown in **Figure 2** at different epochs of the HLE. Based on visual inspections, all surface EMG variables showed consistent linear to moderately curvilinear behavior as a function of time. The slope (b_1) and the intercept (b_0) of the linear model were calculated for each surface EMG variable. As an illustration, the MNFs for the three muscle groups are shown with their least squares regression lines in **Figure 3**. The residuals between the linear model and the data were also calculated, as measures of the accuracy of the linear fit. **Table 1** presents the means and standard deviations of the slope, the intercept, and the residuals during the 20 s, simultaneous surface EMG recordings. The mean residuals in the MNF and MDF were under 0.27 Hz. The mean slopes of the MNF and MDF, respectively, of the SCM (−0.27, −0.24 Hz/s) were higher than those of the SHM (−0.14, −0.13 Hz/s) and the IHM (−0.08, −0.09 Hz/s). While the mean intercepts of the MNF and MDF were comparable, the mean slopes of the RMS and ARV did not seem to have consistent patterns.

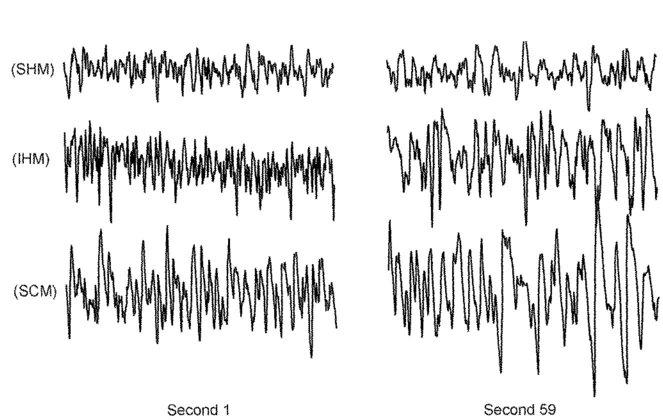

Figure 2.
A 0.5-s sampling of surface EMG signals from the SHM, IHM, and SCM muscle groups at 1 s and 59 s of the isometric head lift exercise.

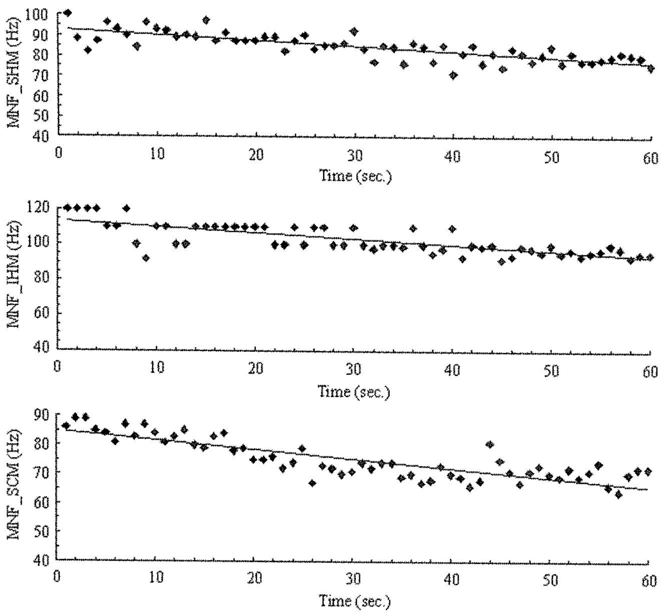

Figure 3.
Sample plots of the mean frequency (MNF) of surface EMG detected from the SHM, IHM, and SCM muscle groups during the isometric head lift exercise. Regression lines are also shown for each muscle group.

Table 1.
Mean and standard deviations of the residuals, intercepts, and slopes of the regression lines are summarized for all subjects during the first phase of the isometric head lift exercise.

Group	Var	Rs	b0	b1
SHM	MNF	0.22±0.16	80.3±14.5	-0.14±0.12
	MDF	0.21±0.23	60.9±10.3	-0.13±0.12
	RMS	0.19±0.17	72.3±23.6	-0.23±1.56
	ARV	0.18±0.16	55.6±19.3	-0.07±0.88
IHM	MNF	0.27±0.24	92.6±25.6	-0.08±0.10
	MDF	0.23±0.21	76.9±27.9	-0.09±0.14
	RMS	0.30±0.20	90.6±38.8	-0.17±2.22
	ARV	0.28±0.18	70.2±29.1	-0.16±1.48
SCM	MNF	0.25±0.23	79.1±18.4	-0.27±0.24
	MDF	0.17±0.19	66.4±13.4	-0.24±0.19
	RMS	0.25±0.27	103.9±53.9	0.58±0.55
	ARV	0.25±0.28	82.5±42.8	0.44±0.44

Group=muscle group; Var=output variables; Rs=residuals, in Hz or mV; b0=intercept, in Hz or mV; b1=slope, in Hz or V/s; SHM=suprahyoid muscle group; IHM=infrahyoid muscle group; SCM=sternocleidomastoid muscle group; MNF=mean frequency, in Hz; MDF=median frequency, in Hz; RMS=root mean square, in mV; ARV=average rectified value, in mV.

Table 2 shows the means and standard deviations of the same parameters during the second half of the exercise protocol, when each muscle group was tested individually during three successive trials. The mean residuals of the MNF and MDF were under 0.62Hz. The mean slopes of the MNF and MDF respectively had an average of (−0.31, −0.29 Hz/sec.) in the SCM, (−0.25, −0.21 Hz/sec.) in the SHM, and (−0.25, −0.20 Hz/sec.) in the IHM. Unlike the first phase of the protocol, the mean intercepts of the MNF and MDF showed consistent patterns. The mean intercepts of the MNF and MDF, respectively, had averages of 75 Hz and 64 Hz in the SCM, 82.6 Hz and 63.7 Hz in the SHM, and 95 Hz and 79 Hz in the IHM. The mean slopes of the RMS and ARV were all positive, indicating an increase in the surface EMG power of each muscle group. Also, the mean intercepts of the RMS and ARV of the SCM were higher than those of the SHM and IHM.

DISCUSSION

In the elderly, the cross sectional area of the UES opening is significantly smaller compared to the young (1–3). The Shaker HLE is a simple isotonic/isometric head-raising exercise that has been shown to increase the anteroposterior diameter and cross sectional area of the deglutitive UES opening (2). The purpose of this study was to analyze which muscle groups were affected by the exercise. Simply identifying which muscles were electrically active would not address which muscles were being physiologically affected by the exercise and strengthened. It is necessary to show evidence of fatigue to determine which muscles would have a training effect from the exercise.

Skeletal muscle fatigue has been defined as a failure to maintain the required or expected force during a muscle contraction (10). Functions of the central nervous system, the muscle cell membrane, muscle end plate, muscle T-tubular system, and the energy supply to the muscle may all contribute to muscular fatigue. Surface EMG is often used as a clinical tool in the study of localized skeletal muscle fatigue (11–13). During fatigue, the power spectra of the EMG signals shift in a predictable manner. Several studies have demonstrated that sustained isometric contractions produce a shift of the mean power frequency to lower values. An increase in power at lower frequencies and a decrease in power at higher frequencies has also been observed (14–16). Because of these shifts

Table 2.
Mean and standards deviations of the residuals, intercepts, and slopes of the regression lines are summarized for all subjects during the second phase of the isometric head lift exercise.

Group	Trial	Var	Rs	b0	b1
SHM	1	MNF	0.37±0.29	82.0±12.4	-0.21±0.14
		MDF	0.32±0.24	63.9±3.6	-0.20±0.11
		RMS	0.37±0.30	64.9±22.1	0.25±0.28
		ARV	0.37±0.30	51.3±17.4	0.20±0.21
	2	MNF	0.45±0.29	82.9±11.5	-0.26±0.11
		MDF	0.36±0.25	63.4±8.7	-0.20±0.08
		RMS	0.38±0.28	66.7±23.2	0.38±0.46
		ARV	0.38±0.28	52.9±18.4	0.30±0.36
	3	MNF	0.53±0.22	82.8±9.0	-0.29±0.16
		MDF	0.41±0.25	63.8±6.2	-0.23±0.14
		RMS	0.36±0.28	71.4±27.2	0.34±0.46
		ARV	0.35±0.28	56.6±21.5	0.26±0.36
IMH	1	MNF	0.43±0.33	97.4±14.2	-0.25±0.14
		MDF	0.34±0.27	80.9±11.8	-0.21±0.11
		RMS	0.38±0.29	100.9±66.6	0.75±1.14
		ARV	0.37±0.29	78.7±50.2	0.54±0.83
	2	MNF	0.48±0.35	95.4±13.5	-0.27±0.17
		MDF	0.36±0.30	79.5±11.2	-0.22±0.16
		RMS	0.35±0.30	117.1±91.2	0.94±1.73
		ARV	0.34±0.30	90.6±68.8	0.68±1.30
	3	MNF	0.41±0.34	92.1±15.1	-0.23±0.12
		MDF	0.32±0.31	76.7±12.5	-0.17±0.10
		RMS	0.36±0.35	116.0±80.1	0.88±2.17
		ARV	0.36±0.35	89.3±58.8	0.68±1.72
SCM	1	MNF	0.62±0.19	76.8±17.7	-0.32±0.11
		MDF	0.46±0.17	64.6±13.8	-0.27±0.15
		RMS	0.61±0.18	120.9±96.2	1.19±1.20
		ARV	0.60±0.18	96.6±77.5	0.92±0.93
	2	MNF	0.62±0.24	75.4±17.1	-0.31±0.12
		MDF	0.45±0.23	64.0±13.4	-0.30±0.18
		RMS	0.50±0.32	126.4±91.5	1.30±1.67
		ARV	0.50±0.32	101.2±74.9	0.97±1.21
	3	MNF	0.58±0.26	73.2±17.4	-0.29±0.11
		MDF	0.43±0.25	62.9±12.9	-0.30±0.19
		RMS	0.46±0.24	133.5±102.9	0.86±0.80
		ARV	0.46±0.24	106.3±83.2	0.65±0.63

Group=muscle group; Var=output variables; Rs=residuals, in Hz or mV; b0=intercept, in Hz or mV; b1=slope, in Hz or V/s; SHM=suprahyoid muscle group; IHM=infrahyoid muscle group; SCM=sternocleidomastoid muscle group; MNF=mean frequency, in Hz; MDF=median frequency, in Hz; RMS=root mean square, in mV; ARV=average rectified value, in mV.

in the spectral analyses of surface EMG activity seen with muscle fatigue, this technique allows the evaluation of which muscles are most affected by an exercise.

Surface EMG signals were detected from the SCM, SHM, and IHM muscle groups, indicating their involvement in the HLE. This study confirms prior studies that have shown that the onset of muscular fatigue begins immediately after the start of the exercise. Furthermore, the rate of muscular fatigue (represented by the slope of the linear model) of the SCM was higher than those of the SHM and IHM. The difference in the slope was statistically significant ($p<0.05$, independent samples T test) for the

MNF and MDF, a pattern consistent in both phases of the exercise. This finding suggests that the SCM muscle group may fatigue faster than the SHM and IHM muscle groups. Consequently, the SCM muscle group may play a limiting role in the timing of the HLE, since it does not have a role in the swallow process. In the second phase of the exercise protocol the mean intercepts of the MNF and MDF of the SHM and IHM remained relatively constant throughout the three trials. However, the mean intercepts of the MNF and MDF of the SCM decreased throughout the trials. This particular finding suggests that the SHM and IHM recovered quickly during the 1-min resting period. The SCM did not show this pattern and seemed to fatigue progressively throughout the trials, with limited recovery. These potential differences among the SCM, SHM, and IHM groups may be due to differences in muscle architecture.

As a result of this study, it appears that surface EMG spectral analysis of the SHM, IHM, and SCM muscle groups during the HLE will allow objective monitoring of the exercise protocol, to ensure inter-subject consistency in performing the HLE during clinical studies. The fatigue process of these muscle groups can be assessed periodically in dysphagia patients as they undergo the HLE protocol. In future studies, surface EMG spectral analysis can also be explored as a tool to examine the optimum timing of the HLE.

CONCLUSION

In general, our findings suggest that during the HLE the SHM, IHM, and SCM muscle groups begin to show signs of fatigue as soon as they become active. The fatigue patterns observed with surface EMG of these muscle groups are indications that they are physiologically affected by the HLE. The SCM muscle group fatigued sooner than the SHM or the IHM muscle groups. Because of its higher fatigue rate, the SCM muscle group may be a limiting factor in the timing of the HLE.

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REFERENCES

1. Kern M, Shaker R, Arndorfer R, Hofmann C. Effect of aging on the cross-sectional area of upper esophageal sphincter (UES) opening during swallowing. Gastroenterology 1994;106:A613.
2. Shaker R, Kern M, Bardan E, Taylor A, Stewart ET, Hoffman RG, Arndorfer RC, Hofman C, Bonnevier J. Augmentation of deglutitive upper esophageal sphincter opening in the elderly by exercise. Am J Physiol 1997;272:G1518–22.
3. Shaw DW, Cook IJ, Gabb M, Holloway RH. Influence of normal aging on oral-pharyngeal and upper esophageal sphincter function during swallowing. Am J Physiol 1995;268:G389–96.
4. Easterling C, Kern M, Nitschke T, Grande B, Daniels S, Cullen GM, Massey BT, Shaker R. Effect of a novel exercise on swallow function and biomechanics in tube fed cervical dysphagia patients: a preliminary report. Dysphagia 1999;14:119.
5. Alfonso M, Ferdjallah M, Shaker R, Wertsch JJ. Electrophysiologic validation of deglutitive UES opening head lift exercise. Gastroenterology 1998; 114(4):G2942. 6. Buxbaurn J, Mylinski N, Parent E. Surface EMG reliability using spectral analysis. J Oral Rehabil 1996;23:771–75.
7. Eberstein A, Beattie B. Simultaneous measurement of muscle conduction velocity and EMG power spectrum changes during fatigue. Muscle Nerve 1985;8:768–73.
8. Jurell KC, Shaker R, Mazur A, Haig AJ, Wertsch JJ. Spectral analysis to evaluate hyoid muscles involvement in neck exercise. Muscle Nerve 1996;19:1224.
9. Jurell KC, Shaker R, Mazur A, Haig AJ, Wertsch JJ. Effect of exercise on upper esophageal sphincter opening muscles: a spectral analysis. Gastroenterology 1997;112(4):A757.
10. Basmajian JV, De Luca CJ. Muscle Alive. 5th Ed. Baltimore (MD): Williams & Wilkins; 1985.
11. Kramer CG, Hagg T, Kemp B. Real time measurement of muscle fatigue related changes in surface EMG. Med Biol Eng Comp 1987;25:627–30.
12. Lyons M, Rouse M, Baxendale R. Fatigue and EMG changes in the masseter and temporalis muscles during sustained contractions. J Oral Rehabil 1993;20:321–31.
13. Merletti R, Knaflitz M, De Luca CJ. Myoelectric manifestations of fatigue in voluntary and electrically elicited contractions. J Appl Physiol 1990;69(5):1810–20.
14. Merletti R, Lo Conte LR, Orizio C. Indices of muscle fatigue. J Electromyogr Kinesiol 1991;1:20–33.
15. Moritani T, Muro M, Nagata A. Intramuscular and surface electromyogram changes during muscle fatigue. J Appl Physiol 1986;60:1179–85.
16. Naeije M, Zorn H. Relation between EMG power spectrum shifts and muscle fiber action potential conduction velocity changes during local muscular fatigue in man. Eur J Appl Physiol Occup Physiol 1982;50:23–33.

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