Monitoring Breathing Muscle Performance During Singing Noninvasively Using Mechanomyography and Electromyography

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**Summary: Objectives.** The aim of this study was to investigate the performance of mechanomyography (MMG) and electromyography (EMG) in monitoring the sternocleidomastoid (SCM) as accessory respiratory muscles when breathing during singing.

**Methods.** MMG and EMG were used to record the activity of the SCM in 32 untrained singers reciting a monotonous text and a standard folk song. Their voices were recorded and their pitch, or fundamental frequency (FF), and intensity were derived using Praat software. Instants of inhales and exhales were identified during singing from their voice recordings and the corresponding SCM MMG and EMG activities were analysed.

**Results.** The SCM MMG, and EMG signals during breathing while singing were significantly different than breathing at rest ($p < 0.001$). On the other hand, MMG was relatively better correlated to voice intensity in both reading and singing than EMG. EMG was better, but not significantly, correlated with FF in both reading and singing as compared to MMG.

**Conclusions.** This study established MMG and EMG as the quantitative measurement tool to monitor breathing activities during singing. This is useful for applications related to singing therapy performance measurement including potentially pathologically effected population. While the MMG and EMG could not distinguish FF and intensity significantly, it is useful to serve as a proxy of inhalation and exhalation levels throughout a particular singing session. Further studies are required to determine its efficacy in a therapeutic setting.

**Key Words:** Singing muscle—Mechanomyography—Electromyography—Sternocleidomastoid.

**INTRODUCTION**

Singing is a form of art that requires the person to project their voice in specific techniques. Different singing styles produce various genres, such as opera, gospel, soul, rock, and a capella. Singing is a result of coordination of respiration, phonation and articulation. The vocal cords vibrate once the air is forced out of the lungs and towards the vocal chords by integrated action of the respiratory muscles and rib cage. Up to lately, singing is not only considered as a type of entertainment, but studies have also shown that they could be used as a form of therapy or exercise. Today, singing has been acknowledged by our society as another way to enhance our mental and physical health condition. Researchers have documented evidence that singing can improve management for many long-term neurological conditions; such as quadriplegia, Parkinson's disease, multiple sclerosis, and lung diseases, especially chronic obstructive pulmonary disease.

Inspiration happens when the diaphragm and the external intercostal muscles contract, causing the dome and ribs to descend and elevate respectively. Meanwhile, expiration results from the passive elastic recoil of the lungs, rib cage, and diaphragm. However, in spinal cord injury (SCI) population such as quadriplegia, the accessory muscles of respiratory are found to be active during inspiration and expiration, even during exertion and rest. Studies have shown that singing can improve the respiratory dysfunction in quadriplegia. However, it was found that the only measurement device used to measure the activity of the respiratory muscles in these studies is electromyography (EMG).

One of the critical aspect of singing according to most singing teachers and professional singers is breathing control. This is because singing requires fast and strong, but at the same time, extended and regulated inspirations and expirations. Like any other increased metabolic need activity, the activation of the accessory respiratory muscles during inspiration requires extensive and vigorous training in order to achieve a significant result of breathing performance on the targeted population.

Besides, singing also leads to the enhancement of both the impaired respiratory muscles and lung capacity. During the singing process, all the organs involved including the surrounding structures are utilized repeatedly, leading to not only regulation of the system but also improvement of the respiratory muscles. Researchers also came to the conclusion that there were no significant difference between professional singers, vocal music students and normal persons, i.e. untrained singers, in terms of their total lung capacity. This indicates that normal healthy person can take full advantage of the same lung capacity, which would lead to a more efficient breathing technique by increasing their singing training period.
Singing therapy has been recognized as one alternative method to improve the respiratory dysfunction on many pathological populations, as well as the normal, healthy individuals. Nevertheless, it was not literary clear what is the suitable noninvasive surface tool or skin based instrument to quantify their superficial breathing muscle performance when singing. It is also useful to identify and quantify the extent of normal surface muscle activity, that is, sternocleidomastoid (SCM) in varied phonation tasks through surface electrode measures in order to provide a baseline for use of singing therapy for individuals requiring such therapy such as dysphonia. This study therefore aims to investigate the performance of both EMG and mechanomyography (MMG) in monitoring the surface respiratory muscles (SCM) during singing. In particular, this study compared the performance of both EMG and MMG as devices to examine the singing performance and muscle recruitment during singing in a particular singing therapy session.

MATERIAL AND METHODS
In this study, quantitative method was adopted by collecting and analyzing the EMG (Delsys Surface EMG System with TRIGNO Wireless System electrodes) and MMG data (BIOPAC MP150 System with 2-channel VMG) from their SCM muscles while their voice was recorded simultaneously using an iPhone 6 for further analysis. SCM has been identified along with latissimus dorsi as the accessory respiratory muscle most associated with singing, whereby the SCM supports inhalation when lung volume comes close to vital capacity or when breathing is very rapid. As pitch is a perceptual correlate of fundamental frequency (FF), and loudness is a perceptual correlate of intensity, Praat software was used for subsequent voice FF and intensity analysis. In the first part, the performance of the SCM muscle according to both EMG and MMG were analyzed by comparing the respiratory muscles activity with the intensity and FF of the participants’ voices. This was the vocal performance correlation test. Meanwhile, for the second part where breathing activity itself was concerned, the respiratory muscles’ EMG and MMG signal at breathe-in and breathe-out during singing therapy was compared against its resting state. This was named the muscle breathing detection test.

Study protocol
The study protocol is presented in Figure 1. This experiment was divided into two parts. The first part was the deep inhalation test to serve as a baseline measure, that is, the calibration, to determine the maximum respiratory effect on SCM. In this test, the participants inhaled as hard and as long as they can through a spirometer. The second part was the vocal assessment itself. In this part, the participant read a familiar passage (“Rukun Negara”) and sang a familiar folk song (“Rasa Sayang”) with electrodes from both EMG and MMG attached on their SCM muscles (randomly positioned at either left and right side each, as shown in Figure 2). The participants performed all phonation tasks at their self-selected registration choice, including during the phonation task of the folk song. The researchers did not determine or exclude the participants based on the perceived accuracy of their registration choice in the tasks. For the muscle breathing detection test protocol, both EMG or MMG devices were used to monitor the SCM respiratory muscle activity based on the recorded trial.
Subjects
Thirty-two participants (10 males and 22 females; age: 22.7 ± 2.0 years and BMI: 25.0 ± 6.2) were recruited. All subjects were familiar with both the reading passage “Rukun Negara” and folk song “Rasa Sayang”. Subjects were excluded if they have any vocal or respiratory problems or were not fit to speak as normally, as determined by at least two independent researchers. Table 1 shows the demographic information of all participants recruited in the study. The information included their inspiratory flow rate (IFR) which was collected from the calibrated spirometer test. The three-ball incentive spirometer consists of three balls separated by their own chambers. When the participant deeply inhaled through the spirometer, the balls raised one by one, where the IFR increased from 600 to 900 and finally to 1200 cm³/sec. Originally used to exercise the lungs, this spirometer was used in this study to show the participants’ healthy lung capacity. The average IFR from 32 able-bodied participants is 1143.8 cm³/sec. This indicates that the participants generally have a healthy lung capacity, as the maximum rate is 1200 cm³/sec.

<table>
<thead>
<tr>
<th>Demographic</th>
<th>Able-bodied participants (n = 32)</th>
</tr>
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<tbody>
<tr>
<td>Age (y)</td>
<td>22.7 ± 2.0</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.6 ± 0.1</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>66.6 ± 19.4</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>25.0 ± 6.2</td>
</tr>
<tr>
<td>IFR (cm³/sec)</td>
<td>1143.8 ± 119.0</td>
</tr>
<tr>
<td>Gender</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>10</td>
</tr>
<tr>
<td>Female</td>
<td>22</td>
</tr>
</tbody>
</table>

Data collection
Acquisition softwares were used to collect the data from the activity of SCM muscles from EMG (Delsys EMGworks acquisition software) and MMG (BIOPAC AcqKnowledge acquisition software) respectively. Meanwhile, the Voice Memo application from iPhone 6 was used to record the voice of the participants while reading and singing. The recordings were used to determine the correlation between their FF and intensity with the SCM muscles activity while reading and singing.

Data analysis
In the intensity and FF, that is, pitch detection test, the performance of EMG and MMG were compared by correlating each of the device with the participants’ FF and intensity while reading and singing. While EMG waveform permits extraction of FF and register, every subject’s singing voice was not regulated to remain in the same vocal register. In turn, Praat software (Praat, Paul Boersma and David Weenick, Phonetic Sciences Department, University of Amsterdam, The Netherlands) was used to analyze the intensity and FF of the participants’ voice during reading and singing. The analysis on reading was done on the vocal performance test of Rukun Negara, which is exactly before the five principles of Rukun Negara (Appendix 1). Customarily, the passage is read in a monotonous voice. Therefore, the level of FF and intensity were expected to be constant throughout the passage. The length of the vocal performance test ranged from 12 to 14 seconds, depending on how fast or slow the participant read the passage. Meanwhile, the analysis on singing was done on the vocal performance test of the Rasa Sayang folk song with three trials from each participant. This is because, in this part, the range of FF and intensity of the participants’ voice was big, ranging from high to low points. The length of the vocal performance test was fixed at 12 seconds for every participant, since everyone sang with the same track in the background.

All signals from Praat software were processed by removing the noise and infinite impulse response (IIR) filter. Delsys EMGworks analysis software was used to process the signal of the SCM muscle from EMG. The signal was processed with IIR filter and root mean square. Meanwhile, BIOPAC AcqKnowledge analysis software was used to process the SCM muscle activity from MMG. The signal was processed with both IIR filter and vibrography filter. All of the processed data from the EMG, MMG, and Praat software were exported into Excel file for further analysis.

In the muscle breathing detection test, the performance of both EMG and MMG were compared by observing their ability to differentiate between resting and breathing activities in singing (SPSS Statistics, International Business Machines (IBM) Corporation, USA). For this breathing detection test, a different procedure was conducted. Instead of analyzing a whole chorus of Rasa Sayang, the analysis was made on three different activities during singing; rest, breathe in, and breathe out. The analysis was not made in reading activity because the breathe-in and -out was less consistent and unclear. It was much easier to identify all three activities (rest, breathe in, and breathe out) during singing. Since the Rasa Sayang track was provided to the participants, everyone sang at the same tempo and rhythm. Meanwhile, in reading Rukun Negara, the participants read at different speed and tempo since there was no guidance from a backing track. Therefore, different participants utilized different breathing pattern when reading, making it harder to analyze the data.

The time selected to be analyzed in each three activities (rest, breathe in, and breathe out) was identified using Praat software. In each trial, three different timing of rest, breathe in, and breathe out activities respectively were selected. These timing were selected at the same part of the song for each participant. The average time for the rest period in each participant was at the first second of the recording. For breathe-in and breathe-out activities, the first timing
was selected at the first chorus (refer to Appendix 2) (during “hey lihat nona...”), while the other two were selected in the last chorus (during “rasa sayang...” and “hey lihat nona...”). The signals from both EMG and MMG software were filtered and processed in the same way as in the intensity and FF detection test of the study.

**Descriptive data analysis**

In the intensity and FF, that is, pitch detection test, after all of the processed data from EMG, MMG, and Praat software were exported into Excel file, the data were further analyzed. The data from all four parameters; EMG (volts), MMG (VMG), intensity (dB), and FF (Hz), were analyzed to make sure that the range of time and the amount of data were balanced in each of the parameters. Hence, the range of time that was analysed in each trial was made to be constant in every parameter. All four parameters (intensity, FF, MMG (V), and EMG (V)) were reduced to 10 Hz sample size for further analysis. The same procedure was repeated for all trials for both reading and singing in each participant.

The EMG and MMG data were normalized to its maximum recorded voltage value. Once the start time and duration of all three different activities were identified in Praat software, the same time and duration were used in both EMG and MMG normalized data. All nine values in each trial were obtained by averaging the normalized data according to their respective timing. The same procedures were repeated in each trial and participant.

**Data analysis to answer the research question**

To detect the intensity and FF, the data from all participants were normalized, then combined and grouped into each parameter. Once done, they were separated into four different sheets in the Excel file; EMG versus FF, MMG versus intensity, and MMG versus FF. After the dependent and independent variables were assigned, four scattered graphs were obtained from each sheet. Then, the regression line and R² value was plotted and obtained on each of the graph. Finally, the coefficients of correlation, R values from each graph were recorded into a table.

Meanwhile, in order to perform the muscle breathing detection, data from every trials and participants were analyzed using SPSS Statistics software. Before the data were analyzed, the rest, breathe in, and breathe out activities were classified as values labelled one, two, and three respectively in the software. The data were analyzed by using one-way analysis of variance (ANOVA) to determine whether there were any statistically significant differences between the means of all three activities in both EMG and MMG. Then, the EMG and MMG columns were chosen as dependent list, while the activity column was identified as factor. The significance level was fixed at 0.05 (α = 0.05), therefore the confidence interval was set at 95%. Finally, in order to determine which specific activities differed from each other, a post hoc test named the least significant difference test was also conducted in the software. The significant level was also fixed at 0.05 (α = 0.05).

**RESULTS**

**Raw signals**

A sample excerpt of raw data from the FF and intensity of the voice is shown in Figure 3. This excerpt is from the third trial of singing from participant 2 using Praat software. The green and blue lines on the graph represent the participant’s intensity and FF respectively. Meanwhile, the highlighted part is where the signal was analyzed, which also represents the first chorus of the song. The length of this part is 12 seconds.
Figures 4 and 5 illustrate the excerpt of raw data of singing session from MMG and EMG respectively. The data were taken from the third trial of singing session from the third participant.

Meanwhile, Figure 6 illustrates the sample of graphs of EMG versus intensity, EMG versus FF, MMG versus intensity, and MMG versus FF respectively. These graphs were of certain participant’s, after the data were averaged from three trials in each participant. Coefficients of correlation, R of each sample were calculated from the coefficients of determination, $R^2$ shown in each graph.

Correlations between EMG and MMG with FF and intensity

Based on Table 2, MMG had higher R values with intensity in both reading and singing sessions than EMG. At the same time, EMG has higher R values with FF in both reading and singing sessions than MMG. These results indicate that MMG has a relatively better correlation with intensity of the voice in both reading and singing than EMG. On the other hand, EMG has a slightly better, but not significant correlation with FF of the voice in both reading and singing than MMG. However, the R values (Table 2) were too weak and not convincing enough to determine which device is better at monitoring the performance of respiratory muscles with respect to their voice FF and intensity. Every R value obtained from this part of the study was lower than 0.1. These findings, that MMG had better correlation with vocal intensity than EMG, suggests that one measure is better at targeting intensity (MMG) compared to FF (EMG) when testing the SCM.

Table 3 interprets the percentage of participants having higher R values than the ones in Table 2 and their respective
average R values. Based on this table, it elucidates that the R value varied with different participant, where some may have much higher degree of correlation compared to the rest of the participants, and vice versa. All R values presented in Table 3 were less than 0.2.

**Difference in muscle activities between rest, breathe-in, and breathe-out**

Performance of both devices was compared by observing their ability to differentiate between rests, breathe-in, and breathe-out activities while singing. One-way ANOVA was used to determine whether there were any statistically significant differences between the means of those three activities while singing in both EMG and MMG.

Based on the significance value in Table 4, there was a statistically significant difference between rest, breathe-in, and breathe-out activities in both EMG (F_{EMG} (2,816) = 15.723, P_{EMG} = 0.000) and MMG (F_{MMG} (2,816) = 45.913, P_{MMG} = 0.000). ANOVA revealed that the mean value at rest was lower than that of breathe-in and -out activities in both EMG and MMG. This finding suggested that the participants used the SCM muscle much less at resting stage of the singing therapy, compared to both breathing in and out during singing at particular verse and stops in the song. Meanwhile, the mean value during breathe-in was the highest among the three activities in both EMG and MMG. This result shows that among all three activities, the participants utilized the SCM muscle at most while breathing in during singing therapy, including in the middle of the song when they had to catch up their shortness of breath.

Post hoc least significant difference test conducted for both EMG and MMG indicated that there were statistically significant differences between rests and breathe-in activities, and rests and breathe-out activities in both EMG (P_{EMG} = 0.000) and MMG (P_{MMG} = 0.000) (Table 5). However, it was also shown that there was no statistically significant difference between breathe-in and -out activities in both EMG (P_{EMG} = 0.790) and MMG (P_{MMG} = 0.417). This agrees with the expectedly less SCM activity during

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**TABLE 2.**

<table>
<thead>
<tr>
<th>Reading (n = 10)</th>
<th>Singing (n = 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EMG</td>
</tr>
<tr>
<td>Intensity</td>
<td>0.0173</td>
</tr>
<tr>
<td>FF</td>
<td>0.0346</td>
</tr>
</tbody>
</table>

**TABLE 3.**

<table>
<thead>
<tr>
<th></th>
<th>Reading (n = 10)</th>
<th>Singing (n = 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EMG</td>
<td>MMG</td>
</tr>
<tr>
<td>Intensity</td>
<td>80 (0.0868)</td>
<td>40 (0.0679)</td>
</tr>
<tr>
<td>FF</td>
<td>80 (0.0978)</td>
<td>60 (0.1055)</td>
</tr>
</tbody>
</table>

* The data are expressed in percentage, % (average).
at-rest respiration since lung volume is much less during at-rest compared to extended phonation tasks such as speaking or singing, but similarly high in such phonation tasks.

**DISCUSSION**

Kang et al have established that singing is a good respiratory workout. This was supported by a pilot study on group-singing among older adults that reported improved maximum inspiratory and expiratory pressure among the participants.

To understand the potential gains and dose potency of such respiratory workout, one needs to understand the mechanism behind voice production during singing and how it is related to breathing. Many factors influence voice performance when singing, which might explain individual differences and are very much physiological in nature. Yeo et al concluded that FF and relative vocal intensity could detect the vocal fold vibratory patterns at different lung volumes conditions. Therefore, their finding suggested that both FF and relative vocal intensity can be alternative measurements of vocal intensity and FF during singing therapy. This finding was supported by a study on healthy adults, where the effect of different conditions of lung volumes on phonatory and articulatory kinematic behavior was measured by relative vocal intensity.

Glottal open-quotient, which is derived from the differentiated electroglottographic signal based on different glottal configurations, was reported to depend on one’s laryngeal mechanism. Laryngeal airway resistance was also found to be most sensitive to glottic insufficiency, which may be related to perceived breathiness during singing.

In assessing breathing while singing muscle, SCM was selected as it is the most accessible muscle most related to singing. While other actual singing muscle may provide a more accurate representation of the activity, ease of access to the internal muscles such as the laryngeal muscle or the glottis are the main factors influencing the practicality of such assessment. The chest and abdominal walls on the other hand was reported to be monitored through their movements, simultaneously during singing using inductive plethysmography, however this does not directly represent muscle activation.

Each muscle group represents different breathing and vocal production function, and thus has different fiber types and physiological characteristics. The abductor and adductors of the laryngeal muscles contract during inspiration and expiration respectively. Meanwhile, cricothyroid, the vocal cord tensor contracts during deep breathing. Besides respiration, the laryngeal muscles also responsible in phonation. For instance, the contraction of cricothyroid increases the vocal cord frequency. The inner physiology and muscle morphology were also investigated to determine its muscle fiber type, contractile properties and its influence to individual differences in singing voice output, all subjected to neural and hormonal regulation. These may be factors that affected the outcome of our study but could not be accounted for due to its inaccessibility to internal muscle and its structure.

Additionally, the manipulation of lung volume through different singing or reading styles of the participants in this study may have affected the consistency of the outcomes. Less direct biomechanical and neural control linkage between respiratory and articulatory structures was reported and might be a good explanation for the low correlation of

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**TABLE 4. The Results Obtained From ANOVA in Both EMG and MMG**

<table>
<thead>
<tr>
<th>Device</th>
<th>Sources</th>
<th>SS*</th>
<th>Df†</th>
<th>MS‡</th>
<th>F§</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMG</td>
<td>Between</td>
<td>1.219</td>
<td>2</td>
<td>0.610</td>
<td>15.723</td>
<td>p &lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>Within</td>
<td>31.637</td>
<td>816</td>
<td>0.039</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>32.856</td>
<td>818</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MMG</td>
<td>Between</td>
<td>0.572</td>
<td>2</td>
<td>0.286</td>
<td>45.913</td>
<td>p &lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>Within</td>
<td>5.085</td>
<td>816</td>
<td>0.006</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>5.657</td>
<td>818</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* SS: sum of squares.
† df: degree of freedom.
‡ MS: mean squares.
§ F: ratio of two variances.

**TABLE 5. The Results Gained From Post hoc Test (LSD) in Both EMG and MMG**

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Activity</th>
<th>Activity</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMG</td>
<td>Rest</td>
<td>Breathe In</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Rest</td>
<td>Breathe Out</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Breathe in</td>
<td>Rest</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Breathe in</td>
<td>Breathe Out</td>
<td>0.790</td>
</tr>
<tr>
<td></td>
<td>Breathe out</td>
<td>Rest</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Breathe out</td>
<td>Breathe in</td>
<td>0.790</td>
</tr>
<tr>
<td>MMG</td>
<td>Rest</td>
<td>Breathe in</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Rest</td>
<td>Breathe out</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Breathe in</td>
<td>Rest</td>
<td>0.417</td>
</tr>
<tr>
<td></td>
<td>Breathe out</td>
<td>Breathe out</td>
<td>0.417</td>
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</table>
voice characteristics and muscle function performance. Nevertheless, breathing control is an attention-demanding task. Further investigation is recommended to determine the applicability of both MMG and EMG in detecting different levels of muscle activity with respect to either their voice FF or voice intensity, or any other relevant voice measures relevant to respiratory or vocal training. This will allow the use of MMG or EMG as a practical measurement tool, including as part of a singing therapy session in a busy clinical setting.

CONCLUSION
To conclude, based on the data analyses made in the intensity and FF detection test, MMG could monitor the intensity of the voice in both reading and singing relatively better than EMG. On the other hand, EMG seemed to be better at monitoring the FF of the voice in both reading and singing compared to MMG. However, the correlations were too weak. In terms of the breathing muscle activity, both EMG and MMG were found to be similarly able to significantly detect differences between resting and breathing in (p < 0.05), and between resting and breathing out (p < 0.05) respectively during singing therapy.

Acknowledgment
The authors thank all the study participants for their time volunteering.

SUPPLEMENTARY DATA
Supplementary data related to this article can be found online at https://doi.org/10.1016/j.jvoice.2019.06.006.

REFERENCES