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ORIGINAL ARTICLE

### ASSESSMENT AND DATA PROCESSING TOOLS OF INSPIRATORY MUSCLE FATIGUE EVALUATION USING SURFACE ELECTROMYOGRAPHY: A SYSTEMATIC REVIEW.

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#### KEYWORDS:

Electromyography,  
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**Objectives:** To analyze inspiratory muscle fatigue using surface electromyography (SEMG).

**Methods:** Searches were carried out in PUBMED, SCOPUS, CINAHL and SCIRUS databases by two researchers using the MeSH list keywords: *electromyography*, *respiratory muscles* and *muscle fatigue*. Complete cross-sectional studies in English, Portuguese and French from the last 10 years in which SEMG was used to analyze inspiratory muscle fatigue in humans were included. The Agency for Healthcare Research and Quality (AHRQ) scale was used to evaluate the quality of the studies.

**Results:** 12 studies were selected, with total sample of 159 subjects (healthy or with respiratory disease) evaluated during exercise or inspiratory effort. Most studies assessed sternocleidomastoid muscles and some assessed the intercostals and diaphragm muscles. The most common signal processing was frequency analysis; root mean square, power and energy analyses were also found.

**Conclusion:** Validation studies are needed for the standardization of SEMG on this muscle group and as well as myoelectrical signal processing in order to identify the most adequate form of analysis for different muscle activities.

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## **INTRODUCTION**

The coordination and performance of respiratory muscles are the basis of ventilatory efficiency. Thus, any disturbance to the function of these muscles can result in ventilatory insufficiency (1). Respiratory muscle weakness and fatigue occurs in cases of acute or chronic respiratory disorder and primary neuromuscular diseases (2). Respiratory muscle fatigue represents a limit to physical performance (3, 4), which turns the evaluation of these muscles important for the determination of both respiratory function and functional capacity.

Pulmonary function tests, such as the determination of maximal inspiratory pressure (MIP), are normally used to assess respiratory muscle dysfunction (2), but they perform a global evaluation without differentiating muscle groups (5). Balloon-catheter pressure sensor (6), esophageal (7) or needle electromyography (EMG) (8) can be used for a selected evaluation of these muscle groups, but offer the disadvantage of being invasive methods (9). Studies have used EMG for the assessment of respiratory muscles in both animals (10) and humans (7, 11). Surface EMG (SEMG) offers the advantage of a non-invasive assessment of these muscles (2). The performance of different muscle groups during the respiratory process can be evaluated with SEMG (12), allowing the identification of muscle activity in different respiratory phases, body positions and clinical situations with a conscious patient, which makes the diagnostic process easier and more precise.

Knowlton, Bennett and McClure in 1951 (13) were the first to use EMG for the analysis of muscle fatigue. To detect muscle fatigue in humans, EMG analysis in the frequency domain has been proposed, due the signal spectrum changes to a lower frequency during the contraction of muscles experiencing fatigue (3). This method has been validated for biceps brachial (14) and femoral quadriceps (15). Frequency spectrum indexes differences are used in this method, which include median or central frequency

(Fc) and the ratio between high and low frequency components (HF/LF) (3, 16).

Based on this, the aim of the present study was to review the assessment of inspiratory muscle fatigue using SEMG.

## **METHODS**

The procedure described by Sterne, Egger and Smith (2001) (17) was followed in this review. Based on the question "Is surface electromyography adequate for the assessment of inspiratory muscle fatigue?", searches were carried out in PUBMED, SCOPUS, CINAHL and SCIRUS databases by two researchers using the Medical Subject Headings (MeSH) list keywords: *electromyography, respiratory muscles* and *muscle fatigue*. Complete cross-sectional studies in English, Portuguese and French from the last 10 years in which SEMG was used to analyze inspiratory muscle fatigue in humans were included.

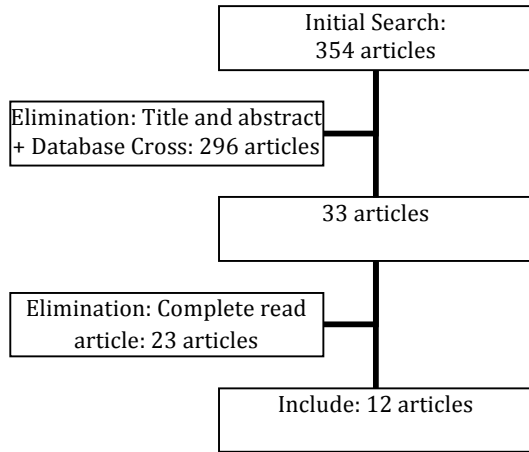
The Agency for Healthcare Research and Quality (AHRQ) (18) scale was used to assess the quality of the studies. The following categories of the scale were used as inclusion criteria: study question (2 points); exposure or intervention (11 points); outcome measures (20 points); and discussion (5 points). These criteria were chosen based on their association with the aims of the present review. To be included, studies needed to achieve a minimal score of 27 points, corresponding to 70% of the total possible score.

## **RESULTS**

After the described database research, a total of 354 articles were found and 12 were selected for the review analysis. Figure 1 presents search steps and filters up to the selected articles. These studies are consisted of a total sample of 159 subjects (healthy or with respiratory disease) who were evaluated during exercise or inspiratory effort. Most studies assessed sternocleidomastoid muscles and some assessed the intercostals and diaphragm muscles. The most common signal processing was

frequency analysis; root mean square, power and energy analyses were also found.

Figure 1: Flowchart of article selection process.



## DISCUSSION

The efficacy of SEMG for the analysis of muscle fatigue has been demonstrated on different muscle groups (14, 15). However, studies in the literature about inspiratory muscles remain scarce. Thus, there is a need of further studies and technique validation of inspiratory muscles for research and clinical practice.

Fatigue analysis using electromyography was first described by Knowlton, Bennett and McClure in 1951

(13). However, it was in 1997 that Potvin & Bent (14) validated this technique on biceps brachial muscles and Gerdle, Larsson and Karlsson (15) validated it on femoral quadriceps muscles in the year 2000. Since then, a large number of studies of different muscle groups have used myoelectrical signals for muscle fatigue assessment (7, 9).

Potvini & Bent (14) used the Fast Fourier Transform (FFT) and central frequency (Fc) in the signal processing, whereas Gerdle, Larsson and Karlsson (15) used FFT and mean frequency (Fm). While these are validated techniques, the studies included in this review used both spectral variables and other types of frequency spectrum processing (4, 16, 19-22) as well as power and RMS analysis (3, 12, 16, 23-26).

Gerdle, Larsson and Karlsson (15) used RMS for muscle fatigue analysis in their validation study and found greater correlation between fatigue and Fm in frequency analysis in comparison to RMS, which had good correlation with peak torque. According to the authors, divergence in the use of RMS is likely caused by the difficulty of this variable and the need for normalization. The studies that employed RMS and power analysis normalized these variable in different ways, such as percentage of mean RMS (Mañanas et al., 2000), in relation to maximal RMS (3, 26) and resting values (12, 23, 24).

Table 1: Characteristics of studies that used frequency analysis for assessment of fatigue

Study	Sample Description	Muscles Evaluated	Electrode Type / Position	Activity during analysis	EMG Filter / Normalization	EMG signal processing
Mañanas et al., 2000	6 M <sup>1</sup> COPD <sup>2</sup> , (68.8 SD 4.3 years)	STMD <sup>3</sup>	Ag-AgCl <sup>4</sup> electrode / 4 cm above clavicle; RE <sup>5</sup> : shoulder	IL <sup>6</sup> incremental and maintained	Band-Pass 8-400Hz / Percentage of mean RMS <sup>7</sup> .	Fm <sup>8</sup> , Fc <sup>9</sup> , HF/LF Ratio and RMS <sup>7</sup>
Mañanas, Fiz, Morera and Caminal, 2001	6 COPD <sup>2</sup> (68.8 years)	STMD <sup>3</sup>	Ag-AgCl <sup>4</sup> electrode (2cm) / NI <sup>10</sup>	IL <sup>6</sup> incremental and maintained	Band-Pass 8-400Hz / NI <sup>10</sup>	Statistic; Morlet Wavelet, WV <sup>11</sup> and CW <sup>12</sup>
Mafinas et al., 2002	12 (24 records)	STMD <sup>3</sup>	Ag-AgCl <sup>4</sup> electrode (1cm) / 6 cm above clavicle; RE <sup>5</sup> : Shoulder	IL <sup>6</sup>	Band-Pass 8-400Hz / NI <sup>10</sup>	Welch Periodogram; Correlograms; AR <sup>13</sup> ; ARMA <sup>14</sup> ; Fm <sup>8</sup> ; Fc <sup>9</sup> ; HF/LF Ratio
Reynaud-Gaubert et al., 2004	7 CRF <sup>15</sup> (3M <sup>1</sup> , 4F <sup>16</sup> ) 33 SD 5 years (5 cystic fibrosis, 2 bronchiectasis)	Di <sup>17</sup>	Ag-AgCl <sup>4</sup> electrode / 6 <sup>th</sup> and 7 <sup>th</sup> intercostal space	Maintained IL <sup>6</sup> : 15, 30 and 50 cmH <sub>2</sub> O	NI <sup>10</sup> / NI <sup>10</sup>	FFT <sup>18</sup> ; Fm <sup>8</sup> ; Total Power; HF/LF Ratio
Segizbaeva and Mironenko, 2008	5 healthy M <sup>1</sup> , 19-27 years	EI <sup>19</sup>	Ag-AgCl <sup>4</sup> electrode / NI <sup>10</sup>	Exercise (bike with respiratory resistance)	NI <sup>10</sup> / NI <sup>10</sup>	Discrete Fourier Transform and HF/LF Ratio
Chien et al, 2010	30 M: 15 OSA <sup>20</sup> (51.3 SD 6.5), 15 healthy (51.2 SD 7.0)	Right DI <sup>17</sup>	NI <sup>10</sup> / DI <sup>17</sup> : 7th or 8 <sup>th</sup> intercostal space between axillary line and clavicle line, RE <sup>5</sup> : Sternum.	MVV <sup>21</sup>	Band-Pass 10-1000Hz / NI <sup>10</sup>	RMS <sup>7</sup> / Fc <sup>9</sup>

<sup>1</sup>Males; <sup>2</sup>Chronic Obstructive Pulmonary Disease; <sup>3</sup>Sternocleidomastoid; <sup>4</sup>Silver/Silver Chloride; <sup>5</sup>Reference Electrode; <sup>6</sup>Inspiratory Load; <sup>7</sup>Root Mean Square; <sup>8</sup>Mean Frequency; <sup>9</sup>Central or Median Frequency; <sup>10</sup>Not Informed; <sup>11</sup>Wigner-Ville Distribution; <sup>12</sup>Choi-Williams Distribution; <sup>13</sup>Autoregressive Model; <sup>14</sup>Autoregressive Moving Average Models; <sup>15</sup>Chronic Respiratory Failure; <sup>16</sup>Female; <sup>17</sup>Diaphragm; <sup>18</sup>Fast Fourier Transform; <sup>19</sup>External Intercostals, <sup>20</sup>Obstructive Sleep Apnea, <sup>21</sup>Maximal Voluntary Ventilation.

Table 2: Characteristics of studies that used root square mean (RMS) and power analysis for assessment of fatigue

<b>Study</b>	<b>Sample Description</b>	<b>Muscles Evaluated</b>	<b>Electrodes Type / Position</b>	<b>Activity during analysis</b>	<b>EMG Filter / Analysis / Normalization</b>
Dornelas de Andrade et al., 2005	14: 7 COPD <sup>1</sup> (66.4 ± 8.7 years) and 7 healthy elderly (68 SD 4.2 years)	STMD <sup>2</sup> and Di <sup>3</sup>	Ag-AgCl <sup>4</sup> electrode (1cm) / STMD <sup>2</sup> : 5 cm below mastoid process; Di <sup>3</sup> : 7 <sup>th</sup> or 8 <sup>th</sup> intercostal space between axillary line and clavicle line.	IL <sup>5</sup> : 5 minutes with 30% of MIP <sup>6</sup>	Band-Pass 20-500Hz / RMS / Time and amplitude normalization
Nobre et al., 2007	10 F <sup>7</sup> (25.3 SD 1.4 years)	STMD <sup>2</sup> and Di <sup>3</sup>	Ag-AgCl <sup>4</sup> electrode (1cm) / STMD <sup>2</sup> : 5 cm below mastoid process; Di <sup>3</sup> : 7 <sup>th</sup> or 8 <sup>th</sup> intercostal space between axillary line and clavicle line.	Incremental IL <sup>5</sup> : 10, 20 and 30 cmH <sub>2</sub> O	Band-Pass 20-500Hz / RMS / Time and amplitude normalization
Hawkes, Nowicky and McConnell, 2007	12 (6 F <sup>7</sup> , 6 M <sup>8</sup> ), healthy (25 SD 9 years)	Di <sup>3</sup> (right) e EI <sup>9</sup>	Ag-AgCl <sup>4</sup> electrode (28mm) / Di <sup>3</sup> : Last intercostal space on mean clavicle line; EI <sup>9</sup> : 5 <sup>th</sup> intercostal space on posterior axillary line; RE <sup>10</sup> : Sternum.	IL <sup>5</sup> : 30 inspirations at 40% of MIP <sup>6</sup>	Band-Pass 20Hz-5KHz / RMS/ Resting values
Perlovitch et al., 2007	20 (7 M <sup>8</sup> , 5F <sup>7</sup> ) healthy, 25 SD 3 years	STMD <sup>2</sup> e EI <sup>9</sup> .	Ag-AgCl <sup>4</sup> electrode / STMD <sup>2</sup> : Midway between angle of the jaw and clavicle; IE <sup>9</sup> : 1 <sup>st</sup> and 2 <sup>nd</sup> intercostal space, 2 cm laterally from the sternum.	Treadmill walk: 2 to 8 km/h.	Band-Pass 20-500Hz / Maximal RMS values
Duiverman et al., 2009	27: 17 COPD <sup>1</sup> (60 SD(54-64)) and 10 healthy (55 (53-59))	EI <sup>9</sup> and Scalene	Ag-AgCl <sup>4</sup> electrode / IE <sup>9</sup> : 2 <sup>nd</sup> intercostal space, 3 cm laterally from the sternum; Scalene: Neck; RE <sup>10</sup> : Sternum.	Maximal incremental cycle ergometry test	NI <sup>12</sup> / logEMG – ratio between peak at resting and maximal activity/ NI <sup>12</sup>
Shadgan, Guenette, Willian Sheel and Darlene Reid, 2011	10 healthy male (27.5 SD 0.7)	STMD, PS <sup>13</sup> , EI <sup>9</sup>	NI <sup>12</sup> / STMD: midway between the mastoid process and the medial end of the clavicle; PS: 2 <sup>th</sup> intercostals space (near sternum); EI: 8 <sup>th</sup> intercostals space at the anterior axillary line.	Incremental IL <sup>5</sup> : 10 minutes starting with 100g load add 50g each 2 minutes.	Low-pass between 10-100Hz / Integrated EMG / Maximal values

<sup>1</sup>Chronic Obstructive Pulmonary Disease; <sup>2</sup>Sternocleidomastoid; <sup>3</sup>Diaphragm; <sup>4</sup>Silver/Silver Chloride; <sup>5</sup>Inspiratory Load; <sup>6</sup>Maximal Inspiratory Pressure; <sup>7</sup>Female; <sup>8</sup>Male; <sup>9</sup>External Intercostals; <sup>10</sup>Reference Electrode, <sup>12</sup>Not Informed, <sup>13</sup>Parasternal.

Despite the divergence and lack of validation in the assessment of muscle fatigue using power and RMS (15), the studies that used this variable found significant results, with higher values at the end of maximal inspiratory effort (16, 24-26). According to Hawkes, Nowicky and McConnell (24), the increase in myoelectrical signal amplitude during progressive workload may indicate greater need of muscle recruitment, which is reflected in greater synergy among muscles during maximal effort. Dornelas de Andrade et al (23) used RMS for the evaluation of inspiratory muscles during endurance exercise and found a significant increase only in the sternocleidomastoid muscles in patients with Chronic Obstructive Pulmonary Disease. Nobre et al (12) found an increase in activity in muscles of the lower rib cage (diaphragm) in healthy subjects. These results demonstrated that, despite the controversy regarding the use of this parameter, RMS has been able to detect different responses in different individuals and muscle groups (12, 23, 26), including respiratory and calf muscles (3, 22).

The existing substantiation of frequency analysis has led to its widespread use. A number of studies using different analysis techniques have been carried out, with diversified forms of processing myoelectrical signals in the frequency spectrum (4, 16, 19-22). These analyses can be time-independent frequency analysis of the signal global frequency, such as FFT, and also time-dependent analysis in which the frequency is analyzed in each instant of time through short-lived time components and wavelet packets, which allows the evaluation of the change in frequency during exercise, with the best adapted signal analysis (27). Although, time-independent frequency analysis is more commonly used (4, 16, 21, 22), the myoelectric signal dynamics turns the time-dependent frequency analysis more suitable than standard methods (27). A comparative study by Karlsson et al (27), analyzed the accuracy and reliability of time-frequency methods and found that the continuous wavelet transform showed best performance in myoelectrical signal analysis.

SEMG on inspiratory muscles is questioned mainly due to cross-talk and cardiac interference. A high-pass filter of

30 Hz is effective at eliminating cardiac interference in the myoelectric signal (28). However, the studies reviewed used a high-pass filter lower than the recommended to eliminate this interference (22-24). Dornelas de Andrade et al (23), Hawkes, Nowicky and McConnell (24) and Chien et al (22) pointed out this interference and, in order to minimize it, the authors only evaluated muscles on the right side of the body. Dornelas de Andrade et al (23) argue that, since the aim of their study was to analyze signals proportionally to a rest period, with noise in both situations, the noise did not affect the results of the study. Chien et al (22) additionally justify that to minimize the possibility of cardiac signal contamination the diaphragm signal was measured from segments between QRS complexes of electrocardiogram. Cross-talk is directly related to electrode position and adjacent muscles in the region evaluated. The articles that addressed issue sought to position electrode in a way to reduce cross-talk (3, 12, 23). In a training and placebo comparison study, Hawkes, Nowicky and McConnell (24) supposed that cross-talk from accessory respiratory muscles did not play a significant role in the changes observed.

The positioning of electrodes for capturing signals from the diaphragm is normally located anteriorly in the seventh intercostal space, where expiratory intercostal activity is found (11). At this region, the action of adjacent intercostal and abdominal muscles is predominantly expiratory, whereas the action of the diaphragm is inspiratory. Thus, the interference should be minimal (23). The action of the inspiratory intercostals is mainly located in the upper dorsal and parasternal region (11), where the electrodes are positioned (23) (and there is, thusly, no interference from expiratory intercostals action).

Surface electrodes have been used to measure electrical activity of the diaphragm, intercostals, scalene and accessory inspiratory muscles. Despite the advantage of SEMG, there is no standardization of electrode positioning, that is, there is no consensus or orientation for positioning electrodes in accordance with the innervation zone, fiber direction, distance between electrodes or cross-talk (2).

## CONCLUSION

The use of SEMG in the assessment of muscle fatigue has proven to be effective in different muscle groups (14, 15). However, inspiratory muscles literature remains scarce. Studies have demonstrated the usefulness and benefits of this method, but the diversity of procedures makes data interpretation and comparison difficult. Both maximal contraction and resting references have been used for signal normalization, which also makes the data difficult to interpret. Thus, there is a need for further studies on SEMG validation for inspiratory muscles and signal normalization. Studies are also needed on myoelectrical signal processing for these muscles to identify the most suitable analysis for each activity and to standardize the techniques, thereby allowing reliable and reproducible studies on the assessment of inspiratory muscle fatigue using SEMG in both research and clinical practice.

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