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Evaluation and Adaptive Attenuation of the Cardiac Vibration Interference in Mechanomyographic Signals

Leonardo Sarlabous, Abel Torres, Member, IEEE, José Antonio Fiz, Member, IEEE, Josep Morera, Raimon Jané, Member, IEEE

Abstract— **The study of the mechanomyographic signal of the diaphragm muscle (MMGdi) is a promising technique in order to evaluate the respiratory muscles effort. The relationship between amplitude and frequency parameters of this signal with the respiratory effort performed during respiration is of great interest for researchers and physicians due to its diagnostic potentials. However, MMGdi signals are frequently contaminated by a cardiac vibration or mechanocardiographic (MCG) signal. An adaptive noise cancellation (ANC) can be used to reduce the MCG interference in the recorded MMGdi activity. In this paper, it is evaluated the proposed ANC scheme by means of a synthetic MMGdi signal with a controlled MCG interference. The Pearson's correlation coefficient (PCC) between both root mean square (RMS) and mean frequency (fm) of the synthetic MMGdi signal are considerably reduced with the presence of cardiac vibration noise (from 0.95 to 0.87, and from 0.97 to 0.76, respectively). With the ANC algorithm proposed the effect of the MCG noise on the amplitude and frequency of MMG parameters is reduced considerably (PCC of 0.93 and 0.97 for the RMS and fm, respectively). The ANC method proposed in this work is an interesting technique to attenuate the cardiac interference in respiratory MMG signals. Further investigation should be carried out to evaluate the performance of the ANC algorithm in real MMGdi signals.**

I. INTRODUCTION

THE surface mechanomyography is a non-invasive technique that measures the low-frequency lateral vibrations of muscle fibers during muscle contraction. In general, it has been found that there is a correlation between amplitude and frequency parameters of the mechanomyographic (MMG) signal and the force produced by the muscle [1-7].

In previous works [8, 9], our group has analyzed the signal acquired by means of a capacitive accelerometer placed on the costal wall of the thoracic cage in order to register the mechanomyographic signal of the diaphragm muscle (MMGdi). The diaphragm is the main respiratory muscle responsible for the respiratory activity. The respiratory muscular fatigue can be monitored by means of techniques that study the muscular activity in amplitude and frequency through the MMGdi signal. In these works it was found a positive correlation between amplitude of the MMGdi signal and the respiratory muscle effort (evaluated by means de inspiratory pressure signal), and a negative correlation between the frequency parameters of the MMGdi signal and the respiratory muscle effort.

The amplitude and frequency content of the MMGdi signal is usually evaluated by means of the root mean square (RMS) and the mean frequency (fm) of the signal, respectively. However, these estimations are greatly affected by the presence of cardiac or pulse vibration interferences that overlap in frequency with the MMGdi signal. The cardiac interference introduces a distortion in both MMGdi signal power and frequency content. Increasing respiratory effort level increases the intensity of the MMG component without altering the intensity of cardiac vibration. Therefore the SNR increases with the respiratory effort influencing to both RMS and fm parameters.

Several methods can be used to minimize the effect of the heart vibrations in the analysis of the MMGdi signal. The most rudimentary method in order to eliminate the cardiac interference is simply by means of the detection and removal of the segments of the MMGdi signal with presence of cardiac noise. However, this method segments the signal and excludes portions of the signal that may contain potentially important information about the contractile activity of the diaphragm muscle. Adaptive filtering techniques have been applied successfully in order to attenuate the electrocardiographic (ECG) component in electromyographic (EMG) signals from the diaphragm muscle [10,11]. The most important part of all these adaptive filtering techniques is the artificial construction of a reference signal that must be highly correlated with the ECG interference but uncorrelated with the EMGdi activity.

In this work, we present an adaptive noise cancellation (ANC) algorithm in order to reduce the cardiac vibration interference while preserving the essential features of the MMGdi signal. In order to quantify the performance of the algorithm and to evaluate the influences of the cardiac interference on the amplitude and frequency parameters of the MMGdi signal, we have applied this ANC algorithm to a synthetic MMG signal corrupted with a real cardiac vibration interference. Therefore, the main purposes of this work were two: (1) to evaluate the effect of the cardiac vibration interference over a synthetic MMG signal corrupted with real cardiac vibration, and (2) to develop and evaluate an ANC based method to attenuate the cardiac vibration interference in the MMG signal.

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L. Sarlabous, A. Torres, and R. Jané are with Dept. ESAII, Universitat Politècnica de Catalunya, Institut de Bioenginyeria de Catalunya (IBEC) and CIBER de Bioingeniería, Biomateriales y Nanomedicina (CIBER-BBN), Barcelona, Spain (e-mail:leonardo.sarlabous@upc.edu, abel.torres@upc.edu, raimon.jane@upc.edu).

J. A. Fiz and J. Morera are with Pneumology Service of Hospital Germans Trias I Pujol, Badalona, Spain, and IBEC and CIBER-BBN, Barcelona, Spain (e-mail: jafiz@msn.com).

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II. METHODOLOGY

A. *Synthetic Mechanomyographic Signal with Real Cardiac Vibration Interference*

The MMG synthetic signal was generated with similar components and characteristics to those of MMGdi signals. First of all, in order to simulate the cyclical behavior of the respiratory MMGdi signal an amplitude modulation envelope has been generated. The amplitude of MMGdi signal is larger in the inspiration phase and lower in the exhalation phase. Consequently, the amplitude of the respiratory MMG signals varies cyclically with a frequency determined by the respiratory rate. Fig 1a shows the synthetic envelope generated (ENV). The respiratory rate was 18 cycles per minute. The inspiratory period was a 50% of the total respiratory period. In turn, the inspiratory period was divided into 3 parts: (1) rise (25%), (2) plateau (50%) and fall (25%). The rising and falling phases were simulated by means of half hanning windows. The duration of the signal was 80 seconds (24 respiratory cycles). Finally, the amplitude of MMGdi signal progressively increases with contraction effort [8,9]. In order to simulate this behavior, the amplitude of the enveloped was increased linearly in each respiratory cycle from 1 to 5.

The MMG signal stems from oscillations or vibrations of low amplitude generated during muscular contractions. These components are related to the mechanical vibrations of the muscle [1]. The signal is dominated by low-frequency components. In general, these components lie in the range between 5 and 50 Hz, the main frequency content of respiratory muscle MMG signals being below 25 Hz. It is well established that the amplitude of the MMG signal is random in nature [1], so the vibratory behavior of the MMG signal was generated using Gaussian noise filtered with a fourth-order Butterworth band-pass filter. The frequency of MMGdi signal decreases with contraction effort [8,9]. In order to simulate this behavior the cut-off frequency of the filter were decreased linearly in each respiratory cycle from [15-25 Hz] to [5-15 Hz] (the mean frequency decreases from to 20 to 10 Hz). Fig. 1b shows the random signal with decreasing frequency (RND).

Fig. 1 c shows the synthetic pure muscle vibration MMG signal (MMGs). This signal has been generated as the multiplication of ENV and RND signals plus a background Gaussian noise filtered between 5 and 50 Hz with an amplitude of 0.1.

Fig.1 e shows the real cardiac vibration or mechanocardiographic (MCG) signal. This MCG signal was acquired with a Kistler 8312B2 capacitive accelerometer placed on the surface of the thoracic cage, between the seventh and eighth intercostal spaces in the left anterior axillary lines. In order to isolate the MCG activity to the respiratory muscular activity the acquisition was made during apnea (absence of respiratory activity) in a healthy subject volunteer. Four segments of 20 seconds of MCG apnea signals were concatenated to obtain a 80 second signal. The electrocardiographic (ECG) signal was acquired simultaneously (Fig. 1d).

Finally, synthetic MMG signal with real MCG noise component added (MMGr) was generated adding the MMGs and MCG signals. The sampling frequency used to generate all the signals was 200 Hz.

B. *MMG Adaptive Noise Canceller*

The block diagram of the MMG adaptive noise canceller is shown in Fig. 2. The primary input to the noise canceller

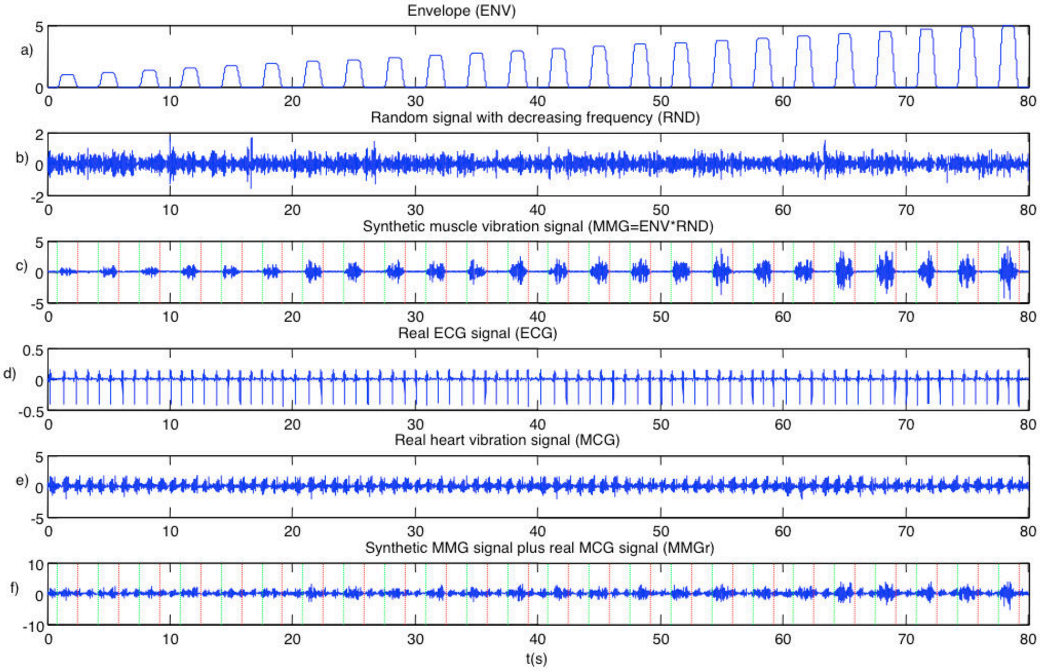

Fig. 1. a) Amplitude envelope of the mechanomyographic (MMG) component, b) random signal with decreasing frequency (RND), c) muscle vibration synthetic MMG signal (MMGs), d) real electrocardiographic (ECG) signal in a apnea epoch, e) real cardiac vibration mechanocardiographic signal of a apnea epoch (MCG), f) Synthetic MMG signal with real MCG noise component added (MMGr).

(d[n]) is the synthetic MMG signal corrupted with the real cardiac vibration interference (MMGr). The reference input (x[n]) must be uncorrelated with the MMGr activity but correlated with the cardiac vibration interference. This signal was artificially generated according to the method described in the section C. The output of the adaptive filter is the cancellation signal (y[n]) which is subtracted from the original signal in order to produce the filtered output (e[n]) that is the MMG signal with a reduction of the cardiac vibration interference. Fig. 3 shows an example of the input and output of the adaptive noise canceller: the primary input (MMGr), the reference input (MCGs), the cancelling output (MCGa) and the error output or filtered signal (MMGf).

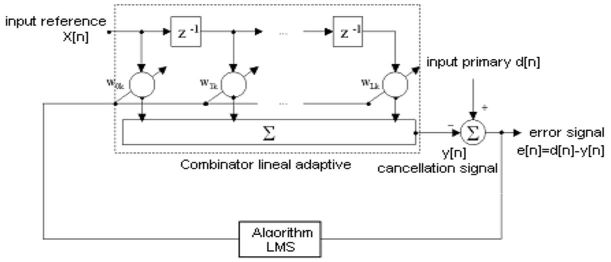

Fig. 2. Scheme of an adaptive noise canceller

C. *Cardiac Vibration Reference Signal*

The first step in the generation of the cardiac reference signal is the detection of the QRS complexes in the ECG signal (Fig. 1d) with a detector based on the Pan-Tomkins algorithm [1]. With these detections the cardiac vibration present in the MMGr corresponding to each beat is averaged in order to obtain a cardiac vibration or mechanocardiographic pattern (MMGp). Fig. 4a shows the aligned cardiac vibration complexes of the 84 beats present in the MMGr signal. Fig. 4b shows the averaged MMGp. Finally, this pattern is convolved with a train of unitary impulses generated from the QRS complexes detections, in which to each detected cardiac beat matches an impulse. The output of this convolution is an estimation of the cardiac activity present in the MMGr signal. This signal is considered as the reference input of the adaptive filter.

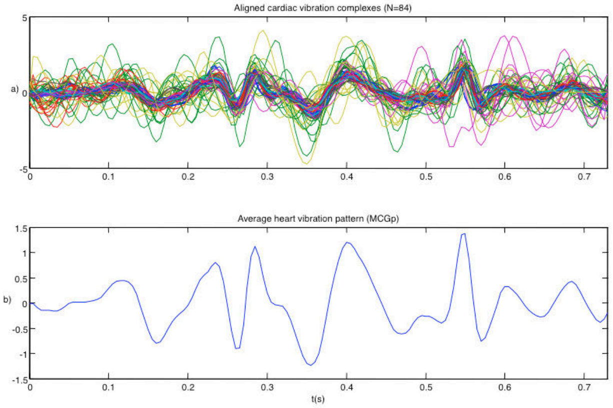

Fig. 4. a) Cardiac vibration complexes aligned based on the R point in the ECG signal (N = 84 beats) b) Averaged cardiac vibration pattern (MCGp).

III. RESULTS

The ANC method described in the previous section was applied over the MMGr signal using the LMS algorithm with a vector of 50 weights (0.25 seconds) and values of the adaptation constant (μ) ranging from 0.0001 to 0.022. Fig. 5a shows the evolution of the Pearson's correlation coefficient (PCC) between the RMS of the filtered MMGr signal (MMGf) with the different μ constants used and the amplitude of the ENV signal. Fig. 5 b shows the evolution of the PCC between the fm of the filtered MMGr signal (MMGf) with the different μ constants used and the fm of the RND signal. The curves show a maximum value of 0.0028 and 0.0022, respectively.

Figs. 6 and 7 compare the RMS and fm parameters obtained with the MMGs and MMGr signals, and the MMGf signal obtained with the ANC algorithm using a μ of 0.0025. Figs. 6a, 6b, 6c shows, respectively, the correlation plots between the amplitude ENV signal and the RMS of the MMGs, MMGr and MMGf. Figs. 6d, 6e, 6f shows,

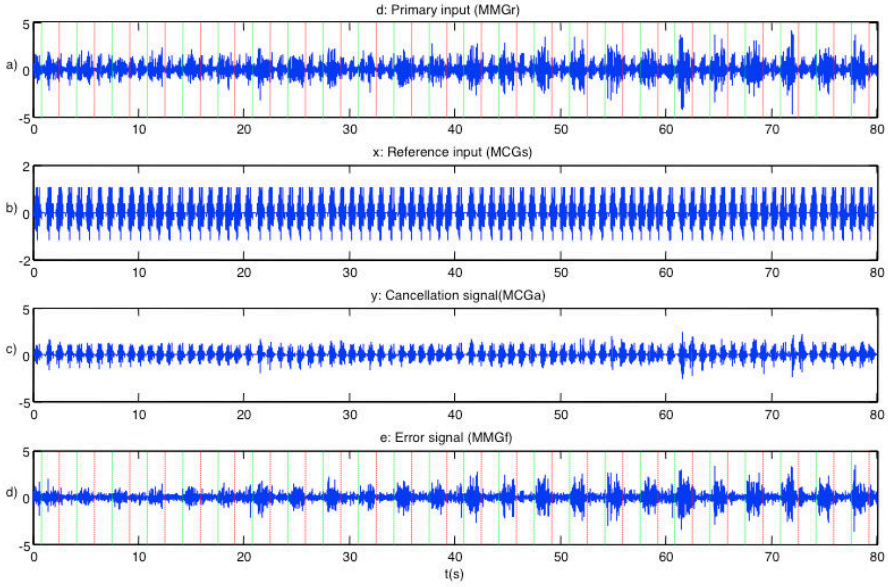

Fig. 3. Input and output of the adaptive noise canceller: a) d: primary input (MMGr), b) x: reference input (MCGs), c) y: Cancelling output (MCGa), d) e: Error Output or filtered signal (MMGf).

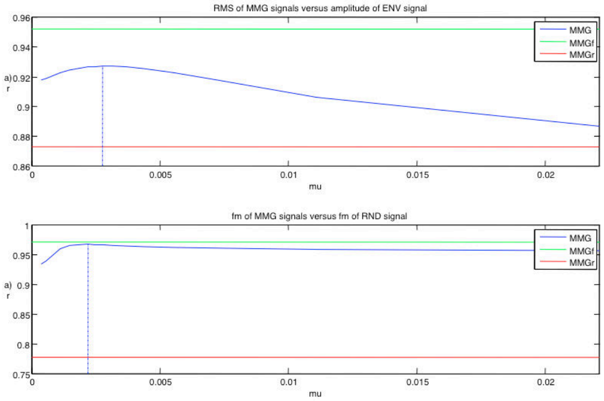

Fig. 5. Evolution with the adjustment constant mu of the LMS algorithm in the adaptive cancellation of the Pearson correlation coefficient between (a) the amplitude of the signal envelope (ENV) and the root mean square (RMS) of the mechanomyographic signal with MCG noise filtered with the adaptive algorithm (MMGf), and (b) the mean frequency (fm) of the random signal (RND) and the fm of the MMGf signal.

respectively, the correlation plots between the fm of the RND signal and the fm of the MMGs, MMGr and MMGf signals. Fig. 7 shows the evolution of the RMS and fm of the MMGs, MMGr and MMGf signals, during the 24 respiratory cycles.

IV. CONCLUSIONS

In this work, we have quantitatively evaluated the effect of adding real MCG noise over a synthetic MMG signal in the amplitude and frequency parameters. The PCC between the RMS of the MMG signal and the theoretical value (amplitude of ENV signal) decreases from 0.95 to 0.87 when adding noise, while the PCC between the fm of the MMG signal and the theoretical value (fm of RND signal) decreases from 0.97 to 0.78. With the ANC algorithm proposed in this work we have managed to reduce considerably the effect of the cardiac noise on the amplitude and frequency MMG parameters: the PCC of the filtered signal were 0.93 and 0.97 for the RMS and fm, respectively. We concluded that the presented ANC method is an interesting technique to attenuate the cardiac interference in of respiratory MMG signals. Further investigation should be carried out to evaluate the performance of the ANC algorithm in real MMGdi signals.

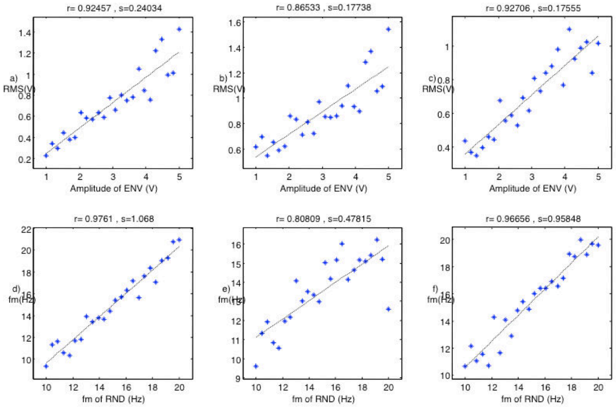

Fig. 6. Correlation plot between the amplitude of the signal envelope (ENV), and the root mean square (RMS) of the mechanomyographic signals (a) without noise (MMG), (b) with mecanocardiographic (MCG) noise added (MMGr), and (c) with MCG noise filtered with the adaptive algorithm (MMGf), and between the mean frequency (fm) of the random signal (RND) and the fm of the signals (d) MMG, (e) MMGr and (f) MMGf.

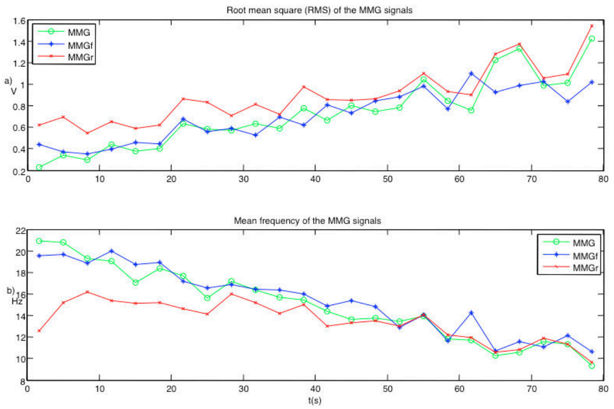

Fig. 7. Evolution of (a) the root mean square (RMS) and (b) the mean frequency (fm) of the 24 respiratory cycles in the mecahnomyographic signal without noise (MMG), the mechanomyographic signal with added mecanocardiographic added (MMGr), and the MMG signal with noise filtered using the adaptive cancellation algorithm (MMGf).

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