Adaptive Filtering for Electromyographic Signal Processing in Scoliosis Indexes Estimation

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Abstract: Adolescent idiopathic scoliosis is defined as a three-dimensional deformity of the spine and trunk occurring in about 2.5% of most populations. It is usually analyzed radiographically, but electromyography (EMG) can be also used, since muscles activity is correlated to deformity progression. EMG ratio is a numerical index used in the literature to provide information about scoliosis progression. Trunk EMG recordings are strongly affected by the electrocardiogram (ECG) of the subject. Previous studies removed this interference from the EMG signal by blanking the QRS complexes of the ECG but, as a consequence, several segments of the signal are removed. Furthermore, the other relevant ECG waves such as P and T are not cancelled and can invalidate the computation of parameters such as the EMG ratio. The aim of this study is to evaluate the possibility, by means of a modified recording protocol including further electrodes, to completely remove the ECG interference by adopting a multi-reference recursive least square (RLS) adaptive filter. The results of the study reveal how the complete clearing of the ECG from the EMG channels leads to different numerical values of the index, compared to the QRS blanking, more reliable and meaningful for the clinicians.

1 INTRODUCTION

Scoliosis is commonly referred to as a lateral curvature of the spine, but the deformity is much more complex. Indeed, it is a three-dimensional deformity of the spine and trunk (M. A. Asher et al.).

Adolescent idiopathic scoliosis (AIS) occurs in healthy pubertal children and the prevalence of AIS with an angle of the spinal curve larger than 10° is approximately 2.5% in the general population (M. Monticone et al.).

The etiology is still poorly defined, even if the main causes could be recognized as: genetic predisposition, skeletal, muscular and neurological disturbances during growth, connectivity tissue abnormalities (M. Monticone et al.).

The primary treatment goal for adolescents is to reduce progression in order to decrease the risk of back pain, disability, breathing problems and cosmetic deformities, and improve their health-related quality of life during adulthood.

The condition of subjects with idiopathic scoliosis is usually analyzed radiographically. However, electromyography (EMG) can be also exploited, since abdominal and paravertebral muscles are essential to maintain or modify the shape of the spine. EMG is the recording of the bio-electrical activity of muscle fibers. For this reason, it has been investigated over few decades to observe which relation could be recognized between paraspinal muscles activity and scoliosis deformity. Some studies (J. Cheung et al) show that the paraspinal muscle activity ratios at the lower end vertebra are correlated to increased axial rotation of the spine, and provide a valuable tool to predict a rapid increase of its curvature. The EMG ratio index involves measurements of the EMG activity on the convex and concave sides of the scoliotic curve, identified from a radiographic image on the coronal plane.

Trunk muscle EMG is contaminated by the electrical activity of the heart (electrocardiogram, ECG), due to its position in the chest close to the recording site. Other noise sources, such as motion artifacts, mains interference, etc., contaminate the EMG making it difficult to obtain the information of interest without appropriate signal processing methods.

Notch filters can remove mains interference from the recorded surface EMG signals very effectively, whereas high-pass filters with a cut-off frequency between zero and 5 Hz may be used to remove

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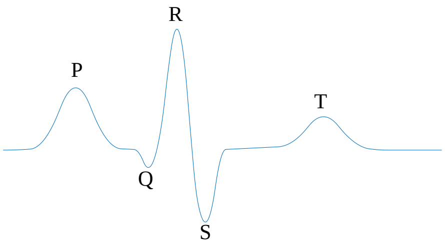

Figure 1: Main epochs of the cardiac cycle as visible in one ECG lead (synthetic data).

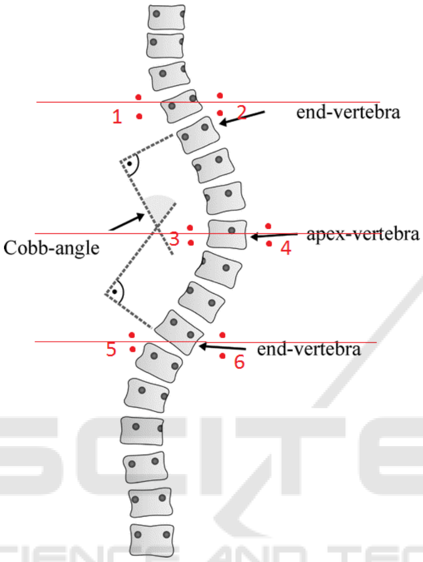

Figure 2: Positioning of the 12 electrodes for the 6-channel EMG recordings following the protocol adopted for this study.

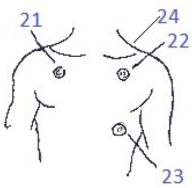

Figure 3: ECG electrodes sites following the protocol adopted for this study.

movement-induced baseline wandering artifacts.

Different methods have been proposed to remove the ECG artifact from EMG signals. This problem is usually solved by blanking the QRS complexes from the ECG signal (J. Cheung et al). QRS is the epoch of the ECG related to the ventricular depolarization, originating the heart systole, and it represents the sharpest and tallest waveform of the ECG, as clearly visible from Fig. 1. This approach is challenged in this paper, since it leads to the cancellation of useful

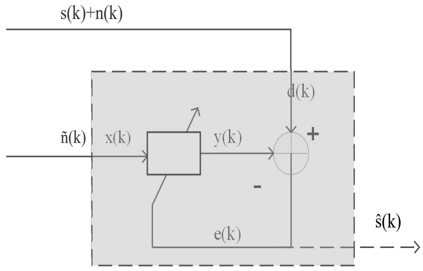

Figure 4: Typical scheme of an adaptive noise canceler.

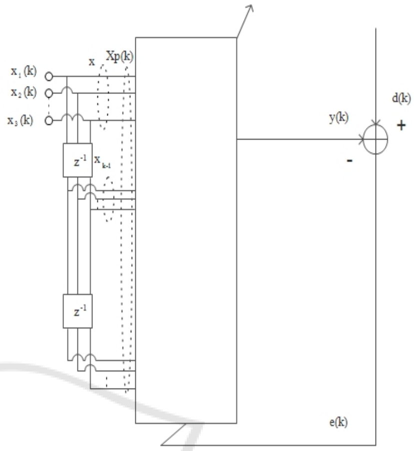

Figure 5: Multichannel adaptive filter.

segments of the EMG signal and, at the same time, it does not solve the problem of removing the other ECG waves (P and T, see Fig. 1).

In a previous work (Lu G. et al), a single-channel adaptive noise canceler based on the recursive least square (RLS) approach was evaluated as effective and efficient for ECG cancellation in surface EMG recordings. In this work, we propose the adoption of multi-reference RLS adaptive filters for ECG interference cancellation in EMG ratio indexes computation (J. Cheung et al), comparing the results with those achievable by using QRS blanking. The results highlight the better quality of the signal processed with the proposed method and, consequently, a more reliable estimation of the EMG ratio.

2 MATERIALS AND METHODS

The acquisition protocol for the EMG signal is first described in this section. Then, the two different algorithms used to cancel the ECG interference from the EMG signals are presented, along with the study population.

2.1 Signal Acquisition Protocol

From a radiographic image of the trunk, in a coronal projection, it was possible to define which were the upper and lower vertebrae and the apex vertebra of the curve deformity. This is important to define the electrodes placement sites. Furthermore, the Cobb angle (i.e. the angle formed between a line drawn parallel to the upper border of the upper vertebral body and a line drawn parallel to the lower border of the lowest vertebra of the scoliotic curve; then erecting perpendiculars from these lines to cross each other, the angle between these perpendiculars being the angle of curvature", see Fig. 2) was determined.

To measure the activity of the paraspinal muscles, in particular of the multifidus muscles, six pairs of disposable adhesive surface EMG electrode (CDES000024 by Spes Medica srl) were placed symmetrically with respect to the superficial spinae muscles at three different levels, corresponding to the upper-end, apex and the lower-end vertebrae of the curve. An example of this electrode positioning is shown in Fig. 2. The electrodes were chosen focusing on the performance in terms of signal recording and children's comfort due to the light adhesive properties of the solid hydrogel.

The EMG measurements were performed at rest in standing position, for 60 s. Four electrode were placed on the torso, as it can been seen from Fig. 3, in order to collect the ECG along three orthogonal axes in space. This enables the reconstruction of the electrical activity of the heart in the three dimensions, yielding a better projection of this activity in possibly any place on the body surface.

Signal acquisition was performed by using a 32-channels physiological recording device, namely the Porti7 by TMSI BV. It is a general purpose recording instrument providing unipolar and bipolar electrophysiological inputs and auxiliary inputs. In this application, 16 unipolar channels were used and the bipolar leads were obtained digitally post-processing the unipolar leads. The sampling frequency was set to 2048 Hz for each channel and the digital data resolution was 22 bits, 71.526 nV per bit, with a gain of 50 mV/V. No analog filtering is present in the signal chain. Decimation and linear phase digital low-pass filtering is performed inside the analog to digital converter (cut-off frequency is 553 Hz).

2.2 ECG Cancellation by Multi-reference RLS Adaptive Filter

Fig. 4 shows the block diagram of an adaptive noise canceller. The aim of an adaptive filter used in an interference cancellation configuration, is to extract a clean version of the signal of interest $s(k)$. This signal is corrupted by the additive noise component $n(k)$. Employing a reference signal strongly correlated to the noise but not to the signal of interest, the adaptive filter adjusts its coefficients in order to obtain an output $y(k)$ that approximates $n(k)$, forcing the error signal $e(k)$ to resemble $s(k)$.

$$d(k) = s(k) + n(k) \tag{1}$$

$$x(k) \approx n(k) \tag{2}$$

$$y(k) = w^T x(k) \tag{3}$$

Adaptation of the filter coefficients follows a minimization procedure of a particular objective or cost function. The classical linear Wiener filter minimises the mean-square error (MSE):

$$\xi(k) = E[e^2(k)] \tag{4}$$

$$\xi(k) = E[d^2(k)] - 2w^T p + w^T R w \tag{5}$$

Equating the gradient vector of ξ respect to the adaptive filter coefficient w to zero minimizes the MSE cost function:

$$\Delta_w \xi_D(k) = -2p(k) + 2R(k)w \tag{6}$$

obtaining:

$$w(k) = R^{-1}(k)p(k) \tag{7}$$

where R is the input signal correlation matrix and p the crosscorrelation vector between the reference signal and the input signal. To be able to solve the Wiener solution, R must be non-singular. If the filter length is greater than that required to reduce the error to zero, $R(n)$ will become singular.

RLS filter family uses the weighted least-squares objective function, instead of the MSE cost function, defined as:

$$\xi_D(k) = \sum_{i=0}^{k} \lambda^{k-1} [d(i) - w^T x(i)] \tag{8}$$

The forgetting factor λ, which is a real valued parameter in the range from 0 to 1, allows to emphasize the most recent error samples, giving to the objective function the ability of modelling non-stationary processes.

The RLS algorithm adaptively updates the coefficient vector to minimize the summation of weighted least-square errors. In particular, it defines the R and p parameters, introducing the forgetting factor λ:

$$R(k) = \sum_{i=0}^{k} \lambda^{k-1} x(i) x^T(k) = X^T(k) X(k) \tag{9}$$

$$p(k) = \sum_{i=0}^{k} \lambda^{k-1} d(i) x(i) 0 X^T(k) d(k) \tag{10}$$

Consequently, the optimum solution takes the form:

$$w(k) = R^{-1}(k)[x(k)e(k) + R(k)w(k-1)] \tag{11}$$

The computation of the inverse matrix of R can be reduced significantly by using the matrix inversion lemma, obtaining:

$$R^{-1} = \frac{1}{\lambda}[R^{-1}(k-1) - \kappa(k)k^T(k)] \tag{12}$$

where:

$$\kappa(k) = R^{-1}(k)x(k) \tag{13}$$

$$k(k) = R^{-1}(k-1)x(k) \tag{14}$$

At each step, the RLS algorithm estimates R and P based on all past data and updates the weight vector using the matrix inversion lemma. The filter coefficient update equation becomes:

$$w(k) = w(k-1) + e^*(k)\kappa(k) \tag{15}$$

The RLS filter does not attempt to solve the Wiener solution at each step, that would require the calculation of repeated inverted R matrix, but updates $R^{-1}(k)$ using $R^{-1}(k-1)$, the inverted R matrix of the previous step. In this case, no matrix inversion is required, as it is shown in Eq. 15. The only invertible matrix that is required to be calculated is $R^{-1}(0)$.

In this application, a multireference RLS adaptive filter is used to process each EMG channel $d(k)$ for ECG interference cancellation. The three projections of the ECG along the three orthogonal axes described by the combination of the four electrodes on the torso represent the three different components of $x(k)$. In the particular case of multi-reference, the block diagram presents a difference in the $x(k)$ input signal, as it is shown in Fig. 5, where the input vector at k instant does not present only one sample, but the samples at k instant of all the inputs considered by the system.

For the RLS filter computation, at $k = 0$, the initial instant, two variables must be chosen from the user: the initial coefficient vector w and the inverse matrix of R. If there are some a priori information, they can be used to set the first values of the w vector, if not, $w(0)$ is set as an array of zeros. Moreover, the forgetting factor λ has to be chosen. It impacts on the ability to track the input signal and on the stability of the filter coefficient. To this aim, λ was empirically fixed at 0.98. As the number of the processed samples increases, the effect of this initialization error will decrease because of the effect of the weighting factor λ.

It is not simple to choose the length of data required for ensuring invertibility of R. The RLS method uses an approximate initialization, so it does not require matrix inversion. At $k = 0$, the coefficient vector w is inizialized to an array of 0, of the length 3 (the length of each of the three reference channel was chosen equal to 1). The initial correlation matrix $R^{-1}(0)$ was set equal to the identity matrix of 3×3, because of the channel length of 1 and the use of 3 channels. The trick behind the chosen $R^{-1}(0)$ is that it could be defined as:

$$R^{-1}(0) = \delta I \tag{16}$$

where δ is the regularization parameter, to which should be assigned a small value for high signal-to-noise ratio (SNR) and a large value for low SNR, which may be justified on regularization grounds (Haykin S.).

To sum up, Alg. 1 presents the pseudocode of this method, where the *invR*, $R^{-1}(k)$, is the result of the combination of the past *invR*, $R^{-1}(k-1)$. Moreover, in the case of multireference adaptive filter, the error vector E is the result of the difference between d, the raw EMG signal, that presents the signal of interest and the noise, and the scalar product of the coefficient vector w and the three reference signals x.

Before feeding the signals to the multi-reference RLS adaptive filter, they have been high-pass filtered in order to remove large baseline wandering artifacts. To this aim, a linear-phase equiripple finite impulse response (FIR) filter (order 1124, 80 dB attenuation) with a cut-off frequency of 5 Hz was designed. Being an offline processing, no special care was paid to the filter order, preferring to achieve a linear phase response associated with filter causality.

Even though the adaptive filter is able to cancel the whole ECG interference, not only the QRS complexes, their attenuation can be used to evaluate the cancellation performance, since it is the highest component of the ECG signal.

2.3 ECG Cancellation by QRS Blanking

QRS blanking (M. Monticone et al.) was performed on each EMG channel, pre-processed using the same FIR filter adopted for the previous method. In this way, variability in the ECG cancellation performance cannot be biased by a different pre-processing stage.

Algorithm 1 : Pseudocode of the multireference RLS algorithm.

for each sample of the X matrix x **do**
  //X contains the x inputs
  $\kappa = invR \cdot X;$
  $k = \kappa/(\lambda + X' \cdot \kappa);$
  $invR = (1/\lambda) \cdot (invR - \kappa \cdot \kappa'/(\lambda + X' \cdot \kappa));$
  $E = d - W' \cdot X;$
  $W = W + E^* \cdot k;$
end for

However, for QRS blanking, the 50 Hz noise was eliminated by using a notch filter. Afterwards, a peak detection algorithm was used to find the R peak of the ECG waves. The peak detection algorithm applied in this work is the Pan-Tompkins algorithm (J. Pan et al.). Pan-Tompkins method filters the ECG signal through a band-pass filter to emphasize the QRS complex band. The filtered signal goes through a derivative filter, then it is squared and a moving window integration is applied. Finally, R peaks detection is performed by means of an adaptive thresholding mechanism. The QRS complexes were removed by deleting the samples in an interval of 125 ms around the R peaks.

No other waves of the ECG signal (i.e., P and T) are removed or attenuated by this approach.

2.4 Paraspinal Activity Ratio

The paraspinal activity EMG ratio is defined as the absolute summated EMG amplitudes, over the total EMG recording time, of an electrode pair on the convex side divided by the same quantinti of a contralateral electrode pair on the concave side. EMG is referred to the erector spinae muscles.

In this way, an activity EMG ratio of one means that the EMG activities on the convex and concave sides of the scoliotic curve are the same. An EMG activity ratio higher than one means that the EMG activity on the convex side is greater than that on the concave side. Finally, an EMG activity ratio lower than one stands for less EMG activity on the convex side than on the concave side (J. Cheung et al). The study (J. Cheung et al) correlates both spinal speed and muscle activity asymmetry to the progression of the idiopathic scoliosis. The evidences from that study reveal that, in the standing condition, the lower end vertebra index values are recognized in the non-progressive groups if they fall in the range [0.43 1.64], while the range [0.80 7.86] is recognized as a progressive idiopathic scoliosis.

Table 1: Study Population.

	Subject 1	Subject 2
Upper end vertebra	D11	D10
Lower end vertebra	L4	L3
Apex vertebra	L2	L1
Cobb angle	14°	19°

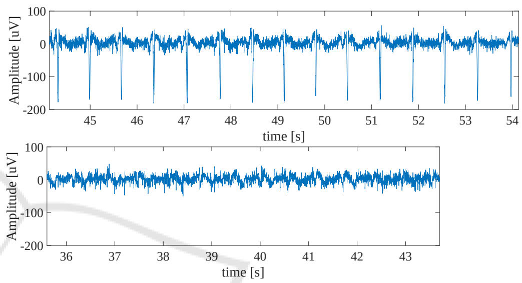

Figure 6: From top to bottom: 5 Hz high-pass filtered signal and processed signal by QRS blanking.

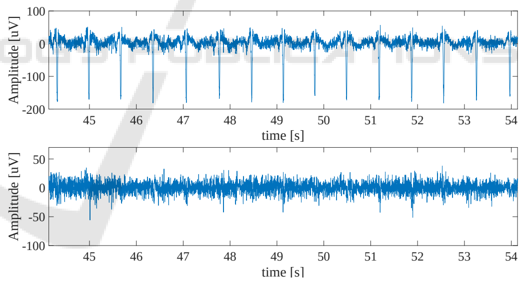

Figure 7: From top to bottom: 5 Hz high-pass filtered signal and RLS adaptive filtered signal.

2.5 Study Population

In order to test the algorithms on real signals, two female subjects, with a right dorso-lumbar adolescent idiopathic scoliosis, were enrolled in the study. The study was performed following the principles outlined in the Helsinki Declaration of 1975, as revised in 2000.

In Table 1, the principal characteristics of the two enrolled subjects are presented. The Upper, Lower and Apex vertebra are referred to the anatomical name of each spine vertebra(C, cervical; D dorsal, thoracic; L, lumbar; S, sacral).

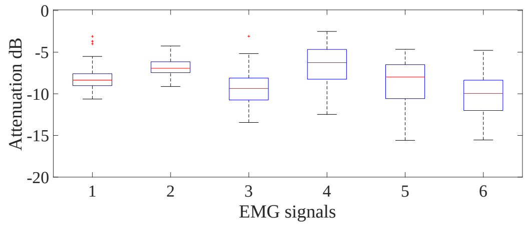

Figure 8: Boxplots of the six signals of Subject 1.

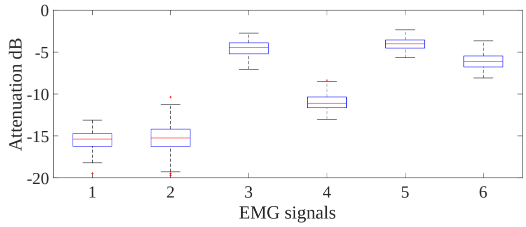

Figure 9: Boxplots of the six signals of Subject 2.

3 RESULTS

3.1 ECG Cancellation Results

The raw signals were first preprocessed by using the 5 Hz high pass filter, mainly introduced to remove the baseline wandering artefact, and then processed according to the two algorithms described above. As it can be seen from Fig. 6, when QRS blanking algorithm is used, the P and T waves keep to stay in the processed signal, despite they are mainly characterized by low frequency components. Moreover, the processed signal is shortened compared to the original one, also losing the EMG information present in the blanked parts. This can be also seen in Fig. 6, where 10 seconds of the original signal correspond to about 8 seconds of the QRS blanked signal.

Conversely, as it can be seen from Fig. 7, by using the RLS adaptive filter, P and T waves are also attenuated without any sample loss.

The attenuation of the QRS complexes provided by the adaptive filter was evaluated for the six EMG channels recorded on each subject. The results of such an analysis are reported in the boxplot in Fig. 8 and Fig. 9. In such figures, the median is highlighted, the box defines the 50% of the samples between the first and third quartile, and the whiskers range from the minimum to the maximum value, excluding the outliers (represented with crosses). The outliers are defined as data larger than q3 + 1.5(q3 - q1) or smaller than q1 - 1.5(q3 - q1), where q1 and q3 are the 25^{th} and 75^{th} percentiles, respectively, corresponding to approximately $\pm$ 2.7σ and 99.3 coverage, if the data are normally distributed.

Table 2: Paraspinal activity ratio results (LE Lower End, UE Upper End).

		Blanking	Adaptive Filter	Δ
Subject 1	Apex Vertebra	0.77	0.63	0.14
	LE Vertebra	0.82	1.05	0.23
	UE Vertebra	0.08	0.77	0.69
Subject 2	Apex Vertebra	0.88	1.2	0.32
	LE Vertebra	0.81	1.04	0.23
	UE Vertebra	0.8	0.98	0.18

3.2 Paraspinal Activity Ratio Results

The EMG activity ratio was evaluated on the signals processed using the two methods. The results are summarized in Table 2.

The absolute difference Δ between the two indexes is quite large, up to 0.69. The achieved results can be ascribed to the poor cancellation of the ECG signal with the QRS blanking methods, as depicted in Fig. 6. In this case, the contribution of P and T waves still affects the EMG signals. Despite the QRS complex is the highest component of the ECG, the other waves exhibit a wider support, so that QRS blanking is not sufficient to obtain an ECG-independent signal for the computation of the EMG activity ratio. The limitation of this study is the small study population, requiring the acquisition of a larger one. Moreover, Δ is remarkably too high, also compared to the typical range of variability of this parameter presented in (J. Cheung et al) and in 2.4. Such a big Δ make the two groups, non-progressive and progressive idiopathic scoliosis, possible to confuse the two population. In order to evaluate the significance of the paraspinal ratio recognizing those two groups, a larger dataset composed by healthy and AID subjects is needed.

4 CONCLUSION

In this work, two processing methods for the reduction of the ECG signal in EMG recordings for the evaluation of the EMG activity ratio index have been presented. QRS blanking and multi-reference RLS adaptive filtering have been used to process real data from subjects with AID. Despite the state of the art in the field only exploits QRS blanking for EMG preprocessing, the results presented in this work suggest that the non-complete removal of the ECG interference could hamper the achievement of a meaningful value for this index.

In the light of the results achieved in this work, we are currently acquiring a larger dataset including healthy subjects and patients affected by AID. This will strengthen the evidences of the present study in terms of EMG activity ratio index pre-processing.

Furthermore, with a larger dataset, homogeneous groups composed of a significant number of subjects can be formed. Such an approach is needed to study the effectiveness of the EMG activity ratio index with the improved pre-processing.

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