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Two-dimensional Compression of Surface Electromyographic Signals Using Column-correlation Sorting and Image Encoders

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***Abstract*—We present a new preprocessing technique for two-dimensional compression of surface electromyographic (S-EMG) signals, based on correlation sorting. We show that the JPEG2000 coding system (originally designed for compression of still images) and the H.264/AVC encoder (video compression algorithm operating in intraframe mode) can be used for compression of S-EMG signals. We compare the performance of these two off-the-shelf image compression algorithms for S-EMG compression, with and without the proposed preprocessing step. Compression of both isotonic and isometric contraction S-EMG signals is evaluated. The proposed methods were compared with other S-EMG compression algorithms from the literature.**

I. Introduction

Surface electromyographic (S-EMG) signals are important tools in the investigation of muscular behavior [1], [2]. The storage and/or transmission of these signals is an issue, because the amount of data is typically large, depending on factors such as the sampling rate, quantization precision, number of channels, and number of subjects, among others.

Several different approaches have been proposed for compression of electromyographic signals. Norris and Lovely [3] investigated the use of adaptive differential pulse code modulation. Guerrero and Mailhes [4] compared different compression methods based on linear prediction and orthogonal transforms. They showed that methods based on the wavelet transform outperform other compression methods. The use of the embedded zero-tree wavelet (EZW) algorithm has also been proposed [5], [6]. More recently, Carotti *et al.* [7] proposed a S-EMG compression scheme using algebraic code excited linear prediction (ACELP), a method originally proposed for speech encoding. Berger *et al.* [8] proposed an algorithm using the discrete wavelet transform and a scheme for dynamic bit allocation of the coefficients using a Kohonen layer. Brechet *et al.* [9] used discrete wavelet packet transform decomposition with optimization of the mother wavelet and of the wavelet packet basis, followed by an EZW-like coder. Filho *et al.* [10] adopted the multiscale multidimensional parser algorithm.

We have recently proposed the use of the JPEG2000 image encoding algorithm for compression of S-EMG signals, by segmenting the S-EMG signal and arranging the segments as columns of a 2D matrix [11]. In this work, we propose the use of a preprocessing step in which the columns of this matrix are reordered based on a measurement of their similarity. We compare results obtained with and without column-reordering, and also evaluate the use of an alternate image encoder, the H.264/AVC intra algorithm.

II. Materials And Methods

A. Signal Acquisition Protocol

Both isometric and isotonic S-EMG signals were used for evaluation of the proposed methods. A commercial electromyograph (Delsys, Bagnoli-2, Boston, MA, USA) was used for signal acquisition. This equipment uses active electrodes with a pre-amplification of 10 V/V and a 20–450 Hz passband. Signals were amplified with a total gain of 1000 V/V, and sampled at 2 kHz using 12-bit quantization (National Instruments, PCI 6024E, Austin, TX, USA). LabView (National Instruments, Austin, TX, USA) was used for signal acquisition, and Matlab 6.5 (The MathWorks, Inc., Natick, MA, USA) was used for signal processing.

Isometric contraction signals were obtained from 4 male healthy volunteers with 28.3 ± 9.5 years of age, 1.75 ± 0.04 m height, and 70.5 ± 6.6 kg weight. Signals were measured on the biceps brachii muscle. The signals were collected using 60% of the maximum voluntary contraction, with a 90° angle between arm and forearm, and in standing position. The protocol was repeated 5 times for each volunteer, with a 48-hour interval between experiments. A total of 19 S-EMG signals was acquired (one volunteer was absent during one session).

S-EMG during isotonic activities (cycling) were obtained from 9 healthy volunteers (6 men, 3 women), with 24.4 ± 4.3 years of age. All subjects presented normal body mass index. S-EMG was measured on the vastus medialis and vastus lateralis muscles, which are leg muscles with high surface electromyographic activity during the proposed

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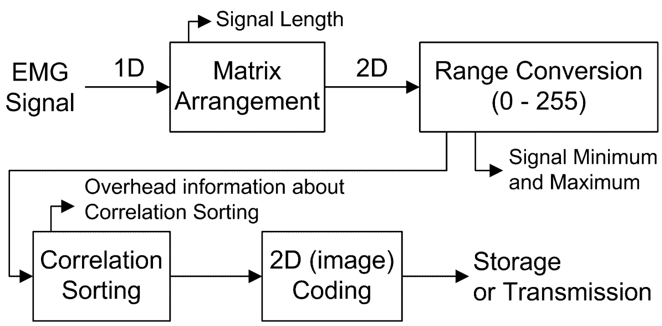
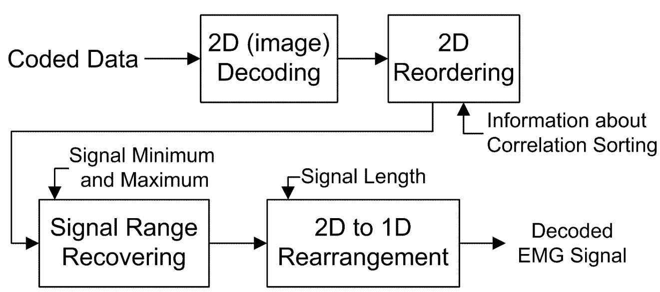
exercise. The exercise was performed using 70% of maximum power and 70% of maximum speed, until exhaustion. This was preceded by a warm-up period with a maximum duration of 4 minutes. This protocol was programmed into the instrumentation of the ergometric bicycle (Ergo-Fit, Ergo Cycle 167, Pirmasens, Germany). Signal acquisition was not performed during warm-up. A total of 18 S-EMG signals was acquired (9 volunteers, 2 electrodes).

B. Compression of S-EMG Signals Using 2D Encoders

Figure 1 shows a block diagram of the proposed coding scheme. The method consists in segmenting each S-EMG signal into 512-sample segments, and then arranging these segments as different columns of a two-dimensional (2D) matrix, which can then be compressed using 2D algorithms. In this work, we investigated the use of two off-the-shelf image encoders: JPEG2000 and H.264/AVC intra.



a) Encoder



b) Decoder

Fig. 1. Block diagram of the proposed compression algorithm.

JPEG2000 [12]–[14] is a state-of-the-art image coding standard which uses embedded block coding with optimal truncation [14] on the subband samples of the discrete wavelet transform of the image.

The H.264/AVC encoder is the latest standard for video compression [15], [16], and provides a two-fold gain in compression efficiency compared to the MPEG-2 and H.263 algorithms [17]. The H.264/AVC intraframe encoder has been effectively used for the compression of ECG signals [18], but has not been evaluated for S-EMG compression.

The number of columns in the 2D matrix is defined by the number of 512-sample segments. The last (incomplete) segment is zero-padded. The matrix is scaled to the 8-bit range (0 to 255). The columns are rearranged, based on their cross-correlation coefficients (this is discussed in the following subsection). The matrix is encoded using one of the above-mentioned image encoders. The list of original column positions is arithmetically encoded. Scaling parameters (maximum and minimum amplitudes) and number of samples are also stored (uncompressed).

The JPEG2000 algorithm was evaluated with compression rates ranging from 0.03125 to 8 bits per pixel. The H.264/AVC encoder was used in intraframe (still image) mode, with DCT quantization parameter values ranging from 51 to 1.

The encoded matrix is recovered using the appropriate image decoder, and the S-EMG signal is reconstructed by rearranging the matrix columns back into a one-dimensional vector and then scaling the signal back to its original dynamic range.

C. Preprocessing based on Correlation Sorting

Adjacent samples of S-EMG signals are typically moderately temporally-correlated. When the S-EMG signal is arranged into a 2D matrix, this feature is preserved along the vertical dimension (columns). However, along the horizontal dimension (rows), such correlation is generally lost. In order to increase 2D-compression efficiency, we attempt to increase the correlation between adjacent columns, by rearranging the columns based on their cross-correlation coefficients.

The matrix of column cross-correlation coefficients (R) is computed from the covariance matrix C, as follows:

$$R(u,w) = \frac{C(u,w)}{\sqrt{C(u,u) \cdot C(w,w)}}. \quad (1)$$

Then, the pair of columns that present the highest cross-correlation coefficient is placed as the first two columns of a new matrix. The column that presents the highest cross-correlation with the second column of the new matrix is placed as the third column of the new matrix, and so forth. A list of column positions in annotated. This procedure is similar to that used by Filho *et al.* for reordering segments of ECG signals [18], but the similarity metric used in that study was the mean squared error. Figure 2 illustrates the result of applying the proposed column-correlation sorting to a S-EMG signal arranged in 2D representation.

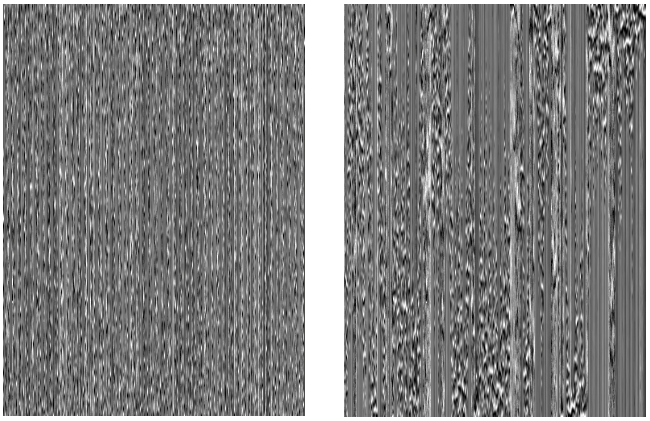
D. Performance Evaluation

The performance of the proposed compression algorithms was measured using two metrics: compression factor (CF) and percentage root mean square difference (PRD).

The compression factor is defined as:

$$CF(\%) = \frac{Os - Cs}{Os} \cdot 100 , \quad (2)$$

where Os is the number of bits required for storing the original data and Cs is the number of bits required for storing the compressed data, including overhead information.



(a) (b)

Fig. 2. S-EMG signal in 2D representation, where each column is a 512-sample segment of the signal. (a) original matrix. (b) preprocessed matrix (after correlation-based column reordering).

The percentage root mean square difference is defined as:

$$PRD(\%) = \sqrt{\frac{\sum_{n=0}^{N-1}\left(x[n]-\tilde{x}[n]\right)^2}{\sum_{n=0}^{N-1} x^2[n]}} \cdot 100 \ , \qquad (3)$$

where x is the original signal, $\tilde{x}$ is the reconstructed signal, and N is the number of samples in the signal.

III. Results

Table I shows mean PRD results for isometric contraction signals. The JPEG2000-based method provided slightly better reconstruction quality (lower PRD) than the EZW-based algorithm by Norris *et al.* [6] for compression factors values ≤85%. However, this difference was not statistically significant. Compared with the method by Berger *et al.* [8], JPEG2000 showed moderately inferior overall performance. The proposed preprocessing stage (correlation sorting) improves the performance of the JPEG2000-based approach. This is especially true for 90% compression, in which its performance is comparable to that achieved by Berger *et al.* The H.264/AVC-based method showed low overall performance, even with preprocessing.

TABLE I
Mean PRD results (in %) for isometric contraction signals

Compression Factor	75%	80%	85%	90%
Norris *et al.* [6]	3.8	5	7.8	13
Berger *et al.* [8]	2.5	3.3	6.5	13
JPEG2000	3.58	4.60	7.05	16.69
c.s. + JPEG2000	3.50	4.48	6.92	13.44
H.264/AVC	5.51	7.03	10.01	16.68
c.s. + H.264/AVC	5.37	6.90	9.93	16.62

c.s. refers to correlation sorting preprocessing.

Table II shows mean PRD results for isotonic exercise signals. The results obtained with the JPEG2000-based approach are significantly better than those achieved by Norris *et al.* When compared with the algorithm proposed by Berger *et al.*, the JPEG2000-based method provides superior results for high compression factors (≥90%). With correlation sorting, the JPEG2000-based approach is superior to all other evaluated methods for the range of evaluated compression rates (75% compression was outside this range). The H.264/AVC-based method achieved better overall performance than the algorithm by Norris *et al.*, especially when preprocessing is used. The preprocessed H.264/AVC-based approach was superior to the algorithm by Berger *et al.* for high compression factors (≥85%).

TABLE II
Mean PRD results (in %) for isotonic exercise signals

Compression Factor	75%	80%	85%	90%
Norris *et al.* [6]	7.85	9	9.5	20
Berger *et al.* [8]	2.6	4.4	7.25	20
JPEG2000	4.27	5.36	7.62	13.61
c.s. + JPEG2000	–	4.39	5.77	9.39
H.264/AVC	5.59	7.21	10.17	16.39
c.s. + H.264/AVC	4.13	5.16	7.12	11.30

c.s. refers to correlation sorting preprocessing.

Figure 3 illustrates the compression quality for a S-EMG signal measured during isotonic muscular activity. The central 2500 samples of the original, reconstructed, and error signals are shown. In this example, correlation sorting was used, and the PRD was 3.82% and 4.43% for the JPEG2000 and H.264/AVC approaches, respectively, with 80% compression factor. The noise pattern observed for both approaches seems visually uncorrelated with the signal.

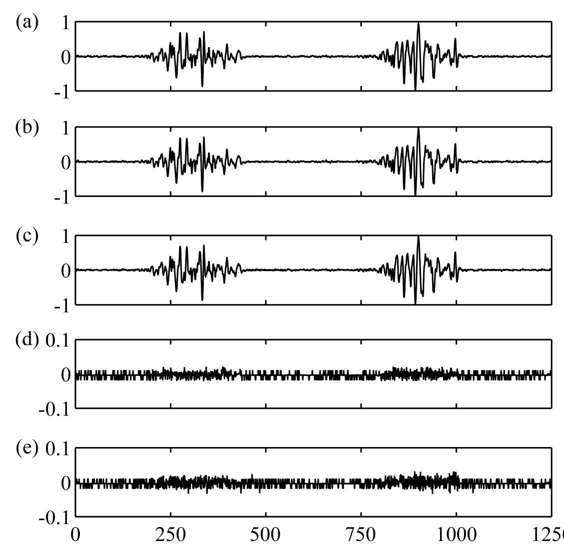


Fig. 3. Representative results for a 1250-ms segment of an isotonic signal (CF=80%): (a) uncompressed; (b) *c.s.* + JPEG2000; (c) *c.s.* + H.264/AVC; (d) JPEG2000 reconstruction error; (e) H.264/AVC reconstruction error. Reconstruction errors are magnified by 10-fold. The reconstruction error of the JPEG2000 algorithm is noticeably smaller than that of the H.264/AVC algorithm. The noise pattern seems visually uncorrelated with the signal.

IV. DISCUSSION

The signal acquisition protocols used by Norris *et al.* [6] and Berger *et al.* [8] for isometric contractions was very similar to the one used in this work: 12-bit resolution, 2 kHz sampling rate, S-EMG measured on the biceps brachii muscle. However, with respect to isotonic exercise, this work used signals from both vastus lateralis and vastus medialis muscles, whereas those studies only used signals measured on the vastus lateralis muscle. Furthermore, since Norris *et al.* did not describe their acquisition protocol for isotonic exercise, it is possible that the contraction level was different from the one used in this work, which could result in a set of signals with different characteristics. These facts must be taken in consideration when evaluating the results presented above.

V. CONCLUSION

This work presented a method for the compression of surface electromyographic signals using off-the-shelf image compression algorithms. Two widely used image encoders were evaluated: JPEG2000 and H.264/AVC intra. A preprocessing step was proposed for increasing inter-column correlation and improving 2D compression efficiency.

The proposed scheme was evaluated on surface electromyographic signals measured during both isometric and isotonic exercise. We showed that commonly available algorithms can be effectively used for compression of electromyographic signals, with a performance that is comparable or better than that of other algorithms proposed in the literature. We also showed that the proposed preprocessing stage significantly improves the performance of the proposed method. Future studies should evaluate what levels of signal distortion are clinically acceptable.

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