Examination of Single Wavelet-Based Features of EHG Signals for Preterm Birth Classification

Suparerk Janjarasjitt, Member, IAENG

Abstract—In this study, wavelet-based features of electrohysterogram (EHG) quantifying the electrical activity of uterine muscles are applied for preterm birth classification. EHG has been shown to provide useful information for uterine contraction that leads to the anticipation of delivery. A wavelet-based feature referred to as \( \Delta l \) in this study is determined from a difference between the logarithms of variances of detail coefficients of EHG data corresponding to two consecutive levels, i.e., \( l \) and \( l + 1 \). Performance on preterm birth classifications using single wavelet-based features of EHG data is examined. A simple thresholding technique is applied for preterm birth classifications. The leave-one-out cross validation is used to validate the performance on preterm birth classifications. From the computational results, it is shown that the wavelet-based features of EHG can provide a reasonable performance on preterm birth classification with the accuracy, the sensitivity and the specificity of 0.7099, 0.6842 and 0.7133, respectively.

Index Terms—electrohysterogram, preterm birth, pregnancy, wavelet analysis, classification

I. INTRODUCTION

The discrete wavelet transform is one of the most significant computational tools that has been applied to various applications including biomedical signal processing. The discrete wavelet transform is a natural tool for characterizing self-similar signals [1], [2]. The derivation of the discrete wavelet transform for the representation of \( 1/f \) processes [1], [3] makes the discrete wavelet transform can be further applied into the fields of fractals and complex systems analysis. Recently, computational tools and techniques applied for complex systems analysis have been widely applied to applications in biology and medicine [4]. One of those various applications in biology and medicine is cardiology where a number of measures derived from concepts of complex systems analysis applied to characterize heart rate variability (HRV).

In Ref. [4], the wavelet-based approach is applied to extract features of RR interval data for congestive heart failure classification. Such wavelet-based feature of RR interval data is demonstrated to be potentially a good feature for the congestive heart failure classification [4]. The similar wavelet-based approach is also applied for examining the characteristics of epileptic ECoG signals in Ref. [5]. In this study, the wavelet-based approach examined in Ref. [4] is applied to the so-called electrohysterogram (EHG) data for preterm birth classification. The EHG data correspond to the activity of uterine muscles [6] whereas the activity of uterine muscles of pregnant women may be used to predict the premature onset of labor [7], [8]. Preterm birth has been one of the most important issues worldwide. Prematurity is the leading cause of newborn deaths [9]. An estimated 15 million babies are born preterm every year [9]. In addition, this number is rising [9]. The preterm prediction and detection are therefore essential as they can help prevent preterm birth. Performance on preterm birth classifications using single wavelet-based features of EHG data extracted using the wavelet-based approach [4] is examined.

The rest of this paper is organized as follows. Section II presents data, wavelet-based feature extraction, and experimental setup. Section III details and discusses the computational results on preterm birth classifications. Finally, Section IV summarizes and concludes the paper.

II. METHODS

A. Data and Subjects

The electrohysterogram (EHG) data examined in this study is obtained from the Term-Preterm EHG Database (TPEHGDB) on PhysioNet (available online at http://www.physionet.org/physiobank/database/tpehgdv/). The TPEHGDB contains 300 recordings of EHG data collected from 1997 until 2006 at the Department of Obstetrics and Gynecology, Medical Centre Ljubljana, Ljubljana [6], [10]. The EHG data were recorded from a general population of pregnant women during regular check-ups either around the 22nd week of gestation or around the 32nd week of gestation [6], [10]. The EHG data were recorded using the sampling frequency of 20 Hz. Each EHG recording is composed of three channels, referred to as \( s_1 \), \( s_2 \), and \( s_3 \), which were recorded from 4 electrodes placed around the navel [6], [10].

All three hundred EHG recordings are classified into four groups according to their corresponding time of delivery (either term or preterm birth) and time of recordings (either early or later period of pregnancy). EHG recordings are classified as term birth if the delivery was after the 37th week of gestation; and preterm birth otherwise. EHG recordings are classified as early period if they were recorded before the 26th week of gestation; and later period otherwise. The EHG recordings that were recorded before the 26th week of gestation and on the the 26th week of gestation or after for the pregnancy with term birth are referred to as TE and TL groups, respectively. Likewise, the EHG recordings that

<table>
<thead>
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<th>TABLE I The number of EHG recordings</th>
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<tr>
<td></td>
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<tr>
<td>Early period</td>
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<td>---</td>
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<tr>
<td>Term birth</td>
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<td>Preterm birth</td>
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were recorded before the 26th week of gestation and on the the 26th week of gestation or after for the pregnancy with preterm birth are referred to as, respectively, PE and PL groups. The numbers of EHG recordings corresponding to each group are summarized in Table I.

B. The Wavelet-Based Features

The discrete wavelet transform (DWT) is applied to decompose an EHG signal into subband components through halfband lowpass and highpass filters. Approximations and details are obtained from the discrete wavelet decomposition using the scaling function and the wavelet function that correspond to, respectively, halfband lowpass filter and halfband highpass filter. For the L-level discrete wavelet decomposition, there are L sets of detail coefficients, i.e., \( d_l \) for \( l = 1, 2, \ldots, L \), and one set of approximation coefficients, i.e., \( a_L \), obtained. Only the detail coefficients \( d_l \) are however used.

The wavelet-based features of EHG signals examined in this study can be obtained by the following steps [4]:

1. Apply the discrete wavelet transform to decompose an EHG signal into \( L \) levels to obtain the detail coefficients \( d_l \);
2. Compute the variance of detail coefficients \( d_l \) corresponding to each level \( l \), \( \text{var}(d_l) \);
3. Take the logarithm to base 2 of the corresponding variance of detail coefficients, \( \log_2 \text{var}(d_l) \);
4. Subtract the logarithm of variance of detail coefficients corresponding to the level \( l \) from that corresponding to the lower level, \( \Delta_l = \log_2 \text{var}(d_{l+1}) - \log_2 \text{var}(d_l) \).

C. Experimental Setup

A segment with length of 8192 samples is obtained from the middle section of each channel of EHG recordings, i.e., \( s_1, s_2, \) and \( s_3 \). The 12th order Daubechies wavelets are applied to decompose EHG segments into \( 7 \) levels yielding \( 7 \) detail coefficients \( d_1, d_2, \ldots, d_7 \) and one approximation coefficient \( a_7 \). The coefficients \( d_1, d_2, d_3, d_4, d_5, d_6, d_7, \) and \( a_7 \) approximately correspond to 5.0–10.0-Hz, 2.50–5.0-Hz, 1.25–2.50-Hz, 0.63–1.25-Hz, 0.31–0.63-Hz, 0.16–0.31-Hz, 0.08–0.16-Hz, 0.00–0.08-Hz subbands, respectively. Accordingly, there are 6 wavelet-based features, i.e., \( \Delta_1, \Delta_2, \ldots, \Delta_6 \), extracted from each EHG segment. Two classifications examined focus on discriminating between pregnancies with term birth and pregnancy with preterm birth. In the first preterm birth classification, single wavelet-based features of EHG segments associated with the TE and PE groups are classified. Single wavelet-based features of EHG segments associated with the TL and PL groups are classified in another preterm birth classification. A thresholding technique is applied for classifying single wavelet-based features into either a term birth pregnancy or a preterm birth pregnancy. A leave-one-out (LOO) cross-validation is used to validate the performance on the preterm birth classifications as the numbers of EHG recordings associated with the PE and PL groups are small. A threshold \( \tau \) is obtained from a training set composed of single wavelet-based features of both positive (EHG segments associated with preterm birth pregnancy) and negative (EHG segments associated with term birth pregnancy) classes except a wavelet-based feature of one EHG segment. The left-out wavelet-based feature is used as a testing sample. This process is repeated to include all samples of wavelet-based features as the testing sample. A threshold \( \tau \) is determined from the training set of wavelet-based features \( \Delta_1 \) as follows [11]:

\[
\tau = \begin{cases} 
\frac{\max M_P + \min M_N}{2} & \text{if } M_P < M_N \\
\frac{\min M_P - \max M_N}{2} & \text{if } M_P > M_N 
\end{cases}
\]

where \( M_P \) and \( M_N \) denote the wavelet-based features \( \Delta_1 \) corresponding to positive and negative classes, and \( M_P \) and \( M_N \) denote the means of wavelet-based features \( \Delta_1 \) corresponding to positive and negative classes, respectively.

The classification is simply performed using the following rules [11]. In the first case, i.e., \( M_P < M_N \), an EHG segment is classified to belong to a positive class if the corresponding wavelet-based feature \( \Delta_1 \) is less than or equal to the threshold \( \tau \); and a negative class, otherwise. On the contrary, in another case, i.e., \( M_P > M_N \), an EHG segment is classified to belong to a positive class if the corresponding wavelet-based feature \( \Delta_1 \) is greater than or equal to the threshold \( \tau \); and a negative class, otherwise.

The performance of the preterm birth classifications using single wavelet-based features is evaluated using three conventional measures: accuracy (\( Ac \)), sensitivity (\( Se \)), and specificity (\( Sp \)) given by, respectively,

\[
Ac = \frac{TP + TN}{TP + TN + FP + FN}, \\
Se = \frac{TP}{TP + FN}, \text{ and} \\
Sp = \frac{TN}{TN + FP}
\]

where \( TP, TN, FP, \) and \( FN \) denote a number of true positives, a number of true negatives, a number of false positives, and a number of false negatives. In addition, the product of sensitivity and specificity, i.e., \( Se \times Sp \), is also determined as a performance measure that justifies both the true positive rate and the true negative rate.

The performances on preterm birth classification using other quantitative features including root-mean-square (RMS), median frequency (\( f_{med} \)), peak frequency (\( f_{peak} \)) and sample entropy (SampEn) provided on the TPEHGBD are also examined and validated using the same procedure. The RMS, median frequency, peak frequency, and sample entropy [6] were determined from filtered EHG signals rather than the original EHG signals. The original EHG signals, i.e., \( s_1, s_2, \) and \( s_3 \), were filtered using three different 4-pole digital Butterworth bandpass filters with 0.08–4.0-Hz, 0.31–0.63-Hz, and 5.0–10.0-Hz.

### Table II

**The \( p \)-VALUES OF \( t \)-TESTS DETERMINING THE SIGNIFICANT DIFFERENCES BETWEEN THE WAVELET-BASED FEATURES OF EHG SEGMENTS.**

<table>
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<tr>
<th>Feature</th>
<th>PE vs. TE</th>
<th>PL vs. TL</th>
</tr>
</thead>
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<tr>
<td>( \Delta_1 )</td>
<td>0.1692</td>
<td>0.0724</td>
</tr>
<tr>
<td>( \Delta_2 )</td>
<td>0.0910</td>
<td>0.4483</td>
</tr>
<tr>
<td>( \Delta_3 )</td>
<td>0.7813</td>
<td>0.8925</td>
</tr>
<tr>
<td>( \Delta_4 )</td>
<td>0.1212</td>
<td>0.5114</td>
</tr>
<tr>
<td>( \Delta_5 )</td>
<td>0.5140</td>
<td>0.4565</td>
</tr>
<tr>
<td>( \Delta_6 )</td>
<td>0.2921</td>
<td>0.1829</td>
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</table>

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Fig. 1. Box plots of wavelet-based features $\Delta_l$ of EHG segments.

0.3–4.0-Hz and 0.3–3.0-Hz passbands [6] referred to as, respectively, the spectral bands $b_1$, $b_2$ and $b_3$.

### III. Results

#### A. Characteristics of the Wavelet-Based Features

The wavelet-based features $\Delta_1$, $\Delta_2$, ..., $\Delta_6$ of EHG segments associated with all groups, i.e., PE, PL, TE, and TL, are compared in box plots shown in Fig. 1(a)–(f), respectively. The wavelet-based features of EHG segments vary corresponding to level $l$, channel, and also group.

Table II summarizes the $p$-values obtained from $t$-tests used to determine whether the wavelet-based features $\Delta_l$ of EHG segments associated with the preterm and term births are significantly different from each other. It is shown that there are statistically significant differences between the wavelet-based features $\Delta_4$ of EHG segments of channel $s_1$ associated with the PE and TE groups, the wavelet-based features $\Delta_4$ of EHG segments of channel $s_3$ associated with the PE and TE groups, the wavelet-based features $\Delta_1$ of EHG segments of channel $s_2$ associated with the PL and TL groups, the wavelet-based features $\Delta_6$ of EHG segments of channel $s_2$...
associated with the PL and TL groups, and the wavelet-based features $\Delta_3$ of EHG segments of channel $s_3$ associated with the PL and TL groups with $p < 0.05$ as written in bold in Table II.

B. Performance on Preterm Birth Classifications

The accuracy ($Ac$), the sensitivity ($Se$), the specificity ($Sp$), and the product of sensitivity and specificity ($Se \times Sp$) of the preterm birth classifications of EHG segments associated with the PE and TE groups using the leave-one-out cross-validation are summarized in Table III. The best accuracy, sensitivity, and specificity obtained for the preterm birth classifications are 0.8519, 0.7368, and 0.9650, respectively, using the wavelet-based feature $\Delta_5$ of channel $s_1$, the wavelet-based feature $\Delta_5$ of channel $s_3$, and the wavelet-based feature $\Delta_5$ of channel $s_1$. The best performance on the preterm birth classification of wavelet-based features of EHG segments associated with the PE and TL groups with respect to the product of sensitivity and specificity is however obtained using the wavelet-based feature $\Delta_4$ of channel $s_3$ with the product of sensitivity and specificity of 0.4880. The corresponding accuracy, sensitivity, and specificity are 0.7099, 0.6842, and 0.7133, respectively.

Table IV summarizes the accuracy ($Ac$), the sensitivity ($Se$), the specificity ($Sp$), and the product of sensitivity and specificity ($Se \times Sp$) of the preterm birth classifications of EHG segments associated with the PL and TL groups using the leave-one-out cross-validation. The best accuracy, sensitivity, and specificity obtained for the preterm birth classifications are 0.7971, 0.7368, and 0.8655, respectively, using the wavelet-based feature $\Delta_4$ of channel $s_3$, the wavelet-based features $\Delta_2$ of channel $s_1$ and $\Delta_3$ of channel $s_2$, and the wavelet-based features $\Delta_2$ of channel $s_2$ and $\Delta_6$ of channel $s_3$. The best performance on the preterm birth classification of wavelet-based features of EHG segments associated with the PL and TL groups with respect to the product of sensitivity and specificity is obtained using the wavelet-based feature $\Delta_1$ of channel $s_2$ with the product of sensitivity and specificity of 0.3702. The corresponding accuracy, sensitivity, and specificity are 0.7391, 0.4737, and 0.7815, respectively.

The quantitative measures, i.e., RMS, $f_{\text{mean}}$, $f_{\text{peak}}$, and SampEn, of spectral bands $b_1$, $b_2$, and $b_3$ of EHG segments are compared in box plots shown in Fig. 2(a)–(c), Fig. 3(a)–(c), Fig. 4(a)–(c), and Fig. 5(a)–(c), respectively. The performances on the preterm birth classifications of various spectral bands, i.e., $b_1$, $b_2$, and $b_3$, of EHG segments associated with the PE and TE groups and those associated with the PL and TL groups using quantitative measures, i.e., root-mean-square (RMS), median frequency ($f_{\text{med}}$), peak frequency ($f_{\text{peak}}$) and sample entropy (SampEn), are summarized in Table V and Table VI, respectively.

The best performances on preterm birth classification using the RMS, median frequency, peak frequency, and sample entropy of EHG segments associated with the PE and TE groups with respect to the product of sensitivity and specificity are, respectively, obtained at the spectral band $b_1$ of channel $s_1$ ($Se \times Sp = 0.2937$), the spectral band $b_2$ of channel $s_3$ ($Se \times Sp = 0.3780$), the spectral band $b_1$ of channel $s_1$ ($Se \times Sp = 0.4181$), and the spectral band $b_1$ of channel $s_1$ ($Se \times Sp = 0.4008$). The accuracy, sensitivity, and specificity obtained for the preterm birth classification using the sample entropy of the spectral band $b_1$ of channel $s_1$ are, respectively, 0.8025, 0.4737, and 0.8462.

The best performances on preterm birth classification using the RMS, median frequency, peak frequency, and sample entropy of EHG segments associated with the PL and TL groups with respect to the product of sensitivity and specificity are obtained at the spectral band $b_1$ of channel $s_1$ ($Se \times Sp = 0.1457$), the spectral band $b_2$ of channel $s_1$ ($Se \times Sp = 0.2967$), the spectral bands $b_2$ and $b_3$ of channel $s_1$ ($Se \times Sp = 0.2834$), and the spectral band $b_1$ of channel $s_1$ ($Se \times Sp = 0.3710$), respectively. The accuracy, sensitivity, and specificity obtained for the preterm birth classification

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<th>Feature</th>
<th>$Ac$</th>
<th>$Se$</th>
<th>$Sp$</th>
<th>$Se \times Sp$</th>
<th>$Ac$</th>
<th>$Se$</th>
<th>$Sp$</th>
<th>$Se \times Sp$</th>
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<th>$Sp$</th>
<th>$Se \times Sp$</th>
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<td>0.6316</td>
<td>0.3566</td>
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Fig. 2. Box plots of RMS of spectral bands $b_1$, $b_2$ and $b_3$ of EHG segments.

Fig. 3. Box plots of median frequency ($f_{\text{med}}$) of spectral bands $b_1$, $b_2$ and $b_3$ of EHG segments.

Fig. 4. Box plots of peak frequency ($f_{\text{peak}}$) of spectral bands $b_1$, $b_2$ and $b_3$ of EHG segments.

Fig. 5. Box plots of sample entropy (SampEn) of spectral bands $b_1$, $b_2$ and $b_3$ of EHG segments.
using the sample entropy of spectral band $b_1$ of channel $s_1$ are 0.7469, 0.4737, and 0.7832, respectively.

**IV. DISCUSSION AND CONCLUSIONS**

The wavelet-based feature $\Delta l$ defined as the difference between the logarithms of variances of detail coefficients corresponding to consecutive levels, i.e., $l + 1$ and $l$, of EHG signals is applied for preterm birth classification. For the EHG segments obtained during early period, i.e., the EHG segments recorded before the 26th week of gestation, the best performance on the preterm birth classification is obtained using the wavelet-based feature $\Delta l$ which corresponds to the 1.25–0.63-Hz and 0.63–0.31-Hz subbands of EHG segments. The best performance on the preterm birth classification for the EHG segments obtained during later period, i.e., the EHG segments recorded on or after the 26th week of gestation, is obtained using the wavelet-based feature $\Delta l$ which corresponds to the 10.0–5.0-Hz and 5.0–2.50-Hz subbands of EHG segments.

The wavelet-based feature of EHG segments provides a substantially better performance on the preterm birth classification using the EHG segments obtained during early period compared to the quantitative measures, i.e., root-mean-square (RMS), median frequency ($f_{\text{med}}$), peak frequency ($f_{\text{peak}}$), and sample entropy (SampEn). On the other hand, the performance on the preterm birth classification using the sample entropy of the 0.08–4.0 Hz subband of EHG segments obtained during later period is slightly superior to that using the wavelet-based features of EHG segments obtained during later period. The computation results suggest that the wavelet-based features of EHG signals can be reasonably used for preterm birth classification.

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