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Accelerometer-based Fetal Movement Detection

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Abstract—**Monitoring fetal wellbeing is a compelling problem in modern obstetrics. Clinicians have become increasingly aware of the link between fetal activity (movement), well-being, and later developmental outcome. We have recently developed an ambulatory accelerometer-based fetal activity monitor (AFAM) to record 24-hour fetal movement. Using this system, we aim at developing signal processing methods to automatically detect and quantitatively characterize fetal movements. The first step in this direction is to test the performance of the accelerometer in detecting fetal movement against real-time ultrasound imaging (taken as the gold standard). This paper reports first results of this performance analysis.**

I. Introduction

MONITORING of the fetus during pregnancy is one of the most important and challenging problems in modern obstetrics. It is widely accepted that fetal conditions during pregnancy significantly affect outcomes after birth [1]. As a consequence, fetal monitoring techniques were introduced in order to detect pathological conditions early enough to enable health care providers to intervene and prevent irreversible damages from occurring [2]. This goal is achievable as the majority of unfavorable fetal outcomes are caused by events that occur prior to the onset of labor [3], [4]. The continued monitoring of fetuses would also provide important insight into understanding the unexplained and unexpected stillbirths that happen late in pregnancy. Many of the clinical signs predicting these deaths are currently not being detected by the available fetal monitoring methods early enough in the pregnancy to allow for timely intervention. Advances in fetal monitoring are required to provide improved diagnosis of fetal health and prognosis of outcome.

One of the most important behavior of the fetus that can be monitored is movement. Fetal movement is considered one of the fundamental expressions of early neural activity as it is generated spontaneously by the central nervous system [5]. Fetal movement can be used to monitor the immediate wellbeing of the fetus and to gain insight into its neurodevelopment status. In fact, it has been estimated that fetal movement is capable of identifying antenatal factors that account for over 60% of neurodevelopment problems recognized in childhood [6]. For example, decreases in fetal movement have been linked to fetal distress and placental dysfunction [7]. Abnormal fetal movement has also been described in fetuses with chromosome abnormalities, anencephaly, prolonged oligohydramnios and cerebral malformations [8]-[10].

There have been several attempts at classifying various types of fetal movements [5], [11]-[13]. In [11], the authors identified four basic fetal movements using a tocodynamometer (strain-gauge) placed on the mother's abdomen: gross rolling movements, simple movements that consisted of head and limb movements, brief movements associated with hiccoughs and respiratory movements. Advances in ultrasound (US) imaging permitted more refined distinction of fetal movements [5].

Currently, there are two general methods for measuring fetal movement: passive and active. Passive methods, such as accelerometry, phonography and tocodynamometry, measure the fetal vibration incident on the maternal abdomen [11], [14]-[16]. Active methods, such as ultrasound, use the echoes from high frequency sound waves directed at the fetus to generate a signal displayed as a sequence of images (real-time ultrasound imaging). Fetal movement can also be monitored using mother perception registered on a 'kick-chart', but this method has been shown to be unreliable [17]. Ultrasound techniques are accurate in identifying fetal movement but there are a number of objections to their routine use in long-term fetal monitoring. Ultrasonic techniques are expensive and require a skilled operator to periodically reposition the transducer at the fetus to identify movements. There is also some concern amongst clinicians as to the safety of the fetus under prolonged exposure to ultrasound radiation [5]. Passive techniques of fetal monitoring, such as accelerometry, lack the imaging capability and therefore the ability to locate anatomical structure compared to ultrasound; but are safe, inexpensive, and simple to implement. Recent advances in solid state technology have allowed the production of new accelerometers that are small, low powered, sensitive, and robust; thus making them ideal for long-term monitoring.

Computerized processing of fetal movements offers several benefits: it eliminates the errors introduced by subjective interpretation of the data, allows adoption of standard definitions of fetal movements, supports fast processing of the data permitting rapid interventions when

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needed, and reduces the load on qualified personnel. This automation becomes critical in the case of long-term monitoring. The objective of this project is to develop and adapt advanced signal processing methods to automatically and accurately detect general movements of the fetus and to characterize these movements in quantitative terms.

II. Data Acquisition System

The system designed to record fetal activity uses tri-axial accelerometers (Fig. 1). It is composed of 4 analog sensors connected to a laptop running PowerLab (ADInstruments, Sydney, Australia) software. One of the accelerometers was placed on the mother's chest as it was intended to be used as reference for identifying artifacts. The rest of the sensors were placed on the mother's abdomen, two on the lower abdomen and one close to the ultrasound probe. The mother was asked to stay still to reduce maternal movement artifacts. Maternal activities such as talking, laughing, and coughing were timely noted by an observer. Though not used in this initial fetal movement detection work, such observations will be used in future investigation to reduce artifacts in the data. Using the described setup, fetal movements from 3 subjects were collected at a sampling frequency of 100 Hz. In addition to acceleration data recorded by the sensors, real-time ultrasound videos were acquired as well as the maternal perception of fetal activity using triggers from a handheld toggle that were digitally transformed into audio pulses. The real-time ultrasound device was a GE Voluson 730 Expert and using a GE AC2-5 probe. The ultrasound videos were later marked offline by a trained clinician. The output of this process was binary signals (expert masks) indicating the timing of fetal movements.

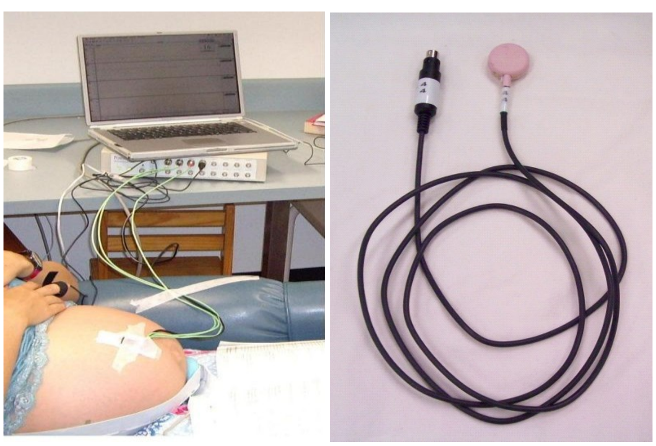

Fig. 1. Data acquisition system and close-up view of a tri-axial accelerometer.

III. Characterization of Fetal Movement

The design of efficient fetal movement detector or classifier rests on the effective characterization of data collected by the accelerometers. This characterization aims at finding features that best differentiate fetal movements among themselves as well as from artifacts. Potentially, these features can be used for fetal movement classification.

We have found that fetal movements can be nonstationary; thus requiring the use of time-frequency analysis. Example of a nonstationary fetal movement felt by the acceleration sensors is shown in Fig. 2. Note how the propagation of the movement is registered differently at the sensors. Fig. 2 also shows that the acceleration signal can be multi-component.

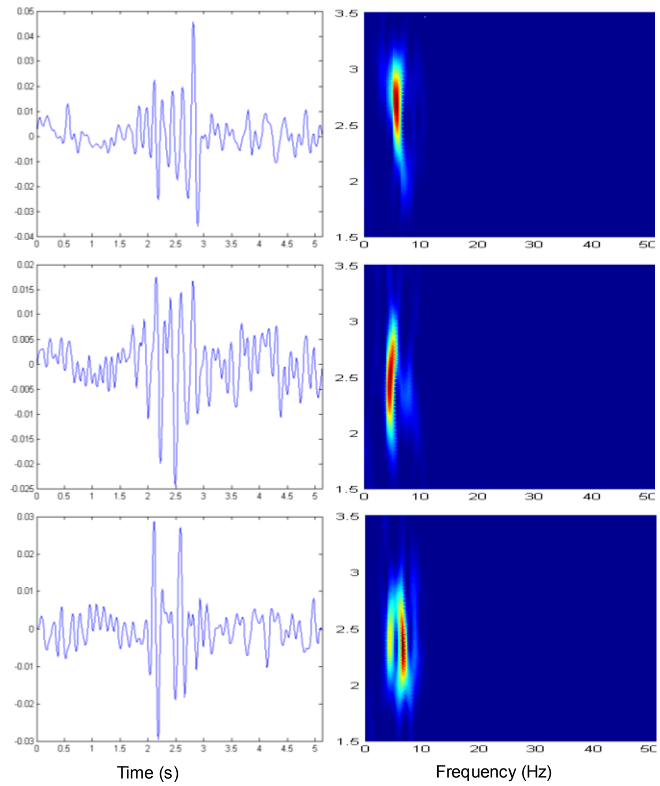

Fig. 2. Time (left) and time-frequency (right) representations of a fetal limb movement as measured by acceleration along the z-axis at sensor 1 (top row), sensor 2 (middle), and sensor 4. Sensor 3 was used as reference. The time-frequency representations were obtained using the spectrogram with a Hamming window of length $M/4$; where M is the signal sample length.

Based on the time-frequency representation of acceleration data, frequency bands suitable for analysis can be determined. Furthermore, information can be extracted from such representations to build time-frequency templates and atoms that can be used in applications like time-frequency matched filter [18] and time-frequency matching pursuit [19]. In this preliminary characterization of acceleration data, we have found that artifacts can mimic fetal movements (see Fig. 3). Work is in progress to design efficient methods to eliminate or reduce the effects of artifacts found in the acceleration data. It was also noticed that fetal activity can manifest itself as short waves (Fig. 2), spikes (Fig. 3), or as a train of spikes.

IV. Methods

In this initial stage of fetal movement detection work, no attempts were made to eliminate artifacts found in the acceleration data. The detection work presented here was based on computing the root-mean-square (*RMS*) of the acceleration magnitude computed from measured axes accelerations (A_X, A_Y, A_Z). The acceleration magnitude was used, instead of axes accelerations, in order to avoid dealing with the unintentional rotations of the sensors during maternal movements. Analysis related to only one accelerometer is reported here. A method to combine the results from all sensors without significantly increasing false positive rate is in progress. The magnitude of the Euclidian norm of the acceleration signal is defined as

$$A = \sqrt{A_X^2 + A_Y^2 + A_Z^2}. \quad (1)$$

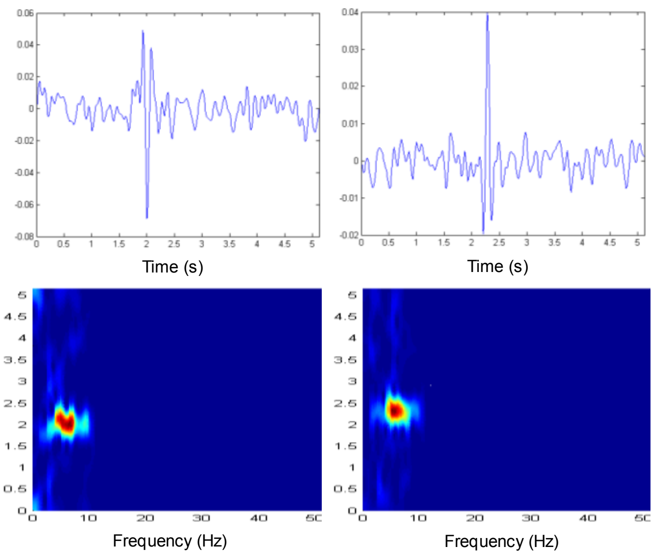

Fig. 3. Spectrograms showing the similarity between an artifact caused by mother's giggle (left) and a fetal movement (right) identified by ultrasound

The acceleration magnitude A of N samples long is segmented into epochs of M samples. The *RMS* of this acceleration magnitude for an epoch k is given by

$$A_k^{RMS} = \sqrt{\frac{1}{M}\sum_{i=1}^{M}\left(A_{(k-1)M+i}\right)^2}\,; \;\; k = 1,2,\dots,\frac{N}{M}. \quad (2)$$

The *RMS* data along with expert masks identifying fetal movements that were generated by marking the acquired ultrasound videos were used to study the performance of the accelerator-based fetal movement detection system.

V. Results and Discussion

RMS values were obtained using acceleration magnitude data. The *RMS* signals were filtered using a high pass IIR filter with a cut-off frequency of 2 Hz and then divided into epochs 1.2 seconds long. The choice of cut-off frequency was guided by findings as in Figs. 2 and 3. Analysis based on lower frequency bands is in progress. As for the choice of M, it has been found that better detection is achieved with epoch sizes equivalent to fetal movement durations which are 1 to 1.5 seconds long.

Any *RMS* value higher than a predetermined threshold was classified as fetal movement. The data-dependent threshold was defined as the *median of all epoch RMS values*. By comparing with ultrasound expert masks, the performance of the proposed fetal movement detector was evaluated and is shown metrically in Table I and graphically in Fig. 4. The epoch-based performance metrics are sensitivity (*SEN*), specificity (*SPE*), and accuracy (*ACC*) defined by

$$SEN = 100 \times TP\,/\,(TP + FN) \quad (3)$$

$$SPE = 100 \times TN/(TN + FP) \quad (4)$$

$$ACC = 100 \times (TP + TN)/(TP + TN + FP + FN) \quad (5)$$

where *TP* and *FP* stand for true positive and false negative respectively.

TABLE I
EPOCH-BASED DETECTOR PERFORMANCE

Record	*SEN (%)*	*TP*	*TP+FN*	*SPE (%)*	*TN*	*TN+FP*	*ACC (%)*
1) 32 wks	50	265	533	52	283	541	51
2) 32 wks	52	58	111	55	185	335	54
3) 35 wks	76	180	236	55	513	936	59

The best performance among the three records was achieved using record no. 3. At 76% *SEN,* the majority of fetal movements have been detected. However, the overall accuracy of 59% is still relatively low; being affected by a low 55% specificity. Table I seems to indicate the dependency of the detector performance on the fetus gestational age. Specificity is comparable between the three records, but sensitivity is significantly higher for the 35 weeks fetus. The older the fetus, the stronger the movements are and hence the enhancement in the detector capability. This conclusion will be validated with more data collection. Table I also indicates a common low specificity. This is due to factors like 1) artifacts and 2) limb movements occurring outside the range of US probe and hence not captured in the ultrasound video (e.g., movement at 140 seconds for record no. 3 which was also felt by the mother). Sensitivity was affected by fetal movements which could be slow (< 2 Hz), too weak, or too deep to propagate to the abdomen wall where the accelerometers were positioned. The presented method uses the acceleration magnitude and thus strongly depends on the fetal movement strength. Therefore, there is a tendency for weak movements to have *RMS* values below the detection threshold and consequently were misclassified. Additional features are needed to identify such movements. Low frequency activity will also be investigated using other techniques.

Though considered low, the detector performance is much higher than maternal perception of fetal activity. In [20], maternal perception of fetal movements has been determined to have a sensitivity of around 36%.

Finally, Fig. 4 shows that the proposed detector is generally accurate in identifying episodes of fetal activity and episodes of inactivity. An episode of activity is defined as a sequence of fetal movements separated by relatively short inactivity instances. It may be clinically viable to assess fetal wellbeing from this perspective where focus is placed on detecting the frequency of activity episodes in a given time period rather than focusing on the detailed behavior of fetal movements during a given activity episode. Nevertheless, work is in progress to improve the fetal movement detector performance by identifying additional characterizing features and by investigating alternative techniques.

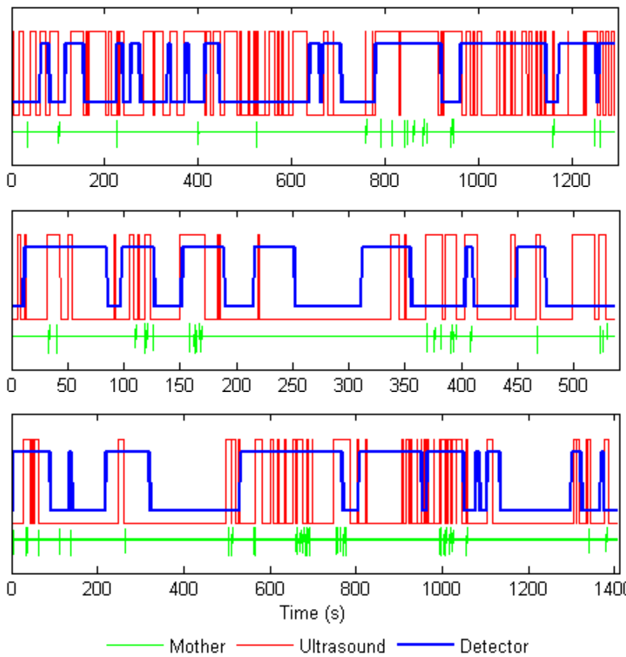

Fig. 4. Graphical presentation of fetal movement detector performance for data acquired from the three records indicated in Table I. Mother perception of fetal activity is shown in green.

VI. Conclusion

In this paper, we presented first results of an accelerometer-based fetal movement detector using the *RMS* of acceleration magnitude. Initial results show the technique to be more effective in detecting fetal movements than perceived by the mother. We have shown that the proposed detector performs better in identifying episodes of fetal activity and episodes of inactivity. Work is in progress to: acquire more data, identify a better position for the reference sensor, use advanced techniques to identify and remove artifacts, and design a more adequate detection process.

Finally, the use of the accelerometers constitutes a promising advancement in the automatic detection of fetal movement especially for long term recordings. The low cost, lightweight, and non-intrusive system which is sensitive to small movements constitutes a viable alternative to ultrasound and may ultimately identify the at-risk fetus to allow timely clinical intervention.

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