VSB TECHNICAL UNIVERSITY OF OSTRAVA | FACULTY OF ELECTRICAL ENGINEERING AND COMPUTER SCIENCE

Automatic Detection of Fetal Movement by Abdominal Electrocardiography

Automatická detekce pohybu plodu pomocí abdominální elektrokardiografie

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Bachelor Thesis

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Description:

The bachelor's thesis focuses on the current possibilities of measuring, processing, and evaluating various biological signals for the needs of automatic detection of fetal movement and fetal motility monitoring. The theoretical part of the thesis deals with the introduction of the fetal movements monitoring using various biological signals and medical devices. The theoretical part of the bachelor's thesis further describes manifestation of fetal movements in various signals (in both time and frequency domain) and in the change of fetal heart rate trace. Moreover, the theoretical part will also describe the methods and parameters used to assess the current fetal health state and diagnose possible fetal distress. The greatest attention will be paid to the field of abdominal electrocardiography.
The primary goal of the bachelor thesis is a detailed analysis and classification of methods and available hardware and software tools for fetal monitoring, especially abdominal electrocardiography. The output of the bachelor's thesis will be a software tool for automatic detection of fetal movements. Its accuracy will be evaluated using real data from clinical practice.

Thesis outline:
1. Review of various techniques for measurement, processing, and evaluation of different biological signals for the needs of automatic detection of fetal movement and fetal motility monitoring.
2. Extensive review of medical devices and software applications for monitoring fetal movements.
3. Analysis of the manifestations of fetal movements on various signals (in the time and frequency domain), as well as on the fetal heart rate trace and their evaluation to assess the current health status of the fetus and diagnose possible fetal distress.
4. Design and development of a graphical user interface for automatic detection of fetal movements. The experiments will be performed on real data from clinical practice.
5. Evaluation of achieved results.

References:

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Abstract

The aim of the bachelor's thesis is to introduce an extensive review of fetal movement monitoring methods. The theoretical part describes currently available fetal monitoring methods, primarily non-invasive fetal electrocardiography. The thesis continues to thoroughly describe and characterize fetal movements and the current possibilities of fetal movement detection. The output of the bachelor's thesis is an analysis of the manifestation of fetal movements on various biological signals, which were further used in the design and development of the graphical user interface for automatic fetal movement detection. Developed fetal movement detection algorithms were evaluated on clinical practice data.

Key Words

Fetal monitoring, fetal movement, fetal movement detection, non-invasive electrocardiography, cardiotocography, fetal heart rate, fetal ECG signal, fetal well-being, fetal distress

Abstrakt

Hlavním cílem předložené bakalářské práce je představit rozsáhlý přehled metod sledování pohybu plodu. V teoretické části jsou popsány momentálně dostupné metody monitorování plodu, především neinvazivní fetální elektrokardiografie. Předložená bakalářská práce dále důkladně popisuje a charakterizuje pohyby plodu a současné možnosti detekce pohybu plodu. Výstupem bakalářské práce je analýza projevů pohybů plodu na různých biologických signálech, které byly dále využity při návrhu a vývoji grafického uživatelského rozhraní pro automatickou detekci pohybu plodu. Vyvinuté algoritmy byly následně vyhodnoceny na datech z klinické praxe.

Klíčová slova

Fetální monitorace, fetální pohyby, detekce pohybů plodu, neinvazivní elektrokardiografie, kardiotokografie, srdeční frekvence plodu, fetální EKG signál, zdraví plodu, ohrožení plodu

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List of Abbreviations

ACG	actocardiography
B-mode	brightness mode used in ultrasonography
Bpm	beats per minute
CTG	cardiotocography
EMG	electromyography
fECG	fetal electrocardiography
FDA	Food and Drugs Administration
fHR	fetal heart rate
fHS	fetal heart sounds
fMCG	fetal magnetocardiography
FIGO	The International Federation of Gynecology and Obstetrics
FMS	fetal monitoring system
FSE	fetal scalp electrode
fVCG	fetal vectorcardiography
GUI	graphical user interface
ICA	independent component analysis
I-fECG	invasive fetal electrocardiography
MODWT	maximal overlap discrete wavelet transform
mECG	maternal electrocardiogram
MRI	magnetic resonance imaging
NI-fECG	non-invasive electrocardiography
PCA	period component analysis
SNR	signal-to-noise ratio
STFT	short-time Fourier transform

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Introduction

Fetal monitoring represents a significant part of every woman's pregnancy, which monitors the development of the fetus, helps with the early diagnosis of possible fetal distress, and ensures a smooth delivery. The presented bachelor's thesis is explicitly dedicated to fetal movements, representing a significant evaluation parameter of fetal well-being. Even though pregnant women are encouraged to monitor fetal movements, reduced fetal movement is often overlooked, resulting in severe fetal distress and a higher occurrence of stillbirths.

The main aim of the bachelor thesis is to introduce currently available fetal monitoring methods with their advantages and disadvantages. The greatest attention is paid to the field of abdominal electrocardiography. Furthermore, fetal movements and their basic categorization are introduced to further review all possibilities of fetal movement monitoring and their feasibility in clinical practice. Moreover, the importance of fetal movements and why their monitoring should be encouraged among both mothers and clinicians is explained.

The methodology is then dedicated to the analysis of manifestations of fetal movements on various signals, such as a heart rate trace and fECG obtained by NI-fECG. The manifestations are described and further used as parameters in developed algorithms for fetal movement detection. The output of the bachelor's thesis is the design and development of a graphical user interface for automatic fetal movement detection. The evaluation of achieved results is performed on real data from clinical practice, which contain references to the state of the fetus.

1 Fetal Monitoring

The interest in monitoring the human body can be dated 2400 years ago when Hippocrates described listening to the body's internal activity by placing the ear on the skin area closest to the examined organ [1]. The very first mention of detecting fetal heart sounds (fHS) can be dated to the 17th century when Marsac, a French physician, reportedly heard fetal heart sounds by placing the ear on the maternal abdomen. However, it was not until the invention of the stethoscope in 1816 that it opened the door for abdominal auscultation, helping Viscount de Kergaradec to detect and describe fHS [2]. The following years led to many new findings regarding fetal health and fetal distress based on the fHS and the fetal heart rate (fHR) calculation.

In 1906, Cremer discovered and recorded the first transabdominal fetal electrocardiogram using a string galvanometer electrocardiograph along with an external electrode placed on the abdomen and an internal electrode inserted either into the vagina or the rectum [3], [4]. In 1958, Dr. Edward H. Hon developed a new method and technology for continuous fHR monitoring based on abdominal electrocardiography, which he improved a few years later by introducing a fetal scalp electrode. This allowed physicians to continuously record the fHR tracings as well as document them visually on paper [5]. Finally, in the early 1960s, obstetrician Konrad Hammacher and Dr. Hon introduced cardiotocography (CTG), a new method of monitoring fetal heart rate and uterine contractions continuously and simultaneously, which can be used both during pregnancy and labor. This eventually led to the development of the first commercial fetal monitor in 1968 by Hewlett-Packard [6].

Figure 1: Hewlett-Packard 8020A Cardiotocograph – first commercial fetal monitor [7]

Eventually, in 1986, *The International Federation of Gynecology and Obstetrics (FIGO)* approved guidelines for the use of fetal monitoring, including the widespread agreement on required aspects of CTG monitoring, in particular terminology, indications, and interpretation. The latest consensus of the FIGO guidelines was concluded in 2015, updating the old guidelines as well as including new currently used methods of fetal monitoring [8].

Years of study and searching for proper techniques to monitor the fetus have allowed physicians to begin to look at the fetus as a patient. Therefore, the primary purpose of fetal monitoring is to assess fetal health conditions in order to detect fetal distress so that appropriate medical intervention can begin in time [9]. Information about fetal health conditions can be obtained by picking up various signals from the maternal abdominal wall or using a fetal scalp electrode [10], [11]. These signals may be in the form of electrical potentials and magnetic fields caused by the bioelectric activity of the fetal heart or acoustic vibrations caused by the mechanical activity of the fetal heart. Based on the detection of these signals, there are several methods used to monitor fetal health conditions, which are described in detail below [10].

1.1 Current Methods of Fetal Monitoring

As mentioned above, intermittent auscultation is one of the oldest techniques used for fetal monitoring to this day. In 1895, a French obstetrician Adolphe Pinard designed a wooden tool known as a Pinard horn. The Pinard horn is a bell-shaped tool capable of amplifying fetal heart sound waves and transmitting them to the physician's ears [1]. Today's Pinard horns are usually made from wood or metal and are frequently used by midwives in most developing countries as well as most of Europe [12]. An alternative to the Pinard horn is a DeeLee stethoscope that features a metal headband helping the obstetrician work hands-free. One of the advantages of intermittent auscultation is its easy availability and sustainability, allowing healthcare providers to use it even in the lowest resource settings. On the contrary, one of the main disadvantages of intermittent auscultation is that it takes time to develop the required clinical skills to identify fHS correctly due to incompatible positioning or surrounding noise [1].

Figure 2: Available tools for intermittent auscultation: a)The Pinard horn [13] - left; b) The head stethoscope, also known as a fetoscope [14] - right

The most widely used methods of assessing fetal health conditions today are based on Doppler ultrasound. A hand-held fetal Doppler ultrasound monitor can detect fHR using the Doppler effect and is an alternative to the Pinard horn. Unlike the Pinard horn, the fetal Doppler is, among others, capable of providing a steady number of beats per minute and audible auscultation using an audio output that allows others, including the mother, to hear the fetal heart sounds. The use of the fetal Doppler is quick, uncomplicated, and does not require any particular clinical skills; therefore, it is also suitable for home use. However, one of the main disadvantages of using the fetal Doppler by an untrained person is the risk of confusing the fHS with the maternal heartbeat, which may lead to a false assurance regarding the fetus's health. Moreover, among other disadvantages of fetal Doppler monitoring is the need for a power source, the electronics prone to failure, and higher acquisition costs [15].

Figure 3: The hand-held fetal Doppler [16]

The second method, using the Doppler ultrasound, is cardiotocography which presents the continuous technique for fHR and uterine contractions monitoring. The CTG records the fHR and the uterine contractions by two transducers placed on the mother's abdomen. The ultrasound transducer is placed over the area where the fetal heart occurs and provides information about fHR. In order to reconstruct the authentic fHR, around five consecutive heart cycles are needed for the resulting heart rate trace. The abdominal pressure transducer, detecting uterine contractions, is placed over the area of the uterine fundus and provides information about the duration and frequency of contractions [17], [18]. Besides the baseline fHR and uterine activity, the CTG offers information about additional measurable parameters related to fHR, such as decelerations, accelerations, and fetal heart rate variability (fHRV) [17].

Even though CTG monitoring has become a standard procedure used during pregnancy and labor in most countries, the evidence regarding the benefits of continuous CTG monitoring is scientifically inconclusive. However, according to most experts, CTG monitoring should always be considered in all cases of high-risk pregnancies and labors due to the elevated risk of fetal hypoxia/acidosis [11]. Recent studies (e.g., [19], [20], [21], [22]) have shown that CTG analysis, despite the existing guidelines and standards, very often leads to misinterpretation of the fHR tracings, such as deceleration of fHR baseline and variability; therefore, it is a subject of disagreement among clinicians. Due to the overuse and problematic CTG analysis, cesarean delivery has increased by 63% within the last 50 years [11], [21].

Figure 4: The cardiotocograph (CTG) – placement of transducers [23]

Another Doppler ultrasound-based technology method is fetal actocardiography (ACG), a technique broadly used in Japan [24]. It is a method that detects not only the fHR but also the fetal movements. The fetal movements produce low-frequency Doppler signals between 40–60 Hz, which can be detected by the same ultrasound Doppler technology used for fHR detection. However, a bandpass filter must be used to separate lower frequencies caused by maternal movement and respiration as well as higher frequencies caused by fetal heart movement. Therefore, the actocardiogram can simultaneously provide fHR and fetal movement information using only one transducer [24], [25]. Furthermore, since fHR accelerations accompany the fetal movements, the fetal actocardiography allows a better and more accurate diagnosis of nonreactive fetal states than the CTG does [24].

Fetal echocardiography, also known simply as fetal echo, is a method used to evaluate the morphology and functionality of the fetal heart. The fetal echo combines pulsed and color flow Doppler ultrasound along with ultrasound brightness mode (B-mode) imaging producing a two-dimensional image of the fetal heart. The fetal echo can be performed either with the transabdominal or transvaginal transducer as early as 9 to 11 weeks of gestation [26]. One of the main advantages of fetal echo is the ability to evaluate and diagnose possible fetal heart anomalies or defects resulting in congenital heart disease, which according to [27], is one of the most frequently diagnosed congenital disorders occurring in 0,8 % to 1,2 % of newborns worldwide. Moreover, fetal echo is also capable of evaluating fHR by means of pulsed wave Doppler. The pulsed Doppler waveform with two prominent peaks, E, representing the velocity throughout early ventricular filling, and A, representing the peak velocity throughout the atrial contraction, is shown in Figure 5 [28].

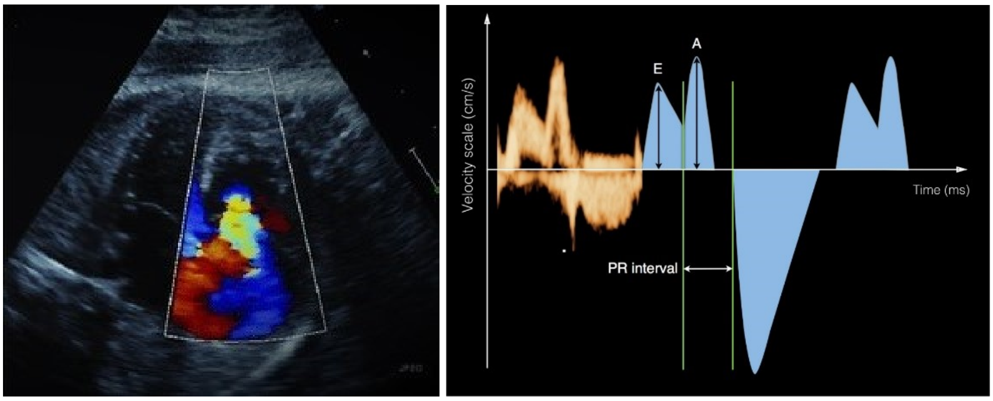

Figure 5: Fetal echocardiogram showing a) The four-chamber ultrasound image with the color flow Doppler [29] - left; b) The pulsed Doppler waveform measured across atrioventricular valves with marked peaks E and A [28] - right

Fetal magnetocardiography (fMCG) is another non-invasive method used to study fetal health conditions. The fMCG uses a magnetic field generated by the electrical currents occurring within the heart of the fetus. Since the generated magnetic fields reach values only around 10^{-13} Tesla, the superconductive quantum interference device (SQUID) needs to be used to detect such weak magnetic fields [10]. The resulting signal of magnetocardiography is very similar to the one of the electrocardiography; thus, the signal consists of waveforms such as P-wave and QRS complex [30]. Some of the advantages of fMCG are a high signal-to-noise ratio and a very accurate and objective measurement of the fHRV. Unfortunately, the size, cost, and complexity of the necessary instrumentation do not enable the use of fMCG in clinical practice [10].

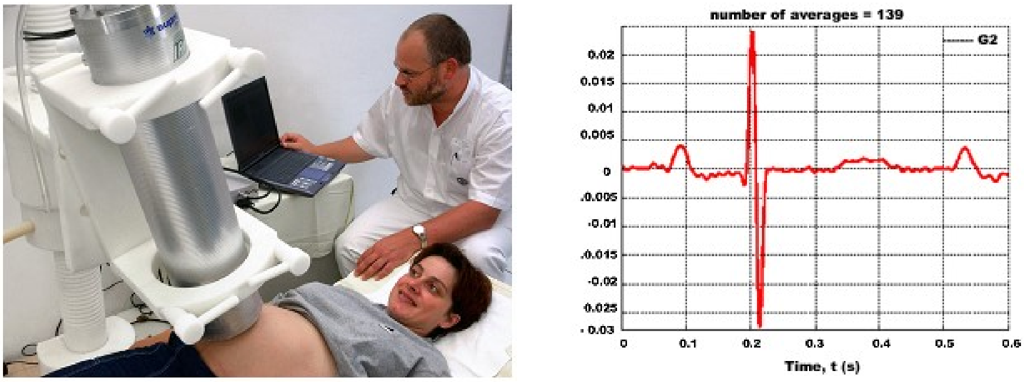

Figure 6: Fetal magnetocardiography using the SQUID (left); fetal magnetocardiogram (right) [31]

The last well-known and studied technique of fetal monitoring is fetal electrocardiography (fECG). The fECG is a method that allows invasively or non-invasively to measure the electrical activity of the fetal heart and is used to detect abnormal fHR and its patterns during pregnancy or labor. The invasive fECG uses a fetal scalp electrode (FSE), a spiral wire, placed on the scalp of the fetus to record the fetal electrocardiogram. Due to its invasiveness, this method can be used only at the time of delivery when the amniotic sac has ruptured and the cervix is sufficiently dilated [32]. Moreover, using FSE is associated with an increased risk of infections, bruising, and injury of the fetal scalp [33]. Despite these disadvantages, it is one of the most accurate methods for measuring fetal cardiac activity since it is less affected by artifacts, fetal and maternal movement, or maternal obesity [34]. On the other hand, the non-invasive fECG (NI-fECG) uses surface electrodes placed on the maternal abdomen and can be used both during pregnancy and labor [32]. The method of non-invasive fECG is thoroughly described in Chapter 2.

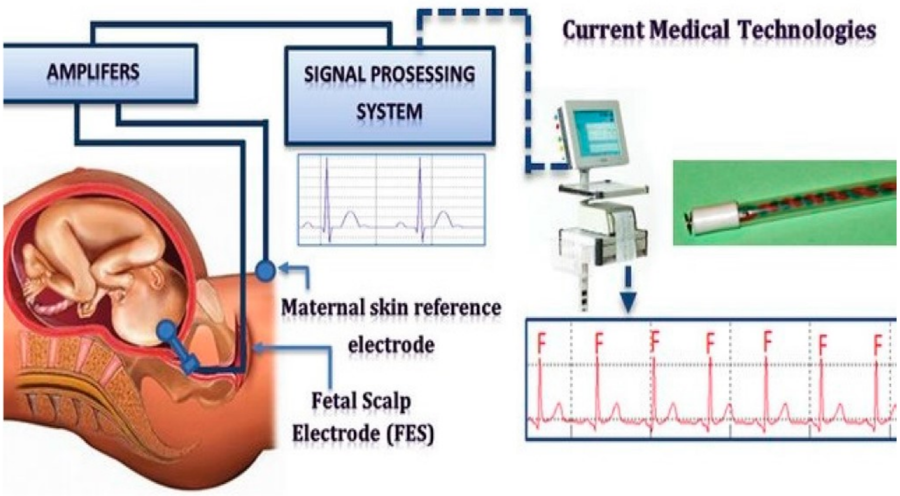

Figure 7: Invasive fetal electrocardiography using the fetal scalp electrode [35]

2 Non-Invasive Fetal Electrocardiography

This chapter is dedicated to a thorough description of NI-fECG, a method of fetal monitoring that can be used, as mentioned in Chapter 1, to assess fetal well-being both during pregnancy and labor. Moreover, unlike nowadays's most prevalent CTG, the fECG signal carries valuable information about pathologies such as intrapartum hypoxia, myocardial ischemia, or metabolic acidosis, manifesting as morphology changes in the fECG waveform [36].

2.1 NI-fECG Recording and Signal Processing

The fetal heart is one of the first organs to develop during the organogenesis of the embryo. By the seven weeks of gestation, the fetal heart has a similar anatomic characterization as the heart of an adult person and can pump blood throughout the developing fetal body. Even though the mechanical function of the fetal heart is different from the one of an adult person (due to the different oxygen supply of the fetus), the ECG signals recorded from both fetal and adult hearts are somewhat similar, both containing the P waves, QRS complexes, and T waves [37]. The non-invasive electrocardiograph, similar to the electrocardiograph used in adults, uses standard surface electrodes placed on the maternal abdomen with the help of an electrolyte gel to reduce the skin's impact on the impedance and to ensure good contact. One of the problems of the NI-fECG is the missing standard for electrode configurations on the maternal abdomen, mainly due to unpredictable changes in the positions of the fetus. However, several electrode configurations have been proposed by researchers in an attempt to standardize the NI-fECG recording. These configurations can be assessed based on the placement (pure abdominal configuration and mixed configuration covering the area of the abdomen and thorax) and the number of used electrodes [37].

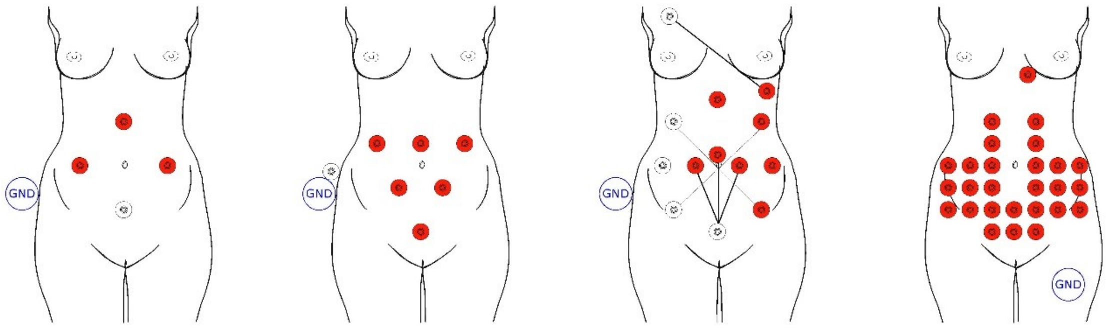

Figure 8: An example of NI-fECG electrode configurations using a different number of electrodes and placement (pure abdominal, mixed) [38]

Electrocardiogram, which can be defined as a graphic representation of bioelectrical signals generated by the human heart, obtained from an abdominal recording, is, however, composed not only of the fetal electrocardiogram but also of the maternal abdominal electrocardiogram (mECG) and noise components [39]. The noise components are a mixture of both physiological (maternal and fetal electromyogram, electroencephalogram, and respiration) and non-physiological interference caused by poor cable shielding, electrode/skin interference, power line interference (50 Hz), and instrumentational noise. The frequency bandwidth of maternal and fetal ECG signals range between

0.5 to 100 Hz and are similar to each other. However, the amplitude of both signals is different as the maternal QRS complexes reach up to 100-150 μV while the fetal QRS complex usually does not overcome 60 μV [37]. Therefore, advanced signal processing is necessary to eliminate maternal and noise interference to obtain the fetal electrocardiogram.

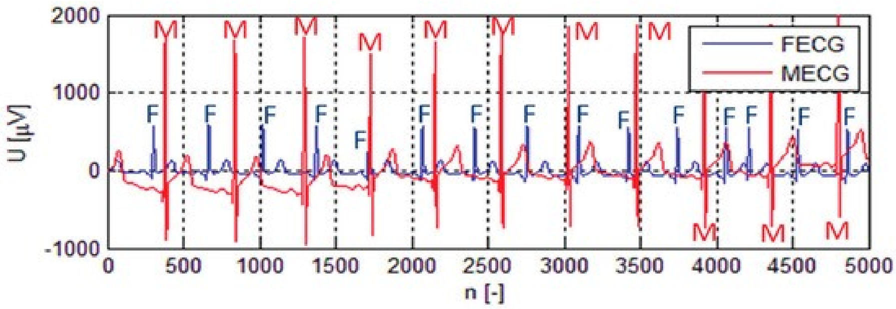

Figure 9: An example of the amplitude difference in fetal and maternal electrocardiogram[35]

2.1.1 Extraction of The Fetal Electrocardiogram

Extraction of fECG is usually performed in two main steps, including abdominal signal prefiltration, which helps eliminate most noise interference and mECG cancellation. The signal prefiltration is generally performed by applying a bandpass filter to eliminate low and high-frequency noise from 0.5 to 40 Hz and a notch filter to eliminate the power line interference. It is important to note that not all noise interference can be successfully eliminated; however, it usually does not interfere with the successful fECG extraction. Since the maternal and fetal frequency bands strongly overlap, linear filtration would not be helpful; other signal processing methods leading to the cancellation of the mECG need to be applied [37], [38].

1) *The Non-Adaptive Filtering Methods* work only with a primary input consisting of the fECG and mECG recorded by means of electrodes placed on the maternal abdomen. These methods have constant coefficient values, do not adapt to existing circumstances, and are time-invariant [38]. These methods can be further divided into two groups depending on the number of used channel sources:

   a) Single-channel signal sources include methods based on wavelet transform, subtraction, averaging, or filtering techniques [38].
   b) Multichannel signal sources include, for example, methods based on blind source separation, which can be performed by independent component analysis (ICA) or period component analysis (PCA) [38].

2) *The Adaptive Filtering Methods* work with the primary input and a secondary input of the mECG recorded on the maternal thorax. These methods are based on a learning system and include non-linear adaptive techniques (e.g., hybrid neural network and artificial neural networks) and linear adaptive techniques based on the theory of Kalman filtering or adaptive linear neuron [37], [38].

2.2 Feasibility of NI-fECG in Clinical Practice

As of today, NI-fECG is not usually used in clinical practice as it has never advanced sufficiently enough to replace other conventionally used techniques, mainly due to the difficulty of extracting the low-amplitude fECG from the abdominal ECG and overall low signal-to-noise ratio (SNR) [40]. Moreover, in the third trimester, a vernix caseosa (i.e., a white, creamy, waxy-like biofilm that helps to protect the fetus's skin) develops and covers the entire body. Furthermore, the vernix caseosa has electrical insulating properties which affect the efficacy of NI-fECG recording [40]. Fetal echocardiography is the primary technique used nowadays to evaluate the fetal heart and diagnose possible heart defects. However, unlike the fECG, fetal echo cannot discern electrical intervals such as QRS duration or QT interval whose length is an important parameter to rule out fetal long QT syndrome, which may cause cardiac arrest, syncope, or sudden death [40], [41]. Beyond diagnostics benefits, the NI-fECG represents a user-friendly method that can be performed in a standard clinic room with no-to-little experience in NI-fECG recording since the extraction and evaluation of fECG signals are automated [40].

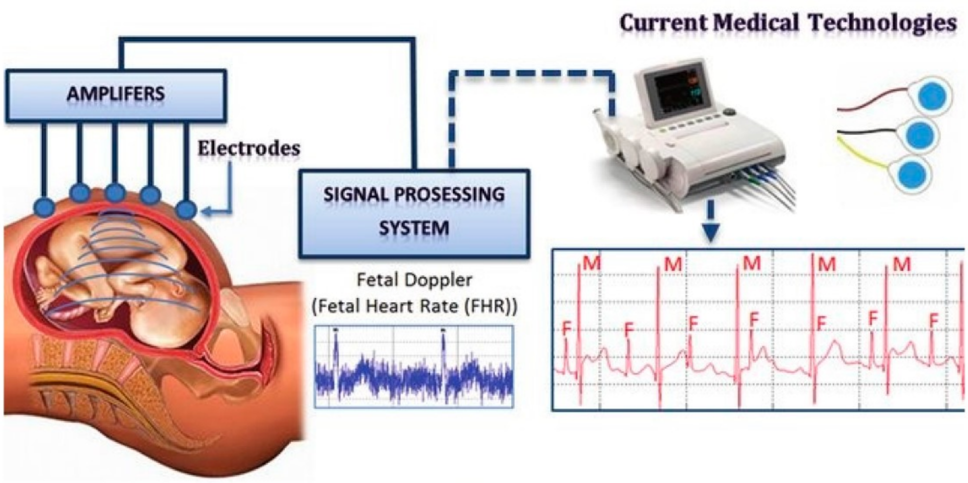

Figure 10: Scheme of Non-Invasive fetal electrocardiography [35]

Among other benefits of NI-fECG is the possibility of continuous recording and no danger to both fetus and mother caused by any kind of radiation or physical injury of the fetus by the fetal scalp electrode used in invasive electrocardiography. The following Table 1 compares several parameters such as clinical feasibility, SNR, or potential health risks in the NI-fECG, I-fECG, and other commonly used techniques in clinical practice.

Table 1: The comparison of the NI-fECG to I-fECG, fECHO, and CTG

	NI-fECG	I-fECG	fECHO	CTG
Clinical Feasibility	High	Medium	Medium	High
Week of Pregnancy	20+	at labour	18+	28+
Costs	Medium	Medium	High	Medium
fHR	Yes	Yes	Yes	Yes
SNR	Low	High	High	Low
Frequency	Continuous	Continuous	Extended Duration	Extended Duration
Potential Health Risks	No	Yes	Yes	Yes
Morphological Evaluation *	Yes	Yes	No	No

* Morphological Evaluation of fECG

2.2.1 Certified and Commercially Available NI-fECG Devices

In recent years, the interest in NI-fECG has increased immensely, developing the most efficient algorithms for fECG signal processing and developing NI-fECG devices both for clinical and home settings. Currently, six certified and commercially available NI-fECG devices have obtained either US Food and Drugs Administration (FDA) or European CE certification, which authorizes them for use in clinical practice [42].

1) *Monica Healthcare Ltd., (UK) - Monica AN24* is an fECG and uterine activity monitoring device using five standard ECG electrodes and holds both FDA and CE certification [42].

2) *GE Healthcare, (USA) – Novii Wireless Patch system* is an fECG monitoring and uterine activity device using five electrodes incorporated into a patch and holds both FDA and CE certification [42].

3) *MindChild Medical Inc., (USA) – MERIDIAN M110 Fetal Monitoring System* is an fECG and uterine activity monitoring device using 28 electrodes incorporated into a patch and holds FDA certification [42].

4) *Nemo Healthcare, (Netherlands) – Nemo Fetal Monitoring System* is an fECG and uterine activity monitoring device using six electrodes incorporated into a patch and holds CE certification [42].

5) *Koninklijke Philips N.V., (Netherlands) – Avalon Beltless Fetal Monitoring System* is an fECG and uterine activity monitoring device using electrodes incorporated into a patch and holds both FDA and CE certification [42].

6) *NUVO Inc., (USA) – Invu System* is an fECG monitoring device using a belt system incorporating eight electrical sensors and four microphones. Invu System holds FDA certification and, contrary to the listed devices above, is the only one focusing on home fECG monitoring [42].

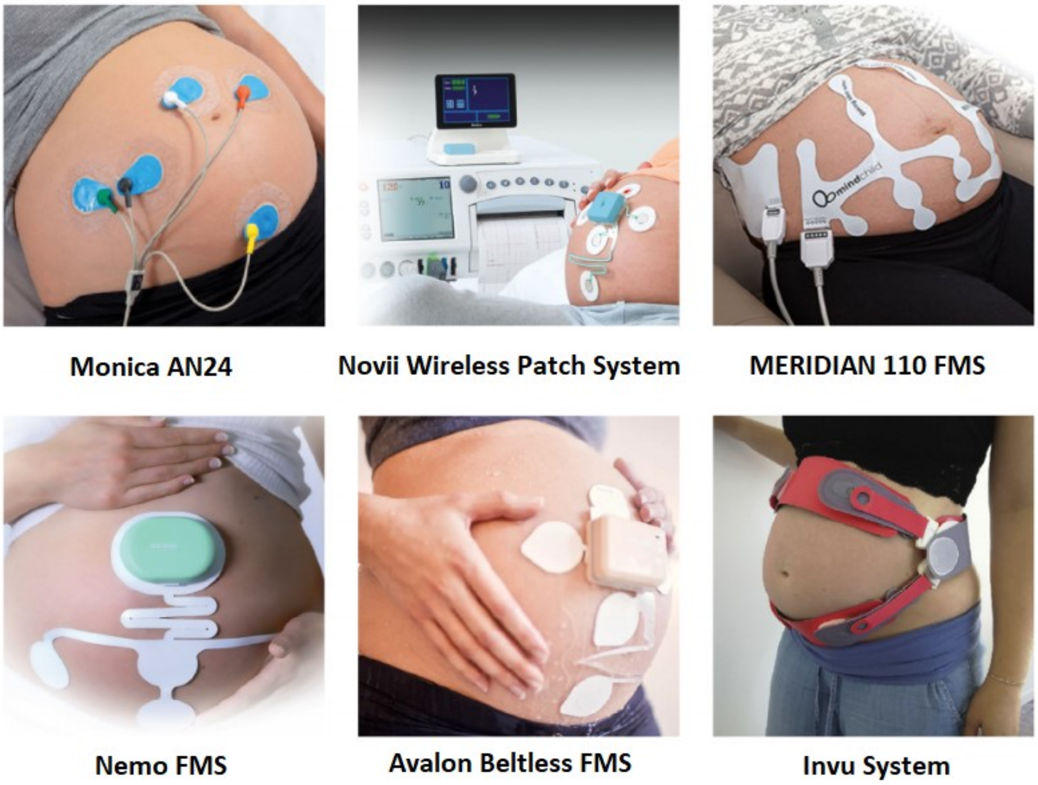

Figure 11: Certified and commercially available NI-fECG devices [42]

3 Fetal motility and movement monitoring

Fetal movements are among the many indicators used to assess fetal well-being during pregnancy. Studies focusing on fetal behaviour have shown the association between fetal movements and the development of central and peripheral structures as well as the physiological state of the fetus in the uterus [43], [44]. Fetal movements occurring throughout pregnancy can be divided into several categories, which are listed below:

1) *General movements* are one of the first occurring movements which set in at early gestation and are present until about 3-4 months of postnatal life [45], [46]. They can be described as a periodic burst of total-body motion changing in intensity, speed, and force. General movements involve arm, leg, and trunk movements which gradually onset and end. They are performed as early as 7-7,5 weeks of gestation and reach their intensity at 10-11 weeks. General movements start to decrease at 14 weeks and continue to occur steadily until 25 weeks of pregnancy. From 27 weeks, studies show that general movements begin to decrease rapidly due to changes in the fetus's proportions, reduced amniotic fluid and space, and presumably due to inhibitory circuits that start functioning at the end of pregnancy [46].

2) *Startles* can be described as a sudden shock-like motion involving the entire body of the fetus and lasting about 1 second. They are mainly present at early gestation, along with general movements. The frequency of startles is highest at 13 weeks and starts to decrease between 14-16 weeks of pregnancy. However, up until 13 weeks, general movements are always preceded by a startle. Therefore, some startles may have a temporary function that helps activate general movements [46].

3) *Isolated movements* involve only specific parts of the fetal body, particularly the head, hands, legs, and feet. They are goal-oriented and seem intentional. Contrary to general movements, the frequency of isolated movements increases toward the end of pregnancy since isolated movements have preparatory functions for delivery and postnatal life. Head movements can be observed throughout pregnancy, although they become more pronounced around 25-26 weeks. They involve extension, flexion as well as head rotations. Hand movements are primarily used as perceptual tools since the palm and fingertips are heavily innervated by sensory fibres. Therefore, fetuses use their hands to touch and sense their body parts, usually the highly innervated ones, such as the face, thighs, knees, and feet. Leg movements are another big group of isolated movements that can be observed throughout pregnancy. They involve both flexion and extension. Even though fetuses cannot use their legs and feet for walking as adults do, they already perform a stepping motion in the uterus, known as the stepping reflex. The stepping reflex disappears six weeks after birth and reappears between 8-12 months [46].

4) *Twitches* are defined as a minor and short involuntary contraction of muscles innervated by a single alpha or primary motor neuron. Contrary to startles, twitches do not involve the entire fetal body and are set later at 10-12 weeks. However, they usually occur in the fetal face,

hands, abdomen, legs, and feet muscles. Furthermore, twitches mostly appear within a rest cycle, outside of periods of general or other fetal movements [46].

5) *Fetal breathing movements.* Although fetal lungs do not actually represent a breathing function since the oxygen is supplied to the fetus through the placenta and the umbilical cord, fetal breathing movements are an essential part of the adjustment for aerial respiration after birth. Breathing movements include downward movements of the diaphragm, the thorax's inward motion, and the abdomen's outward movement. In addition, they are necessary for sustaining lung liquid volume, which helps maintain a high degree of lung expansion. Lung expansion is crucial for structurally and biochemically healthy lung development [46].

Table 2: Summary of main fetal movements occurring throughout pregnancy

Fetal Movements	Description	Onset	Highest Intensity and Time Course
General Movements	A periodic burst of total-body motion changing in intensity, speed, and force.	7-7,5 weeks	10-11 weeks, then they start to decrease towards the end of pregnancy.
Isolated Movements	Goal-oriented movements of specific fetal body parts - head, hands, legs, and feet.	10-13 weeks	The highest intensity occurs towards the end of pregnancy.
Fetal Breathing Movements	The diaphragm's downward movement, the thorax's inward motion, and the abdomen's outward movement.	11 weeks	Breathing movements increase steadily until 38 weeks, when they plateau.
Startles	Sudden shock-like motions involving the entire body.	9 weeks	Thirteen weeks, then they start to decrease towards the end of pregnancy.
Twitches	Minor and short involuntary contraction of muscles which do not involve the entire body.	10-12 weeks	Twitches increase until 30 weeks of gestation, then decrease sharply.

Since fetal movements play a significant role in fetal development and well-being, numerous methods of fetal movement detection, based on different measurement techniques, have been used and studied to assess fetal health conditions within the uterus [47]. It is well known that a decrease of fetal movements is associated with different types of pregnancy pathologies such as intrauterine growth restriction, neurodevelopmental disabilities, fetal asphyxia, placental insufficiency, oligohydramnios (i.e., deficiency of amniotic fluid), or even death [48], [49]. Moreover, according to [50], an estimated 2 million stillbirths occurred in 2019 worldwide, with the highest stillbirth rates in Africa and South Asia. Even though there are methods of fetal movement monitoring used in clinical practice, each has its limitation and performs differently in various situations. Therefore further research is needed to advance fetal movement measuring methods so that early and better diagnosis could help prevent possible complications or stillbirths [51]. The following subchapter is dedicated to various methods intended for fetal movement detection.

3.1 Review of Fetal Movement Monitoring Methods

In 2017, a narrative review [51] provided a descriptive taxonomy of fetal movement monitoring methods identifying four main categories of fetal movement measurement. The categories are named as follows: maternal involvement, clinician involvement, technology-assisted, and automated technology. Even though the review did not include and categorise all existing monitoring methods, the taxonomy is still used for better clarity in this subchapter. In addition, methods that are not categorised in the narrative review are classified according to the needed requirements listed in [51].

3.1.1 Maternal Involvement Measurement Methods

One of the most accessible and easiest ways to monitor fetal movements is by the maternal perception and counting fetal movements. Pregnant women usually start to sense fetal movements around 16-20 weeks of gestation, depending on the sensitivity of the uterine and abdominal wall muscles. Moreover, the resulting sensation can vary during the day, depending on the level of a woman's activity, psychological state, or conscious concentration on fetal movements. In addition, several factors can negatively affect the perception of fetal movements, such as tobacco or other drug use and obesity [51]. Since the percentage of detected fetal movements varies between 37-88 %, the maternal perception of fetal movements is highly subjective and prone to error. However, clinicians encourage pregnant women to track the movement of the fetus and report any change (e.g., change of movement pattern, strength, or reduction of fetal movements) as it can help prevent possible stillbirths [51], [52].

Fetal movement counting presents several continuous measurement methods of fetal movements using maternal perception, which do not require clinical settings. Furthermore, they are based on counting fetal movements over a predefined period, resulting in frequency or span count (i.e., the time taken to reach a certain number of detected movements). These methods include, for example, the Sadovsky, Cardiff, and CLAP Methods [51].

a) *The Sadovsky Method* requires women to count fetal movements three times per day in the morning, noon, and evening. Each session is supposed to last one hour. Further investigation is suggested if less than three fetal movements are recorded within one hour [51].

b) *The Cardiff Method*, also known as the Count-to-ten method, monitors how long it takes to reach a count of 10 fetal movements at a particular time each day. Further medical evaluation is suggested in case the mother perceives less than ten movements within 2 hours [51].

c) *The CLAP Method* is a variation of the Sadovsky Method widely used in Latin America. The method is based on fetal movements counting four times per day for 30 minutes after main meals such as breakfast, lunch, dinner, and right before bed [51].

3.1.2 Clinician Involvement Measurement Methods

Clinician involvement measurement methods require a clinically trained healthcare professional to detect and assess fetal movements only by using human senses (e.g., touch, sight, and hearing). Since the thickness of the anterior abdominal wall is relatively small, clinicians can detect fetal movements by placing a hand on the abdomen or pressing it into the abdominal wall. This method is called manual palpation and is based on abdominal wall deflection measurement. Even though this is not a standard method used to assess fetal movements these days, manual palpation is used to determine the position of the fetus in the uterus by a technique called Leopold's maneuvers [51].

Auscultation, as described in Chapter 1, is a method used to identify fHS using the Pinard horn or the DeeLee stethoscope. As well as manual palpation, auscultation is not primarily used to detect fetal movement as it is nearly impossible to distinguish fetal movement sounds from other bodily sounds. However, since many fetal movements cause the acceleration of the fHR, assessing fetal movements is possible by observing changes in calculated fHR [51].

3.1.3 Technology-Assisted Measurement Methods

This category includes methods requiring the use of medical technology along with qualified healthcare professionals who must interpret obtained data. Among these methods, we can include various ultrasound scan modes, Doppler ultrasound, electromagnetic recording of fetal movements, or electromyography (EMG) [51].

The ultrasound scan is a medical device using high-frequency sound waves to create an image of the human body's internal structures, organs, or even the fetus. Obstetricians usually use ultrasound scans in two modes. Brightness mode (B-mode) creates a two-dimensional image helping obstetricians assess pregnancy features and viability. In contrast, motion mode (M-mode) allows analyzing cardiac rhythm, myocardial wall thickness, and ventricular function. Moreover, both modes can be used to monitor fetal movements in case of suspected fetal distress. In addition, the Doppler ultrasound also allows obtaining information regarding fetal movement thanks to calculated fHR and assessment of its changes. However, it is essential to point out that any ultrasound method should not be used for an extended period due to potential risks concerning prolonged exposure to ultrasound waves [51].

An electromagnetic recording is a method of measuring changes in the electromagnetic field induced by fetal movements. The measurement uses a detector and a coil placed above the umbilicus on the maternal abdomen. The output signal of the device is changed by a frequency change of an oscillator caused by fetal movements affecting the electromagnetic behaviour of the coil. It has been observed that movements towards the coil cause increased signal amplitude, while movements away from the coil cause decreased signal amplitude. Moreover, using a magnetic field has been studied and proven not to cause any harmful effects on both mother and fetus [51], [53].

Another technology-assisted measurement technology is electromyography. EMG is mainly known for its diagnostic purposes to assess the health state of muscles and nerve cells. An EMG uses electrodes (e.g., surface electrodes or electrode needles) to detect electrical signals produced by nerve tissue, which in turn cause muscle contraction. However, a study [54] assessed using EMG for fetal movement detection using four silver-chloride electrodes placed on the maternal abdomen. Such electrodes can detect responses of the maternal abdominal wall to fetal movements, which are registered as movement artifacts in the EMG recording. Additional two electrodes for detecting maternal movements are placed on the inner thigh to distinguish them from fetal movements. Even though the EMG was reported to be suitable for fetal movement detection for both short and extended duration, further research is necessary to put this method into clinical practice [51], [54].

3.1.4 Automatic Fetal Movement Monitoring Methods

The last described measurement methods category includes methods that require technological aid to assess fetal movements without the involvement of a clinician directly. Methods that may be included in this category are cardiotocography, actography, vectorcardiography (VCG), fetal magnetocardiography, and fetal electrocardiography [51].

Cardiotocography, described in Chapter 1, is a method based on Doppler ultrasound using two transducers to measure uterine contractions and fetal heart rate. The detection of fetal movement using the CTG is based on an automated analysis of fHR and its accelerations from the baseline in response to the fetal movement [55]. Since CTG is currently the most used method of overall fetal monitoring in most of the world, clinicians use the CTG to assess fetal movement in case of decreased movement reported by the mother to exclude possible fetal distress. However, one of the most significant issues in evaluating fetal movements, from the signals detected by both CTG transducers, is a large signal noise from maternal artefacts such as maternal breathing, arterial blood flow, and other abdominal sounds. These artefacts cause a larger magnitude of the signal's noise floor, making detecting fetal movements from the desired signals challenging and unreliable [51]. Over the years, however, many researchers have tried to figure out how to refine the detection of fetal movements using the CTG. One way of approaching the issue is through research into transducers and their area coverage and how best to position them on the maternal abdomen, which is addressed, for example, in [55]. Another way of approaching the issue would be through signal processing and developing better algorithms for the automatic detection of fHR changes such as fetal heart rate variability, decelerations, and accelerations, helping in fetal movement assessment, which is addressed, for example, in [56]. These algorithms usually incorporate various filters such as a notch, bandpass, or low and high filters depending on the frequency needed for detecting fetal movements (i.e., usually between 0,3 – 60 Hz) [51].

Cardiotocography is not the only method using transducers for fetal movement detection. A second method used to assess fetal movements by applying various transducers is actography, available on actocardiograph machines or very often as part of the CTG machines [57]. The first type of actographs uses transducers that are Doppler ultrasound-based. As described in Chapter 1, in the actocardiography paragraph, fetal movements produce low-frequency Doppler signals between 40-60 Hz, which can be detected by Doppler ultrasound-based transducers allowing, with the help of a bandpass filter, to detect fetal movements [24]. The second type of actographs measures a deflection of the anterior abdominal wall on the surface of the maternal abdomen. Among transducers capable of detecting the changes in the abdominal wall are strain-gauge transducers, accelerometers, piezoelectric film transducers, or capacitative and inductive transducers. Similar to CTG, one of the most significant disadvantages of assessing fetal movement by actography is a large signal noise caused by maternal artifacts. Therefore, several transducers and multichannel signal processing are recommended to eliminate the signal's noise. Another alternative is using a secondary transducer placed on the maternal chest or thigh to detect maternal motion and other artifacts so they could be compensated [51]. The large signal noise, specifically low sensitivity and specificity, caused by maternal artifacts is not the only disadvantage of cardiotocography and actocardiography. Moreover, ultrasound transducers transmit energy into the body, potentially harming fetal development if used in long-term or continuous use. Therefore, fetal magnetocardiography, vectorcardiography, and electrocardiography started to be more researched for fetal movement assessment.

The fMCG, already mentioned in Chapter 1, is well-known for its high signal-to-noise ratio and accurate measurement of the fHR, allowing assessment of beat-to-beat fetal heart rate variability and even fetal movements. In 2002, researchers Hui Zhao and Ronald T. Wakai first described in [58] a new method of assessing fHR and fetal trunk movement by fetal magnetocardiogram actography. The fMCG actography assesses fetal movement due to the high sensitivity of the acquired fMCG signal to changes in the orientation and position of the fetal heart by comparing fHR oscillations, i.e., periodic variation in RR interval, and actogram oscillations, i.e., periodic variations in QRS amplitude due to changes in the orientation/position of the fetal heart [59]. The result of both tracings can be plotted into an fMCG actocardiogram displayed in Figure 12, where substantial variations in the fetal actogram tracing are evidently associated with the elevated fHR and indicate fetal body movement [59].

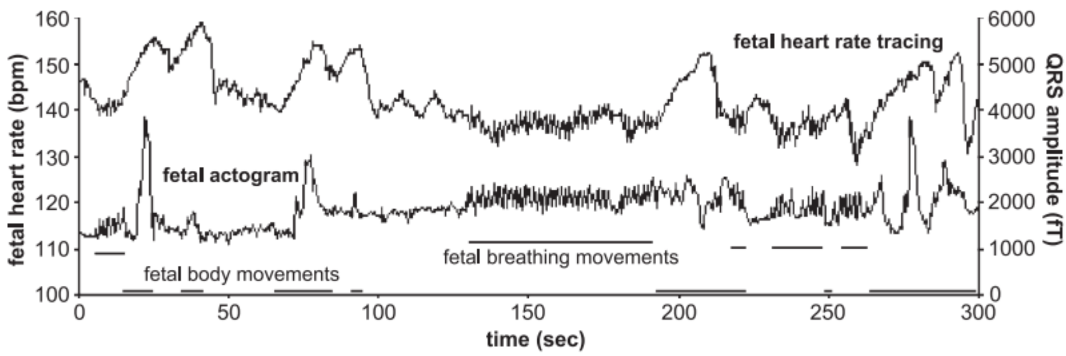

Figure 12: fMCG actocardiogram displaying both tracings of fetal heart rate and fetal actogram with detected body and breathing movements of the fetus [59]

Even though both fMCG and fMCG actography represent an excellent and accurate way of monitoring fetal heart rate and fetal movements, unfortunately, due to the complexity of this technique, cost, and only a few research groups who are currently engaged in fMCG research, this method is not currently suitable for the clinical use [59].

Fetal vectorcardiography (fVCG) presents a method that assesses fetal body movements, fHRV, and overall well-being, similar to fetal electrocardiography and magnetocardiography. Fetal vectorcardiogram, unlike the fECG or fMCG, provides information on the rotation of the fetal heart by calculating the rotation matrix in-between consecutive VCGs, resulting in the description of the fetal heart rotation in three-dimensional space. The fVCG can be produced from the spatial information of the fetal electrocardiogram, obtained by several contact electrodes placed on a maternal abdomen. One of the most significant disadvantages of this method is that only rotational fetal thorax movement can be detected; moreover, inaccurate electrode position and the development of vernix caseosa can distort the VCG tracing [60]. Even though, according to [60], future studies of fVCG are needed to improve fetal movement assessment, for example, by exploiting periodicity and spatial correlation of the VCG. Despite its disadvantages, the fVCG presents a valuable long-term fetal movement monitoring method.

Fetal electrocardiography is the last method described in this category, and it's one of the most promising methods of assessing fetal movement and the overall well-being of the fetus in both clinical practice and home monitoring settings, having the potential to replace the most commonly used CTG machines nowadays. Several NI-fECG methods assessing fetal movements according to temporal and spatial ECG shape identification are being studied, including the fVCG mentioned above [47]. One of the approaches of fetal movement detection is a method based on QRS amplitude variations, which was evaluated, for example, in [47], and is based on tracking changes of the cardiac vector position and orientation towards the measurement electrodes by evaluation of the variations in QRS wave height and shape, resulting in the indicative detection of a fetal thoracic movement. Another approach to detecting fetal movements is through the analyses of fetal heart rate variability through time and spectral domain and their relevant parameters such as standard deviation of normal-to-normal interval (SDNN), root mean square of the successive differences (RMSSDD) for the time domain, and low-frequency power (LF-power), high-frequency power (HF-power) along with the LF/HF-power ratio for the spectral domain [61].

1) *The Standard Deviation of a Normal-to-Normal Interval* refers to the calculated standard deviation of intervals between QRS complexes, more precisely R-R intervals, also known as N-N intervals [61].

2) *The Root Mean Square of Succesive differences* is a parameter referring to the calculated root mean square of differences between successive R-R intervals. It has also been a recognized parameter for measuring short-time parasympathetic activity [61].

3) *Low-Frequency Power and High-Frequency Power* are frequency parameters referring to frequency bands that, according to research, correlate to parasympathetic and sympathetic nervous activity. LF-power represents frequency activity in the 0.04 to 0.15 Hz band, while HF-power represents frequency activity in the 0.2 to 1 Hz band. Moreover, the LF/HF ratio alongside normalized measures of LF and HF powers, defined as $LF_{nu} = LF/(LF + HF)$, and $HF_{nu} = HF/(LF + HF)$ can be obtained from both frequency parameters [61], [62].

The following Table 3 summarizes the results of the systematic review article [61], which reviewed several studies regarding the association of fetal movements and both time and spectral domain parameters compared to rest or non-breathing epochs.

Table 3: Summary of time and spectral domain parameters regarding breathing and fetal body movements in comparison to rest and non-breathing epochs

	Parameters	**Breathing movements**	**Fetal Body Movements**
Time Domain	RMSSD	Increased	Increased
	SDNN	Increased	Increased
Spectral Domain	LF Power	No Data	Increased
	LF_{nu}	No Data	Increased
	HF Power	Increased	Increasing tendencies
	HF_{nu}	No Data	Decreased
	LF/HF Power	Decreased	No Data

Besides the methods mentioned above, detecting fetal movement by assessing the changes in fetal heart rate (e.g., accelerations and decelerations) is another possibility since NI-fECG represents a great and reliable method of fHR monitoring [63].

3.1.5 Summary of Available Methods for Fetal Movement Detection

The following Table 4 summarizes available methods for fetal movement detection, their clinical feasibility, and their accuracy.

Table 4: Summary of available methods for fetal movement detection

Taxonomy	Method	Frequency	Clinical feasibility	Accuracy
Maternal Involvement	Maternal Perception	Continuous	Low *	Low
	Fetal Movement counting	Continuous	Low *	Low
Clinician Involvement	Manual Palpation	On-demand	High	Low
	Auscultation	On-demand	High	Low
Technology - Assisted Measurement	Ultrasound Imaging	On-demand	Medium	High
	Doppler Ultrasound	On-demand	Medium	Low to Medium
	Electromagnetic Recording	On-demand	Medium **	More Research Needed
	Electromyography	On-demand	Medium **	More Research Needed
Automated Technology Measurement	Cardiotocography	Extended Duration	High	Medium
	Actography	Extended Duration	High	Medium
	Magnetocardiography	Continuous	Low **	High
	Vectorcardiography	Continuous	High***	Medium to High
	Non-Invasive Electrocardiography	Continuous	High***	Medium to High

*Only in home settings

**Only in research

*** More research is needed, not commonly used in clinical practice as of now

4 Methodology

This chapter is dedicated to the analysis of the manifestations of fetal movements on various signals, primarily the fECG signal, along with fHR tracing obtained by conventional CTG. Based on the author's research, a graphical user interface (GUI) for the automatic detection of fetal movements is developed and evaluated.

4.1 Analysis of the Manifestations of Fetal Movements on Various Signals

Based on the comparison of available methods for fetal movements detection, their clinical feasibility, the accuracy of fetal movements detection, and considering the safety of both the fetus and the mother, the NI-fECG represents a safe and accurate method for fetal movement detection that has the potential to replace nowadays's conventional CTG used in clinical practice. Therefore, this subchapter analyzes the manifestations of fetal movements on the fECG signal to confirm the suitability of NI-fECG for fetal movement detection both in clinical practice and home settings.

The data used in this thesis has been provided from the dissertation of Ing. Radana Vilímková Kahánková, Ph.D. [64]. Measurements were carried out using the NI-fECG and the CTG on pregnant women at the 36th week of pregnancy at the private clinic in Karviná, Czech Republic. Recordings from both NI-fECG and CTG were done simultaneously. The recording was 60 minutes divided into 20-minute-long intervals during which the fetus was either asleep, awake without any pronounced movement, or awake and moving [64]. The fECG data used for the following analysis have already been preprocessed, the maternal ECG component has been canceled, the fetal ECG component has been extracted, and R-peaks detected.

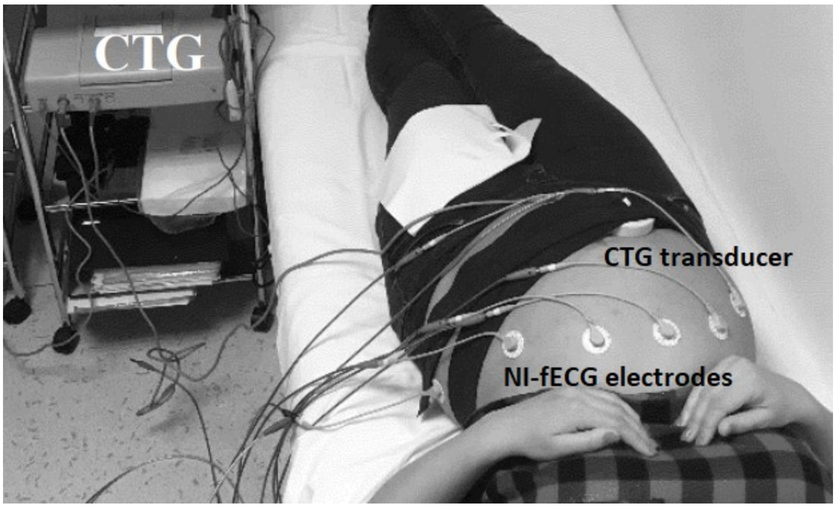

Figure 13: Measurements using the NI-fECG and the CTG at the private clinic in Karviná, CZ [64]

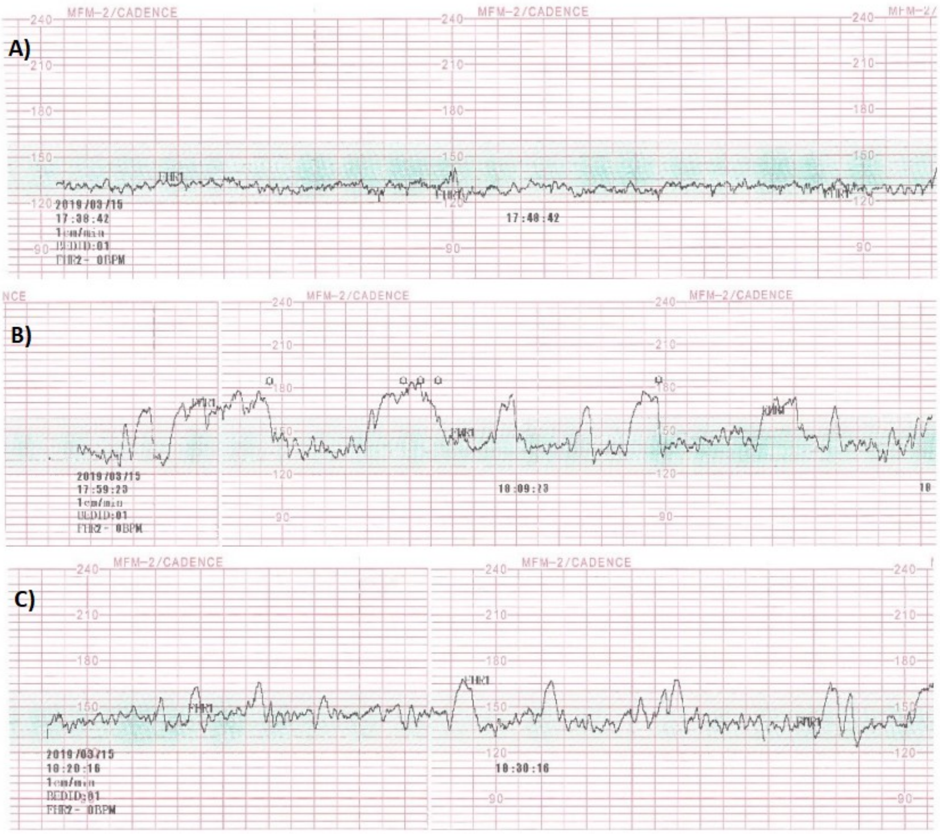

Figure 14: The CTG recording of fHR tracing before the digitalization: A) the fetus was asleep, B) the fetus was awake and moving, C) the fetus was awake without pronounced movement [64]

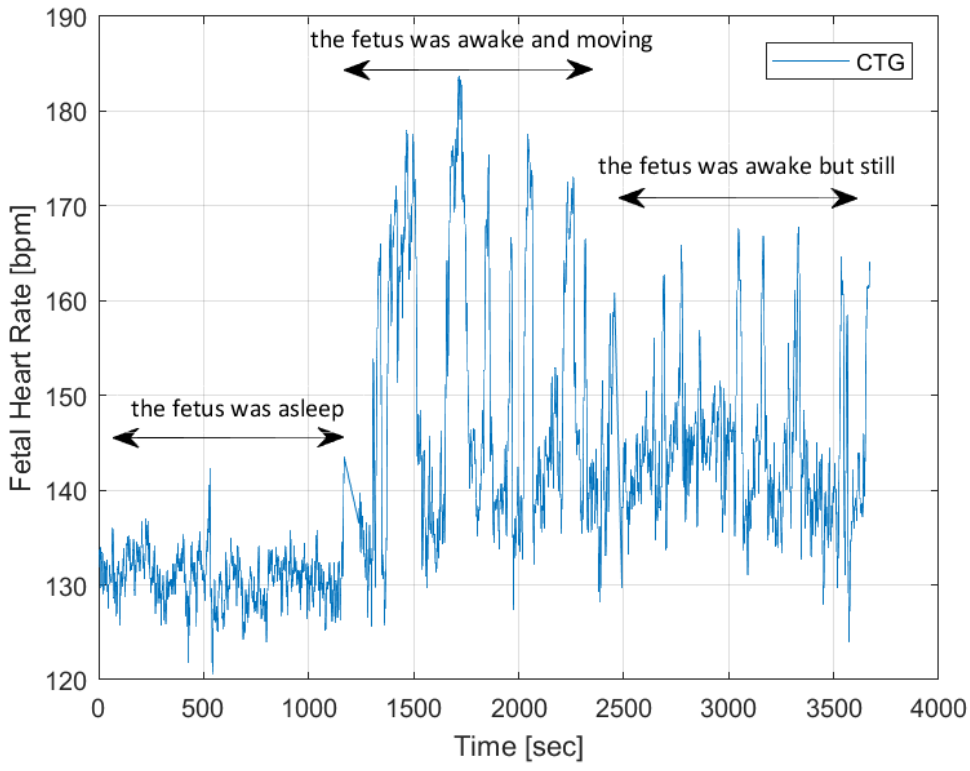

Figure 15:The CTG recording of fHR tracing after the digitalization with marked intervals of the state of the fetus

One of the approaches to detecting fetal movements is the analysis of the fetal heart rate variability and its changes according to movement. Figure 15 shows a digitalized and plotted CTG tracing with marked intervals when the fetus was asleep, awake without pronounced movement, and awake but moving. The resting fHR of a fetus is significantly higher than the one of an adult person, being around 130-160 beats per minute (bpm). It can be seen from Figure 15 that in the case of this particular fetus, the fHR fluctuated around 130 bpm while asleep and between 140-150 bpm with occasional increases in fHR up to 160 bpm while awake without pronounced movement. In the marked interval when the doctor confirmed that the fetus was moving, the fHR increased rapidly and reached values up to 180 bpm, indicating a more significant movement. At first glance, the fECG signal does not showcase the information about fHR; however, it is possible to calculate the fHR by detecting the fetal R-peaks and calculating the fHR from the length of the R-R interval. Figure 16 shows the fECG signal with detected R-peaks and marked R-R interval.

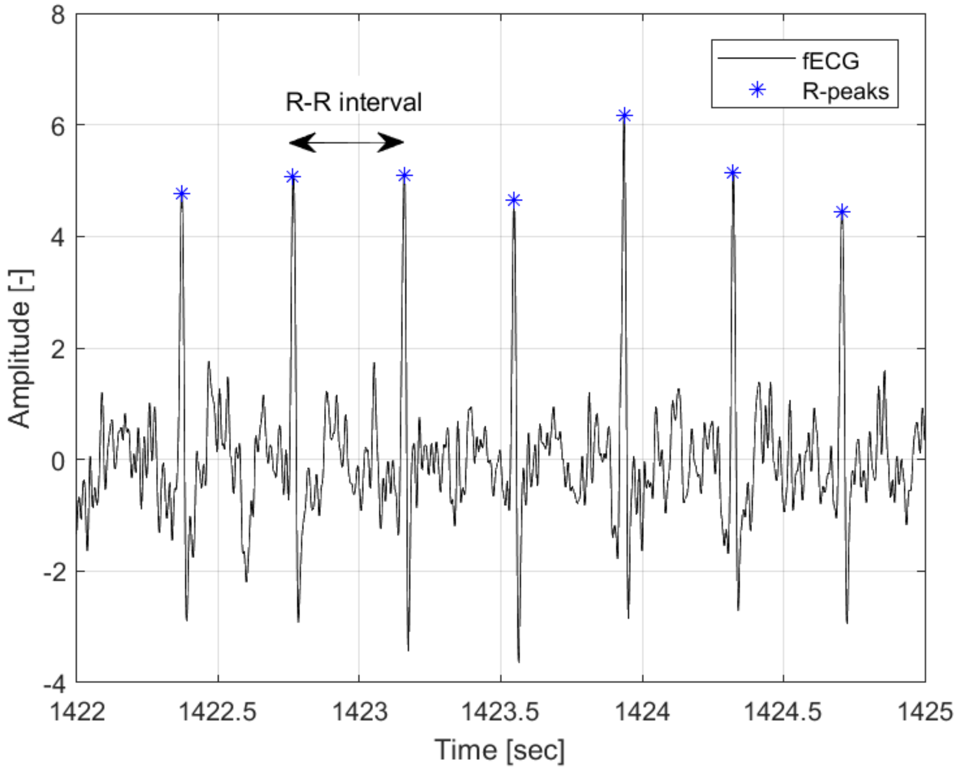

Figure 16:The fECG with detected R-peaks and marked R-R interval

The following Figure 17 showcases a plotted fHR tracing obtained from the fECG signal by calculating the distance between each consecutive R-peaks. Moreover, Figure 18 combines both fHR tracings obtained by means of the CTG and the NI-fECG.

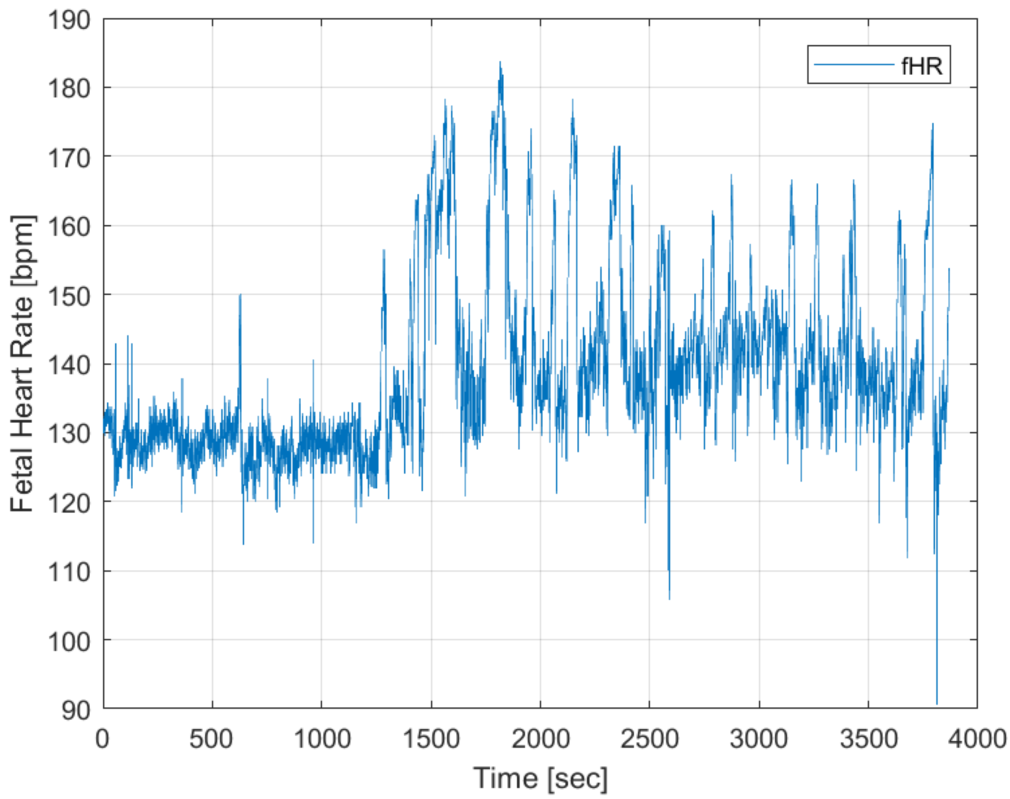

Figure 17: The fHR tracing obtained from the fECG signal

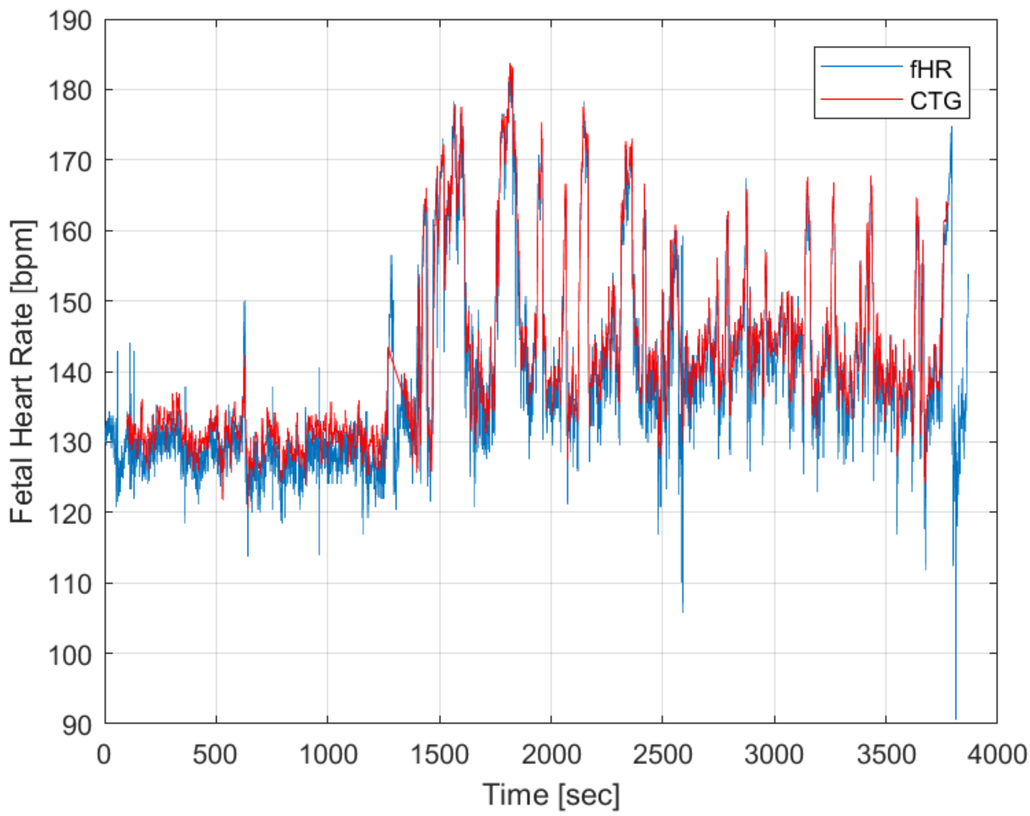

Figure 18:The fHR tracings obtained by the CTG and the NI-fECG

As is evident from Figure 17 and even more so from Figure 18, where both fHR tracings from the CTG and the NI-fECG are compared, with the proper fetal R-peak detection, the fHR tracing can be obtained with considerable accuracy corresponding to the accuracy of other conventionally used methods. Therefore, with the appropriate setting of the fHR threshold, which indicates fetal movements, detection of fetal movements based on the variations in fHR is possible. It is essential to point out that this method might have difficulty detecting small movements that do not increase the fHR enough over the threshold, indicating fetal movement.

Besides the analysis of the change in the fHR, the variation in the amplitude's height and shape of the fECG signal can be studied and evaluated according to the state of the fetus. Figure 19 shows two chosen segments out of intervals when the fetus was asleep (top two segments) and awake while moving (low two segments).

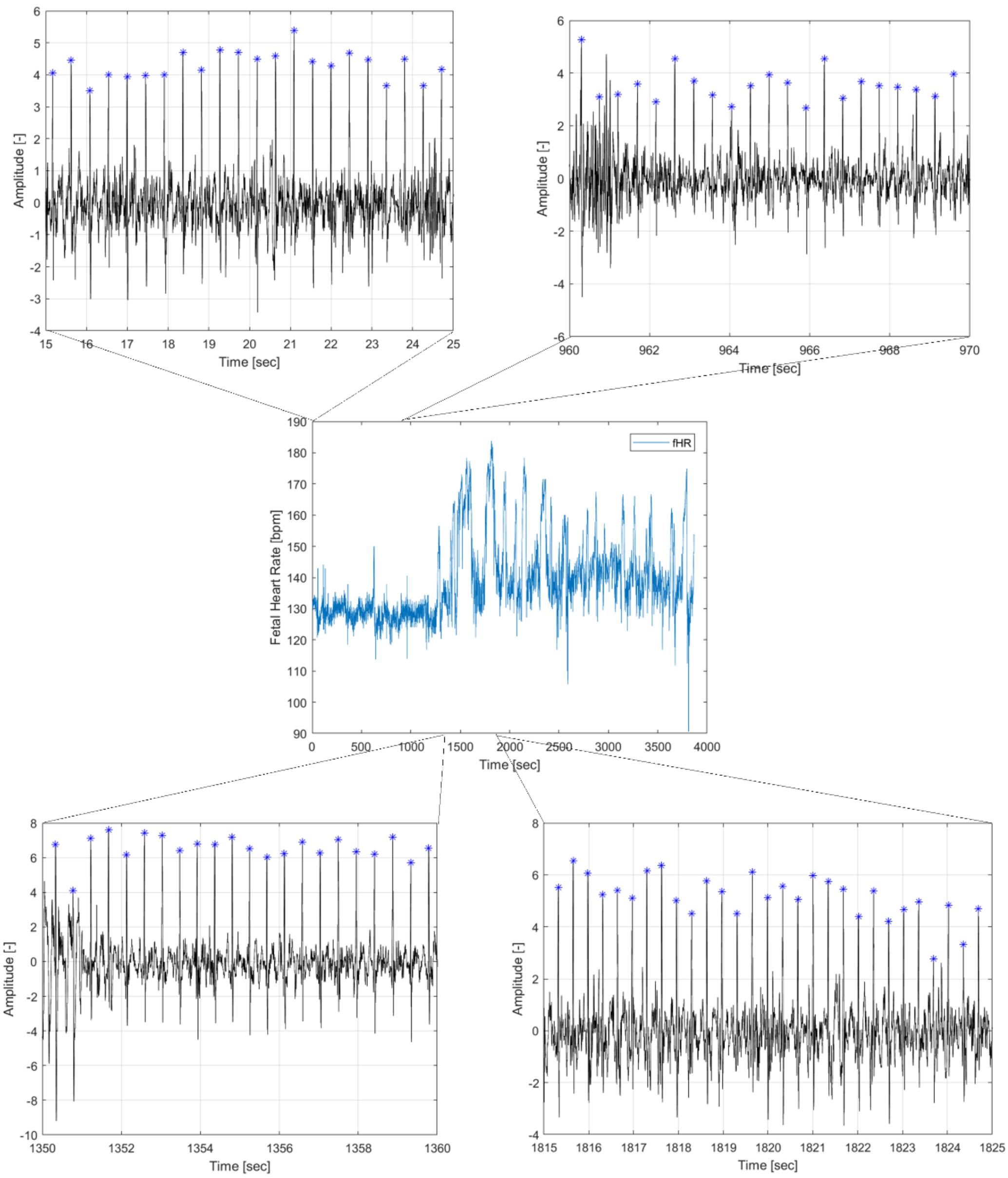

Figure 19: Amplitude differences in fECG signal according to the state of the fetus

Figure 19 shows a noticeable difference in the amplitude of the fECG signal when the fetus is asleep versus moving. In the case of the fetus moving, the QRS complex, specifically the R-peaks, tends to have a much higher amplitude than the amplitude of the QRS complex of the fetus asleep. Moreover, the R-R interval of the fECG signal appears to be shorter, indicating an increased heart rate. Figure 20 and Figure 21 display two-second-long segments of the fECG signal to show the length difference of the R-R interval in more detail, along with the differences in R-peak amplitude.

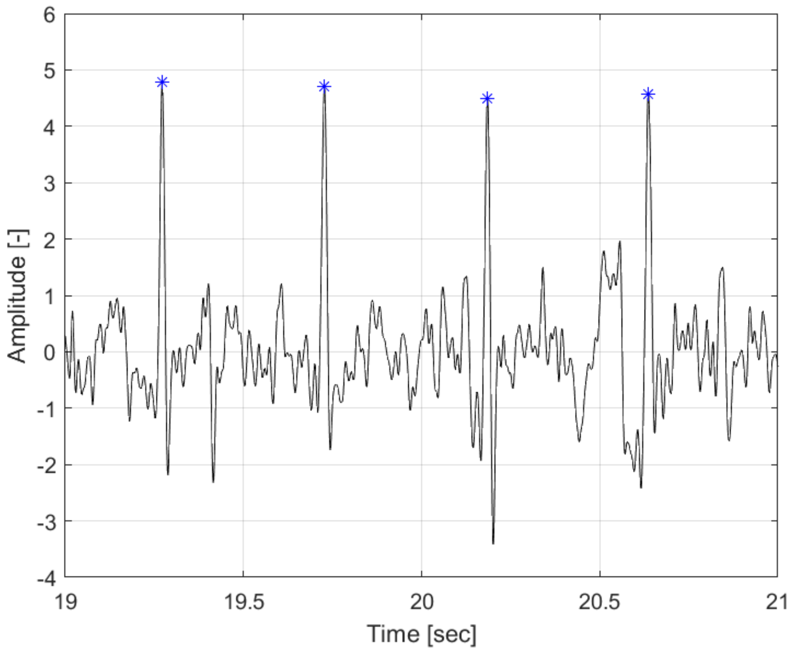

Figure 20: The two-second-long fECG segment while the fetus was asleep

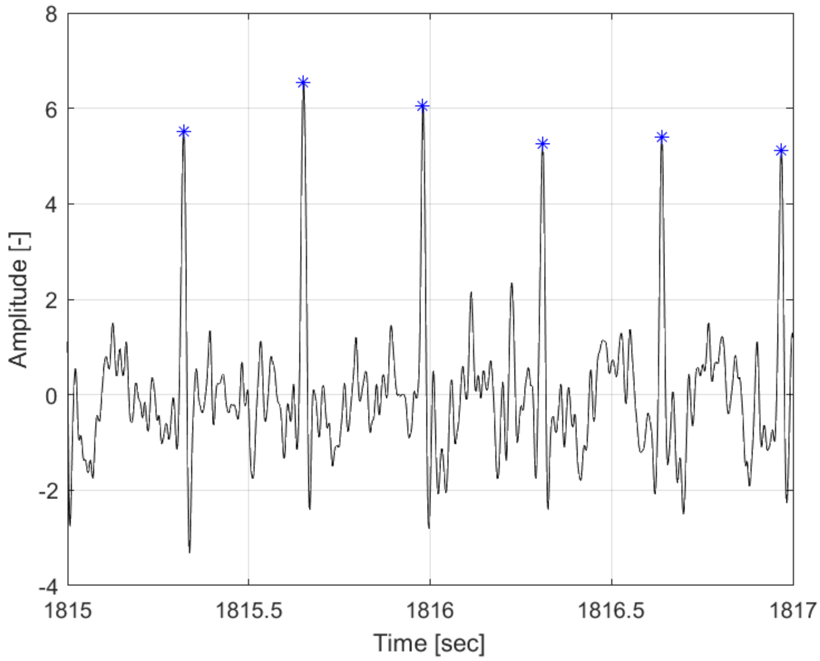

Figure 21: The two-second-long fECG segment while the fetus was moving

To further compare and confirm the hypothesis of whether fetal movements affect the amplitude, the amplitude curve of all individual R-peaks detected in the fECG signal was compared to the fHR tracing obtained from the fECG signal. Figure 22 shows that the amplitude of detected R-peaks increases with the increased heart rate, following a similar curve trend.

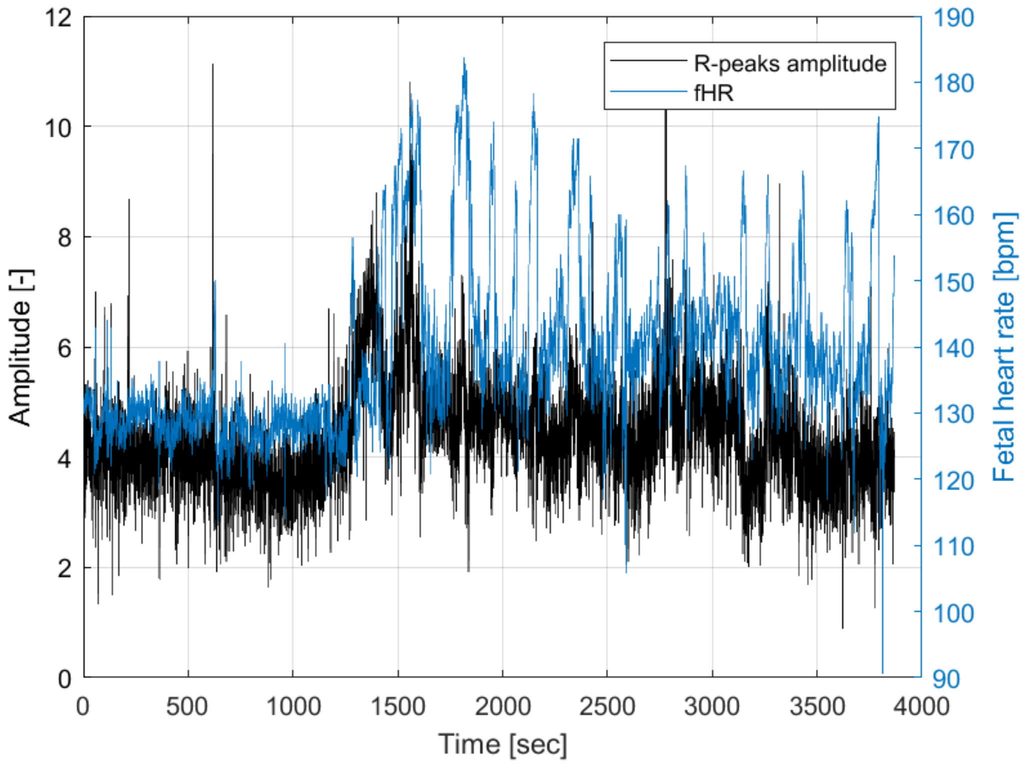

Figure 22: The comparison of the R-peaks amplitude's curve trend to the fHR obtained from the fECG signal

Another approach to analyzing fetal movement manifestation is through the fECG signal's time-frequency representation. Table 3 summarises the results of the systematic review article [61] when it has been observed in multiple studies that fetal movements increase low-frequency activity, especially within the LF Power (0.04 to 0.15 Hz) and HF Power (0.2 to 1 Hz) frequency bands. The time-frequency analysis studies the signal in both the frequency and time domains, helping us to understand how the frequency of the signal of interest changes over time. The following time-frequency analysis was executed through the MATLAB function *spectrogram* that uses the short-time Fourier transform (STFT). The Fourier spectrum is obtained by dividing the signal into smaller equal segments for which the Fourier transform is calculated. The MATLAB function *spectrogram* allows the user to set several parameters such as *window* (i.e., the window used to divide the signal into segments of chosen length), *noverlap* (i.e., the number of samples overlapping between adjoining segments), or *nfft* (i.e., the number of sampling points to calculate the Fourier transform). For the time-frequency analysis, two fECG segments of the fetus asleep and two fECG segments of the fetus moving were chosen to analyse whether there are apparent differences in the presence of lower frequencies.

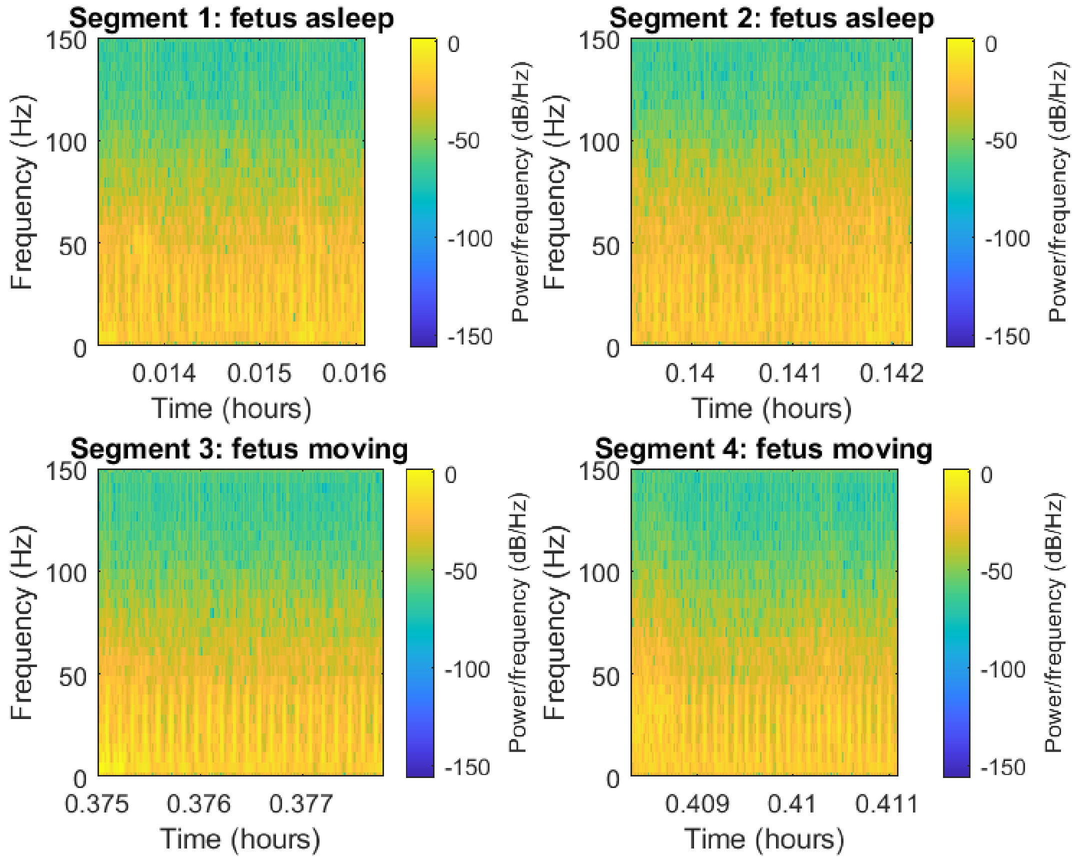

Figure 23: Time-frequency analysis of two fECG segments of the fetus asleep and two fECG segments of the fetus moving

Figure 23 shows a plot of chosen fECG segments analysed through the MATLAB *spectrum* function. Most of the fECG signal's activity can be observed between 0 – 50 Hz in all selected segments without apparent frequency differences between the fetus asleep vs. moving segments. However, a subtle difference in power spectral density (dB/Hz) seems to be higher in segments when the fetus was moving, which could indicate lower frequencies and increased amplitude of the fECG signal. Since it has been shown in the previous analysis that fetal movements indeed increase the amplitude of the fECG signal, the higher values of power spectral density could potentially mean a fetal movement. Nonetheless, due to subtle changes in power spectrum density and without apparent frequency differences, fetal movement detection based solely on time-frequency analysis is not a suitable or reliable method.

4.2 Development of the Graphical User Interface for FM Detection

The following subchapter is dedicated to developing the GUI for automatic fetal detection. The GUI was developed using the MATLAB App Designer, which allows the developer to design the form of the graphical user interface (e.g., buttons, graphs, edit fields), and subsequently program the functions. The proposed program consists of two main parts – a top part dedicated to loading data, choosing the sampling frequency, or plotting the signal, and a bottom part devoted to the fetal movement detection based on two methods – changes in fHR and the amplitude of the fECG signal. These two methods were chosen based on the analysis in the previous subchapter as well as studies [47] and [63] that researched the relevant methods for fetal movement detection.

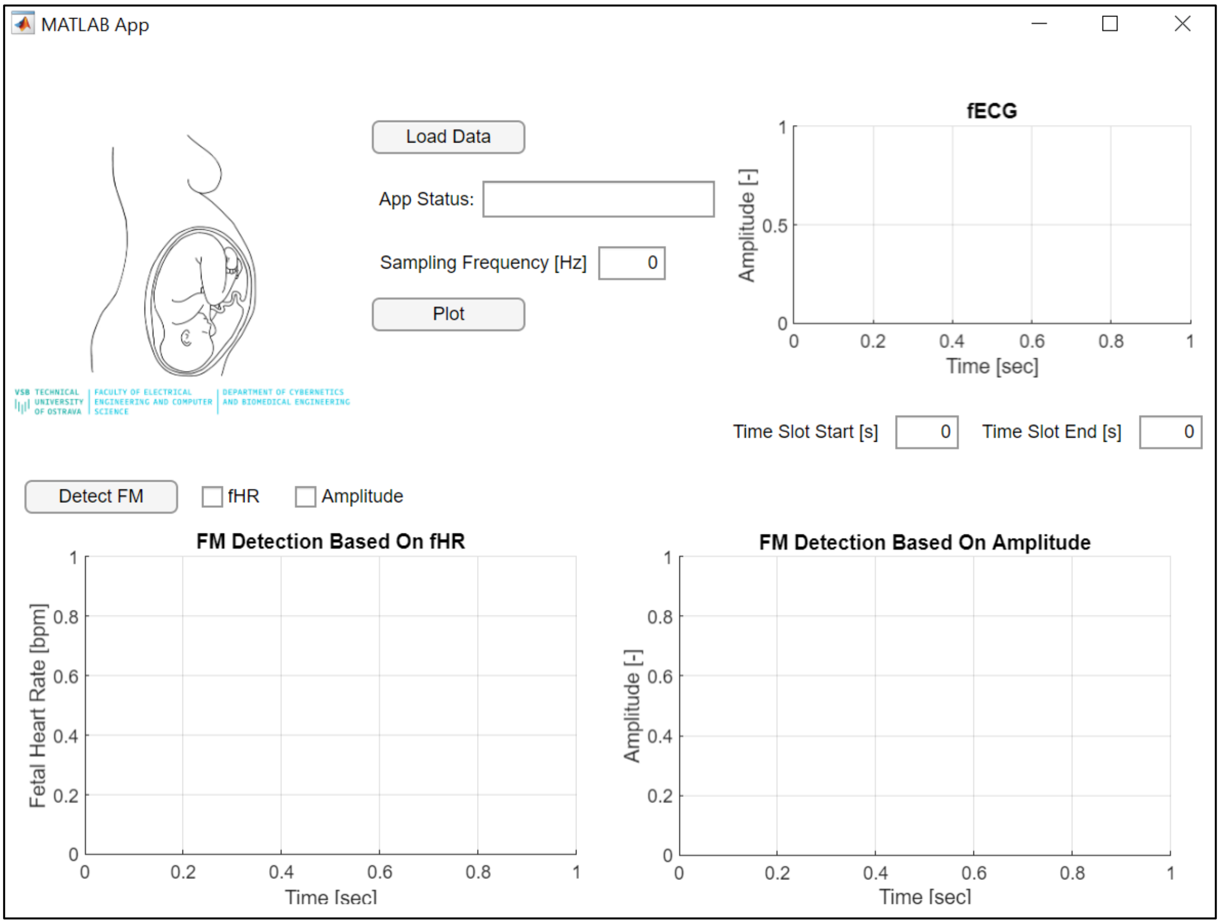

Figure 24: The appearance of the graphical user interface for fetal movement detection

The top part of the GUI consists of the *Load Data* button, which allows the user to pick a signal of interest. The GUI is designed to process extracted fECG signals; therefore, the user should make all necessary steps (e.g., preprocessing and mECG cancelation) to obtain extracted fECG before using the fetal movement detection app. The *App Status* informs the user if selected data were successfully loaded (the *Load Data* button turns green) or whether the operation was canceled by the user (the *Load Data* button turns red) and if it is necessary to load the data again. Below the *App Status* is an editing field to fill in the sampling frequency (Hz) to convert the fECG signal into the time domain. If no value is filled in, the app will not allow the user to plot the fECG signal nor execute the fetal movement detection due to the created condition within the function. Moreover, editing fields *Time Slot Start* and *Time Slot End* were designed to allow the user to zoom in on selected signal parts. Figure 25 shows the plotted fECG signal in its entire length and a chosen part of the desired signal obtained using the *Time Slot Start* and the *Time Slot End* editing fields.

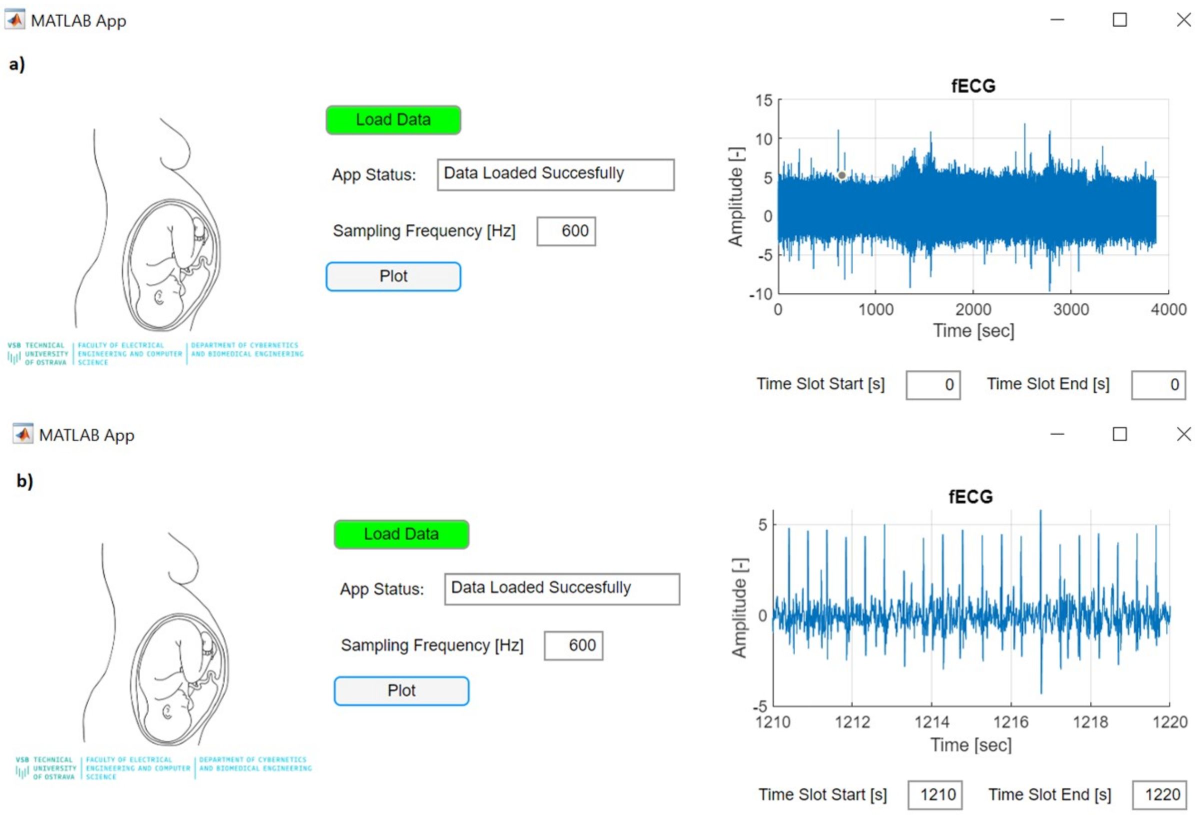

Figure 25: The visualisation of the plotted fECG signal a) in its entire length; b) in the selected time slot

The bottom part of the developed GUI is dedicated to fetal movement detection itself. The user has two options for fetal movement detection to choose from using the *Check Box*. After selecting either one or both desired options for FM detection, the user presses the *Detect FM* button that starts the necessary computing steps to detect FM and subsequently plots the results into the appropriate charts.

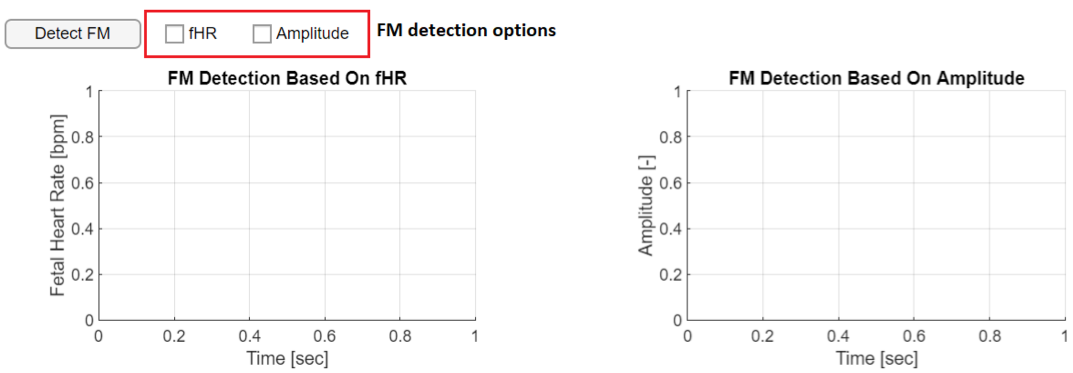

Figure 26: The description of the visual aspect of the GUI dedicated to FM detection

The first chosen method for fetal movement detection is through the changes of the fHR, specifically an increase of the fHR. Figure 27 showcases a data flow diagram of the fHR calculation and fetal movement detection algorithm used in the developed GUI.

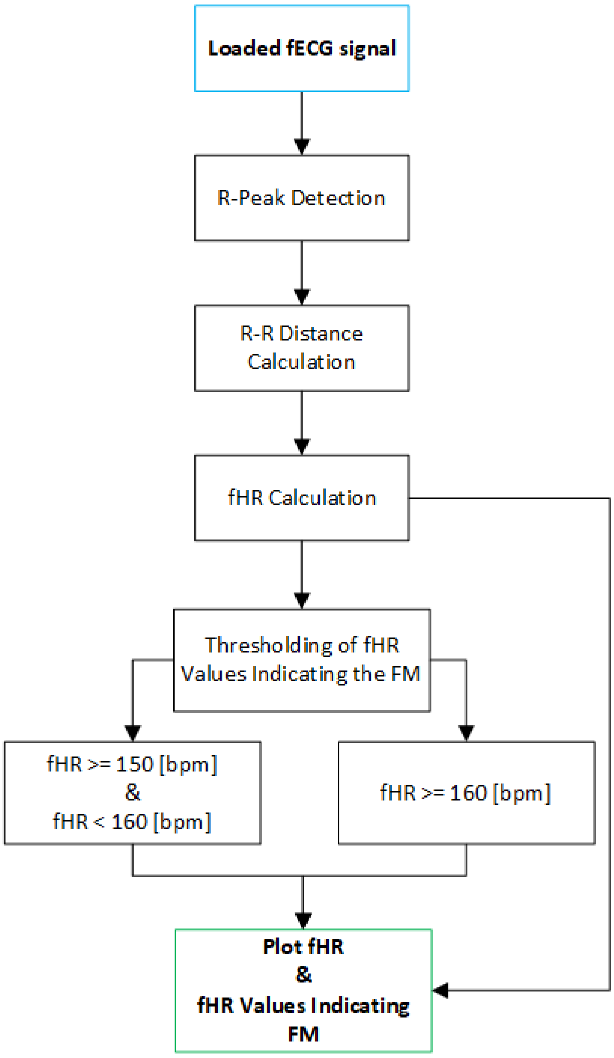

Figure 27: The data flow diagram for FM detection based on changes in the fHR

In order to be able to obtain information about the fetal heart rate, it is first necessary to detect R-peaks. The R-peak detection was performed using the maximal overlap discrete wavelet transform (MODWT), which decomposes the signal into different frequency bands, which further allows work with a reduced representation of the signal of interest. The Sym4 wavelet was used for R peak detection due to its high resemblance to the QRS complex, which can be seen in Figure 28. The MATLAB *findpeaks* function was further used to obtain the amplitude of detected R-peaks and their time instants. Since the calculation of fHR is expressed as $fHR = 60/R - R\ interval$, the distance of each R-R interval was obtained by the MATLAB function *diff*, which returns the distance between adjacent R-peaks. Moreover, the vector of obtained R-R intervals was filtered by the Hampel filter that detects and removes outlier values helping to smooth out the data series. In the next step, the program proceeds to calculate the fetal heart rate. Since the increase in fHR indicates fetal movement, threshold values indicating fetal movement have been introduced in the program. The threshold value for a slight rise in fHR was set to 150 bpm, while the threshold value for a more noticeable increase in fHR was set to 160 bpm. The set threshold values were used in creating conditions for thresholding fHR values. The minor fetal movements are detected when the fHR meets the condition to be in the range of 150 to 160 bpm; on the contrary, the gross fetal movements are detected when the fHR exceeds 160 bpm. The resulting plot with detected fetal movement based on fHR thresholding can be seen in Figure 29.

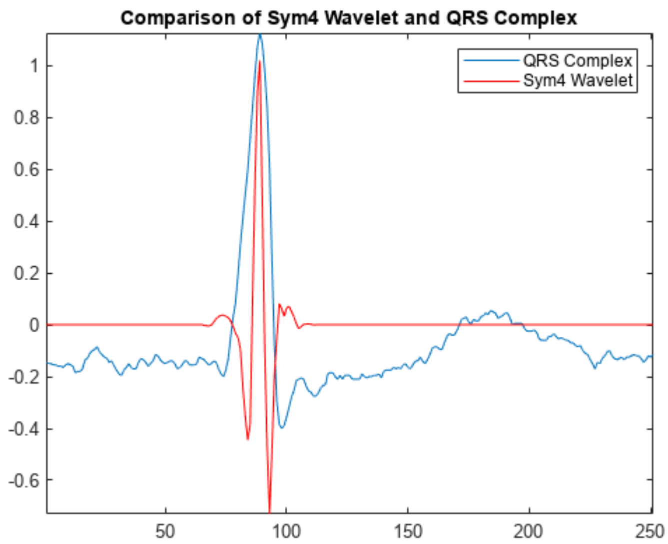

Figure 28: The comparison of the Sym4 wavelet and the QRS complex [65]

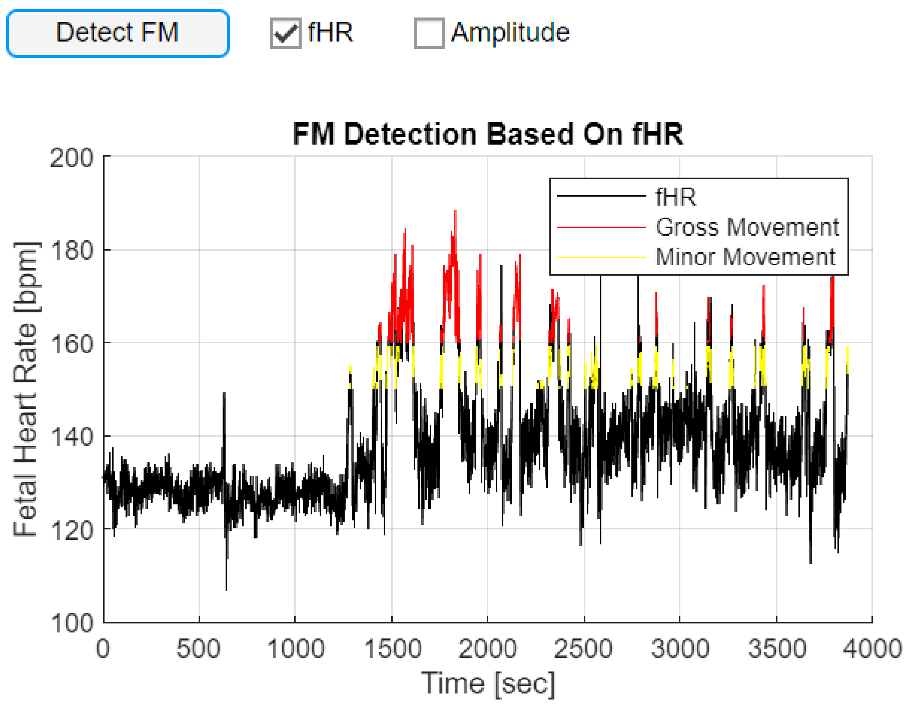

Figure 29: An example of the FM detection based on fHR

The second chosen method for fetal movement detection presented in the GUI is based on increased R-peaks amplitude. Similar to the proposed method based on increased fHR, the first step of the detecting algorithm is the R-peak detection using the MODWT, specifically the Sym4 wavelet. Moreover, the Hampel filter was used to detect and remove R-peaks amplitude outliers that could introduce an error in fetal movement detection. Figure 30 shows the data flow diagram for FM detection based on amplitude.

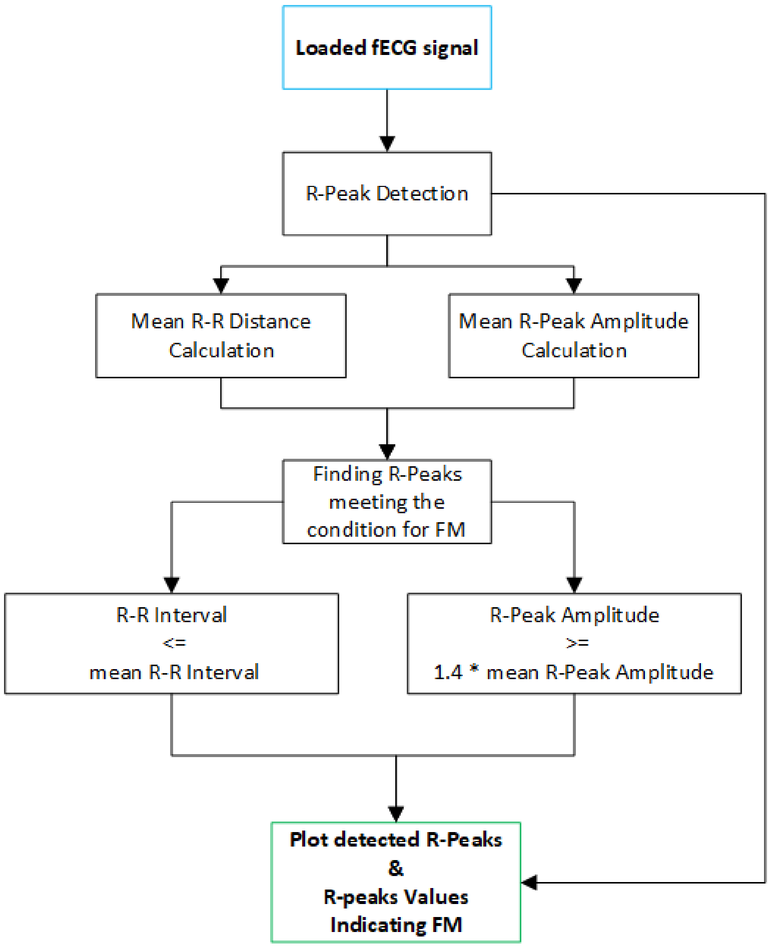

Figure 30: The data flow diagram for FM detection based on amplitude

When the amplitude and time instants of R-peaks are detected using the MATLAB *findpeaks* function, the mean value of the R-peaks amplitude and mean value of R-R interval distance is calculated. The calculated mean values serve to determine and set the correct threshold values for fetal movement detection. To consider the amplitude of an R-peak increased enough, the thresholding value was experimentally set as 1.4 times the mean value of the R-peaks amplitude. Since other influences, besides wrongly detected R-peaks along with not perfectly filtered mECG components remaining in the extracted fECG signal, may cause an increased R-peak amplitude than the movement of the fetus itself, FM detection, in this case, is not based solely on the increase in amplitude but also on the length of the R-R interval. The R-R interval is known to shorten with increasing fetal heart rate; therefore, the condition which excludes the R-peaks with a distance less than the mean R-R interval is included. The plot of the detected fetal movements based on the R-peaks amplitude is shown in Figure 31.

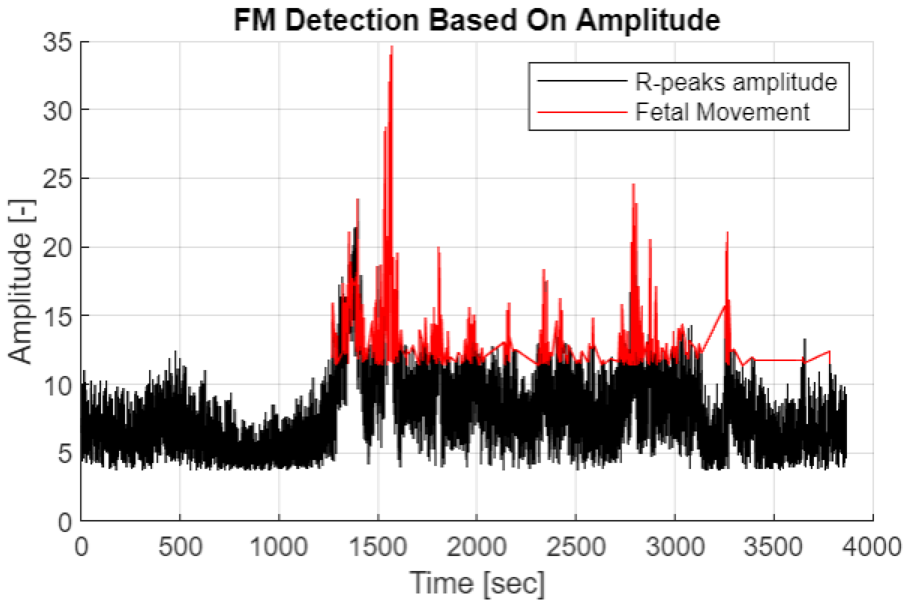

Figure 31: An example of FM detection based on amplitude

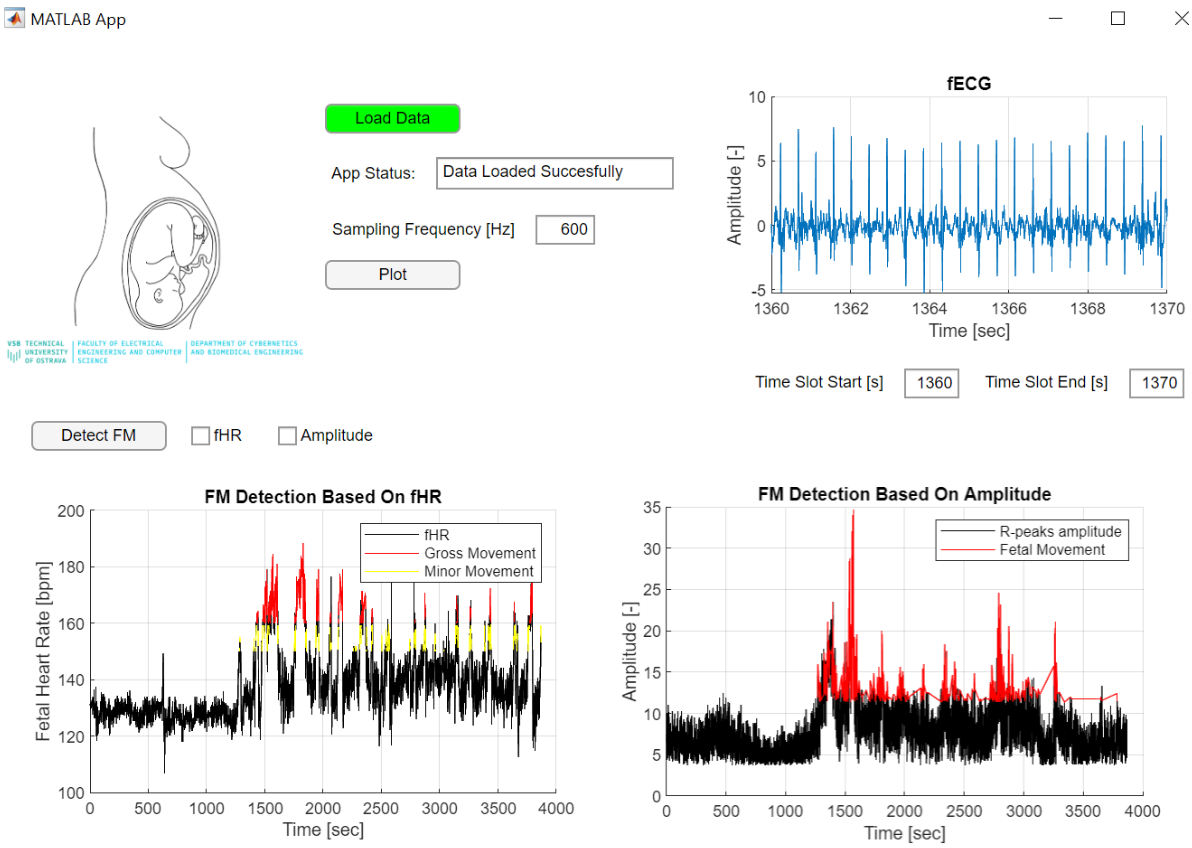

Figure 32: The GUI with the plotted segment of an fECG signal and detected movements based on two available methods

4.3 Discussion of Achieved Results

The following subchapter is dedicated to the review of the achieved results of fetal movement detection analysis and developed GUI. The first part of the methodology was devoted to the study of manifestations of fetal movements on various signals, specifically CTG and fECG. The analysis has shown that fetal movements manifest in several ways, such as increased fetal heart rate or increased R-peak amplitude of the fECG signal. Moreover, time-frequency analysis was conducted to find out whether any apparent manifestations of fetal movements exist and occurred in the spectrogram. The time-frequency analysis was mostly inconclusive since there were no apparent changes in frequencies; however, there is a potential further to study manifestations of fetal movements in the frequency domain as, according to [61], fetal movements do increase specific spectral domain parameters such as LF and HF power.

The second part of the methodology was devoted to developing a graphical user interface capable of detecting fetal movements. The GUI was evaluated using the extracted, approximately 60 minutes long, fECG signal that was simultaneously recorded with CTG. The fECG signal can be divided into three segments when the fetus is asleep (0 - 1200 seconds), the fetus wakes up and starts to move (1200 – 2400 seconds), and the fetus is mostly still without an occurrence of any pronounced movement (2400 – 3800 seconds). The detected fetal movements by the developed app can be seen in Figure 33.

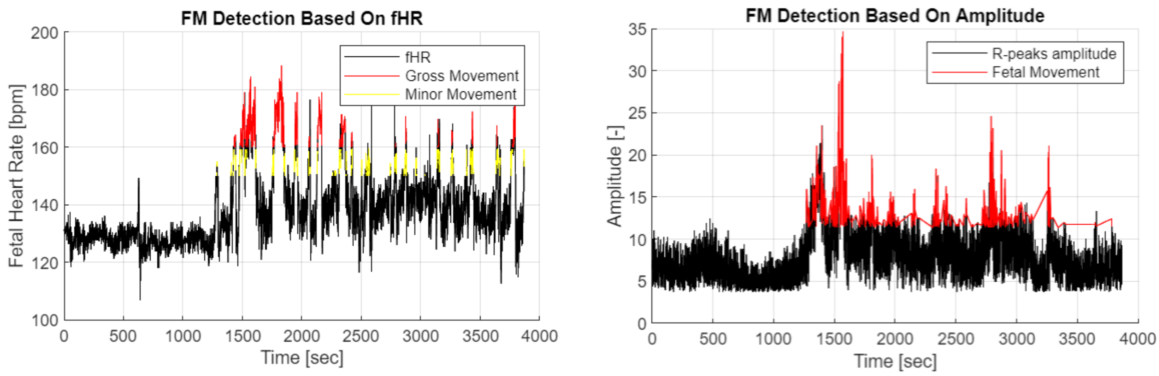

Figure 33: The detected FM by the developed GUI

In both cases, no fetal movements were detected in the first segment when the fetus was asleep. This indicates that threshold conditions, which determine the threshold value suggesting whether a fetal movement is present or not, were chosen correctly since no fetal movements were detected. Figure 33 shows that fetal heart rate and R-peaks amplitude vary significantly during sleep compared to when the fetus is awake. In the second segment, when the fetus woke up and started to move, both presented algorithms correctly detected FM. It is apparent that in both cases, there are spiked values of fHR and amplitude, indicating awakening and moving fetus. The most inconclusive results are contained in the third segment, where the fetus is awake, but there were no pronounced fetal movements confirmed by the doctor; however, fetal movements are detected by both algorithms. These results could lead to two possible scenarios: small, not-so-pronounced movements were present, and the algorithm detected them correctly, or the fetal movements were falsely detected for the following reasons. In the case of FM detection based on fHR, this may be caused by various reasons since fetal movement is not the only parameter that affects increased fetal heart rate. Increased fHR can be caused by maternal and fetal stress, uterine contractions, or other external stimuli, such as sound, light, and vibrations. The algorithm for FM detection based on amplitude seems to be a little bit more precise as there are areas within the third segment where FM are detected due to a noticeable increase in R-peaks amplitude; however, there are also segments without any detected fetal movement, or the detection is solely based on an increased amplitude of a single R-peak. Since a single increased R-peak amplitude does not indicate fetal movement, further development and refinement of the presented algorithm could contribute to better FM detection. Overall better detection results based on changes in R-peaks amplitude may be caused by using two threshold conditions – the first condition is based on the actual increase in amplitude. In contrast, the second condition is based on the length of the R-R interval, which shortens with increasing fetal heart rate. This shows that using more threshold conditions based on several parameters that influence fetal movement might be more effective and, therefore, represents an opportunity for further study and development within the follow-up diploma thesis. Moreover, the study of the changes in the cardiac vector position and orientation could be incorporated as those changes were shown to have an impact on fetal movement as well. Further improvement of the presented GUI, as part of the diploma thesis, could also include the creation of the preprocessing algorithm for the fECG signal, such as abdominal signal prefiltration and mECG cancellation.

One of the most significant issues regarding fetal movement detection, which has put a certain limit to the presented thesis, is the missing references and datasets that could be used for FM detection algorithms testing. Unfortunately, there is no existing database of fECG signals containing references to detected fetal movements; thus, testing new algorithms and the statistical evaluation of the presented methods is nowadays impossible. The creation of a database of the fECG signals with appropriate fetal movement references represents an essential step in the near future, which could lead to the creation of the gold standard for fetal movement detection. This would make it easier for researchers to analyse further the manifestations of the fetal movements on fECG signals and test new methods for their detection.

Conclusion

The presented bachelor's thesis has focused on the current possibilities of measuring, processing, and evaluating various biological signals for the needs of automatic fetal movement detection.

Chapter 1 introduced the history of the development of fetal monitoring and further described the principle of fetal monitoring methods, along with their advantages and disadvantages, that are currently used in clinical practice or clinical research. Chapter 2 was dedicated to the NI-fECG, a reliable method of fetal monitoring capable of monitoring fetal heart rate variability, diagnosing fetal distress due to the analysis of the QRS complex, and detecting fetal movements. Ni-fECG represents an extensively researched method, as it can potentially replace nowadays's conventionally used CTG. Moreover, the fECG signal contains more valuable information regarding the well-being of the fetus, which could help with the early diagnosis of any fetal distress, preventing the possible stillbirth.

Chapter 3 was devoted to the introduction of fetal movements and their detection. The first part of the chapter has described how fetal movements are categorized, how they manifest, and why they are vital parameters to look at when assessing fetal well-being. The second part of the chapter was dedicated to an extensive review of fetal movement detection methods which are researched or already used in practice. The summary of the available FM detection methods can be seen in Table 4.

The last chapter was dedicated to analyzing the manifestations of fetal movement on fetal heart rate trace obtained by CTG and fECG signal obtained by NI-fECG. The analysis has shown that fetal movements manifest as increased fHR and R-peak amplitude. The graphical user interface detecting fetal movements was developed and evaluated based on these findings. The presented GUI can detect fetal movements based on two methods from which the user can choose. The evaluation has shown that fetal movement detection based on changes in R-peaks amplitude is slightly more effective, probably due to more threshold conditions implemented in the algorithm. One of the most significant limits of fetal movement detection is a missing gold standard and database with fECG signals with fetal movement references, which could be used for testing algorithms such as the one presented in this thesis. Nonetheless, the proposed thesis shows the importance of fetal movement monitoring since fetal movement significantly impacts overall fetal well-being. Moreover, the detection of fetal movements may be valuable as an additional tool used in fetal magnetic resonance imaging since fetal artifacts play a significant role in the quality of a taken image.

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Attachment

An electronic appendix is attached in IS Edison to this bachelor's thesis.

Attachment 1 – The graphical user interface for automatic FM detection

Attachment 1 includes the developed graphical user interface developed in MATLAB App Designer.

Attachment 2 – The fECG data used in the evaluation of the presented GUI

Attachment 2 includes the fECG signal used to analyze the manifestations of FM movements on various signals and further evaluate the developed GUI.