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Fetal Movement Measurement and Technology: A Narrative Review

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ABSTRACT Fetal movement counts have long been used as a measure of fetal well-being but with advancing technology, such counts have been supplanted as the primary measure. Despite the new technologies used in standard clinical practice, the stillbirth rate has not reduced significantly worldwide. Each method of assessing fetal movement has limitations with different methods performing better in different situations. No one method is universally superior. This paper aims to introduce the reader to the broad range of assessment methods, both potential and actual, used to determine fetal movement. These assessment methods are assembled into a taxonomy: maternal involvement, clinician involvement, technology-assisted, and automated technology. A brief historical and technological overview and the expected measurements of each assessment method are described. All reviewed methods have value, but actography appears to offer the most potential by complementing existing approaches. Further research is required to evaluate the suitability of fetal movement assessment and the response to it.

INDEX TERMS Fetal movement, ultrasound, actography, auscultation.

I. INTRODUCTION

Fetal movement has long been used as an indicator of fetal well-being [1]. Assessment of fetal movement is an accepted method of identifying adverse pregnancy outcomes, including intrauterine growth restriction and placental insufficiency [2]. Gross involuntary fetal movement begins as early as 7 gestational weeks [3]. As muscular and neurological development continues, independent voluntary movement of the limbs, such as kicking, begins around 12 gestational weeks [3]. However, maternal perception of fetal movements (or quickening) commonly starts at around 16-20 weeks, depending on parity [4]. Fetal movement assessment includes most voluntary and involuntary gross bodily movement, excluding hiccups and related phenomena [4]. In women at higher risk of fetal compromise, observation of fetal movement to detect potential issues is recommended during the third trimester, beginning from 28 gestational weeks onward [5].

With the advent of ultrasound technology and blood test screening, fetal movement is no longer the primary clinical test of fetal well-being. However, for practical and safety reasons, these technologies cannot be used continuously [6], so assessment of fetal movement continues to play an important role. While clinical health care has improved perinatal mortality rates [7], fetal movement continues to be [5] associated with general fetal health and nervous system development [8], [9]. The use of fetal movement measurement to identify pregnancy risks, particularly stillbirth, continues to undergo development in terms of both policy [10]–[14] and technology [15]. Globally, up to 2.6 million third trimester stillbirths occur each year, with the majority occurring in low and middle income countries [10]. Stillbirths in high income countries also continue to occur, with estimates of 3.5 per 1000 births [11], indicating the ongoing need for development in this field [12], [16]. To date, there has been limited account of the methods used to measure fetal movement. Greater understanding of fetal movement measurement and methods may advance technology and research in this area. This review aims to describe the range of potential and established technical techniques and metrics for fetal movement through the development of a descriptive taxonomy. This review will provide those new to the field with sufficient technical and procedural background to contribute to the field.

II. METHOD

A broad search of relevant, peer reviewed, English language articles was completed in mid-2016 using a range of key

TABLE 1. Summary of fetal movement measurement methods.

METHOD	OUTCOME	FREQUENCY	TYPE OF RECORD	TAXONOMY LEVEL
Maternal perception	Binary evaluation of health	Continuous	None	Maternal involvement
Fetal movement counting	Frequency Count Span Count	Continuous	Reliant on maternal adherence	Maternal involvement
Manual palpation	Frequency Count Span Count	On demand	Reliant on clinical personnel	Clinician involvement
Auscultation	None reported	On demand	Reliant on clinical personnel	Clinician involvement
Ultrasound Imaging	Frequency Count Span Count	2-3 times	Recorded with other observational notes	Technology-assisted
Doppler ultrasound	Binary evaluation of health	On demand	Reliant on clinical personnel	Technology-assisted
Other methods	Frequency Count	On demand	Recorded alongside raw data	Technology-assisted
Actography	Frequency Count Span Count	Extended duration	Digital record produced for duration	Automated technology
Cardiotocography (CTG)	Frequency Count Span Count	Extended duration	Digital record produced for duration	Automated technology

Summary includes measurement outcome, expected frequency during normal pregnancy, type of record produced for later clinical review, and taxonomy level

words particular to the research question: What methods are used for the measurement of fetal movement?

Keywords were composed according to the fetal movement techniques in question and combined with "fetal move*" (e.g. "auscultation fetal move*", "accelerometer fetal move*", "doppler fetal move*"). PubMed, Web of Science and Science Direct bibliographic databases were used with no date limits set. From this initial search, a comprehensive snowballing technique was undertaken, where the reference list of key papers were reviewed until no new fetal movement measurement methods or documents emerged.

Based on an initial review of the retrieved papers, a draft taxonomy was developed to enable categorisation of the fetal movement measurement methods identified in the literature (see Table 1). This taxonomy guided the categorisation of each measurement method described in the studies encountered.

It was anticipated that multiple measurement methods may be combined, for example cardiotocography (CTG). When this occurred categorisation was based on the method most clearly associated with fetal movement counting. Where possible standard information about each measurement method was extracted including: a summary of the basis of fetal measurement; the measurement outcome, or count metric; and the frequency and nature of stored records. In recording the summary of the basis of measurement there was no attempt to list all variants of a method, rather the intent was to obtain a brief historical perspective and a description of the common elements typically used. This review was not intended to be exhaustive or representative of the prevalence of different approaches in the literature or in clinical practice, as such summary statistics of different methods were not extracted.

III. RESULTS

A. FETAL MOVEMENT MEASUREMENT TAXONOMY

Four main categories of fetal movement measurement were identified for the taxonomy. Categories were based on the primary requirement needed for movement assessment to be possible. The taxonomy categories are: *maternal involvement; clinician involvement; technology-assisted; and automated technology*. For example, to be included in the maternal involvement category, mothers were responsible for the assessment of fetal movement. All the methods reviewed are summarized in Table 1. The different ways of measuring outcomes were also classified and included: frequency count, span count and binary evaluation. Frequency count refers to the number of movements observed over a fixed time period. Span count refers to the time period taken to reach a fixed number of movement observations. Binary evaluation refers to an assessment of whether the fetus was judged to be potentially at risk or not. Additional unique measurement metrics were categorised, for example the proportion of active fetal time.

B. MATERNAL INVOLVEMENT MEASUREMENT

The primary requirement for these methods is the involvement of the pregnant woman in the assessment of fetal movement. These methods include maternal perception of any fetal movement and formal counting methods.

Fetal movement is sensed in pregnant women by the uterine and associated abdominal wall muscles [17] any time after 16-20 weeks gestation [3]. Therefore, the conscious perception of movement is reliant on the sensitivity of uterine/abdominal muscles and the level of mental focus on resulting sensations [5], [18]. For this reason, maternal perception of fetal movement can vary between women and for an individual woman across the day, dependent on her activity [19]. If the woman adopts a relaxed position, such as lying down, and is asked to specifically pay attention in a quiet room, movements that were previously not perceived are recognized easily [18].

Maternal perception correlates well with strong general body movements [20], [21]. Maternal perception can be negatively impacted by an anterior placenta, use of tobacco and other drugs, nulliparous mother, maternal psychological factors (i.e. interest in the health of the fetus) and maternal position and activity during counting [5], [16], [21]. Maternal sensitivity to fetal movement is not well correlated to gestational age (post-quickening), maternal age or obesity [20]. Formal counting may increase maternal anxiety in some women while in others increase the feeling of being "in control" [22]. Mangesi *et al.* [16] reports evidence of reduced anxiety levels among women who routinely counted fetal movement during pregnancy.

Maternal counting of fetal movement is a continuous measurement and does not require a clinical setting. The resulting measure is either a frequency or span count, recorded on a daily basis if the mother is adherent. Maternal perception is subjective and there is a wide range in accuracy [5], [23]. Due to the subjective nature of the reported data, its use in making objective diagnostic conclusions requires broad margins to account for error.

1) MATERNAL PERCEPTION

The most common method of fetal movement assessment is maternal observation [22]. There are two main categories of this method, informed and uninformed maternal awareness [24]. Some health care professionals inform women of the importance of fetal movements and encourage them to report any change, including change in pattern or reduction in fetal movement strength [24]. Recommendations exist for pregnant women to self-monitor fetal movement but not to formally count movements on a daily basis [2], [5]. Maternal observation can help prevent stillbirth [25]. In contrast if uninformed, women may not be aware of what is abnormal or the importance of seeking appropriate clinical help if changes in fetal movements are observed. A key aspect of maternal observation is that it is entirely subjective and does not provide additional diagnostic information. It is a binary trigger for further investigation.

2) FETAL MOVEMENT COUNTING

There is a broad range of methods for formally measuring fetal movement using maternal perception. Each method has at its core counting by the mother of the fetal movements perceived over a specified period of time. The period in which counting occurs varies. Fetal movement research prior to the 1970s asked mothers to record every fetal movement felt over a 12-hour period (e.g. 8am to 8pm). Such counts were used to calculate a daily fetal movement count (DFMC) [17], [26]. The long duration count method was largely discarded due to lack of evidence of impact [22] and the burden on mothers, particularly difficulties with adherence [26] although DFMC does appear in the literature extrapolated from shorter time periods [27]. Another development from this early work was the establishment of associated thresholds which trigger further investigation [17], [26].

The Sadovsky Method requires pregnant women to count fetal movement three times per day [17]. Each session involves counting the number of movements felt during one hour, once in the morning, once at noon and again in the evening [17]. This approach aims to reduce the burden on mothers while providing opportunity to detect timely decreases in fetal movement. Research using this approach showed that despite the ongoing presence of fetal heart tones, decreases in fetal movement could be discerned for more than a week before fetal death occurred. Movements over the three time periods were combined to calculate a DFMC with daily measures compared for each individual [17]. The Sadovsky Method recommends further investigation if there are less than three fetal movements in an hour [17].

Count-to-ten (or Cardiff Method) involves measuring the amount of time it takes to get to a fixed number of fetal movements [26]. The initial research concluded that less than 10 counts per 12 hours occurred for the lowest 2.5 percentile of movement counts for 61 women, who reported a total of 1,654 movements over the 12-hour period, and delivered healthy infants. Using this population-based approach, the 10 count threshold was quickly adopted. The method was modified so that at a convenient time, mothers record how long it takes to reach a count of 10 movements [22], [27]. One common threshold (or alarm limit) for further investigation, is less than 10 movements in 2 hours [28]. There are several variants of the count-to-ten method, such as the Hollister chart which uses an arbitrarily chosen count target, removes the requirement for a consistent start time and uses a threshold for further investigation of two consecutive days without reaching the count target [1].

Derived from the Latin American Centre for Perinatology, the CLAP method is widely used in Latin America [29] and is a variation of the Sadovsky method. Mothers assess fetal movement for 30 minutes after major meals (breakfast, lunch, dinner) and directly before bedtime [9]. The threshold for further investigation is based on the sum of all counts across the day. An additional advantage of the number of observations was a belief that it would assist maternal bonding but adherence to the protocol was low for CLAP (64%), compared with count-to-ten (91%) [9].

Recent innovations in health communication modalities include the development of mobile applications (apps), to engage women in fetal movement awareness and assessment [31]. Such apps may help to better inform, improve counting adherence and provide a digital record.

C. CLINICIAN INVOLVEMENT MEASUREMENT

The primary requirement for these methods is the involvement of a clinically trained health professional to assess fetal movement. These methods include manual palpation and auscultation, either through the use of a Pinard horn or fetoscope. Access to clinical facilities is not required because the use of technological aids is minimal. While auscultation makes use of auditory aids, these enhance rather than replace a clinician's sensory input. Methods that depend on devices that replace a clinician's sensory input, such as Doppler ultrasound, are not included in this category.

As such, clinician involvement methods can be used in any environment or situation where the clinician can reasonably perform the described method. However, by the category definition, all the included methods are limited by the achievable accuracy of detecting events occurring in a body within the bounds of the natural human senses.

1) MANUAL PALPATION

The anterior abdominal wall is relatively thin. This can be exploited to physically observe the fetus by measuring deflections of the abdominal wall. As far back as 1905, Johann F. Ahlfeld recorded observations that human fetal breathing movements could be seen by careful observation of the maternal abdomen [32]. By extension, any impact with sufficient force by the fetus with the abdominal wall will result in a deflection that could be measured.

Manual palpation involves a health care practitioner using their hands to sense pressure changes due to resistance through the abdominal wall. Health professionals are reassured by feeling fetal movement during palpation of the pregnant abdomen, but this is not a formalized method of assessing fetal movement in use today. An example of this technique is Leopold's maneuvers, which are used to determine the orientation of the fetus [33]. Manual palpation can be performed either by pressing into the abdominal wall to detect the fetus [33] or by laying the hand on the abdominal wall to sense outward deflection. Manual palpation has only been reported to measure as a count per fixed time period [34]. Records are reliant on the practices of the clinical personnel involved.

2) AUSCULTATION

Early auscultation techniques involved placing an ear to the abdomen and listening to the heart beat of the fetus [33]. Obstetric auscultation is an antenatal fetal surveillance technique that is commonly performed using a stethoscope, Pinard horn or fetoscope. [33], [35]. Auscultation is primarily used to identify the fetal heartbeat [37], not to formally monitor FM.

Though it is not precisely coupled, fetal movement can be inferred from fetal heart rate observations. Many fetal movements will cause a fetal heart rate acceleration [38]. Direct measurement would rely on listening to and identifying fetal movement sounds within the uterus and the exclusion of other bodily sounds that may occur during the process. Auscultation without technological aid is challenging, as the noise of fetal movement at the abdominal wall is near the limits of human hearing [38]–[41]. Obstetric auscultation can be performed at any point during the pregnancy, though applicability of this method are gestational-age dependent.

D. TECHNOLOGY ASSISTED MEASUREMENT

The primary requirement for these methods is the use of technological aid with interpretation by a trained health professional to assess fetal movement. These methods include various forms of ultrasound scans such as A-mode, B-mode, M-mode, 3D and Doppler assisted ultrasound, and provide additional assessment modes, specifically visual output, not available otherwise.

Within prenatal diagnostics, ultrasound is commonly used for fetal morphology, analysis of amniotic fluid volume, biometric analysis, and further investigation of potential developmental issues [2]. Evaluation of these factors is most commonly performed between 18 and 22 weeks of gestation as there is a higher chance of detecting major congenital anomalies, though dating the pregnancy is more accurate if done earlier [42].

Diagnostic ultrasound is an electronic monitoring technology that substitutes a clinician's direct vision with an image produced by reflections from pulses of high frequency sound [43]. These reflections are produced by the propagation of an ultrasound wave encountering the boundary of two substances with differing specific acoustic impedance ("defined as the product of the density of the material and the velocity of the sound wave in it") [44]. A property of this reflection is described by Rayleigh's law in that a larger acoustic difference will provide a more significant reflection. This also implies the requirement for a conduction gel to be used to minimise the liquid-gas boundary between the device and the patient [44]. To achieve best results and minimise possible refractions, the sensor should be positioned at a right angle to the body being analysed [44], [45].

No cases of harm have been reported since the introduction of modern medical ultrasound. However, concerns about the potential for tissue damage due to absorption of ultrasound waves has resulted in recommendations to limit it to medical use only [6], [35]. With increasing power limits on modern ultrasound devices, only trained personnel should be tasked with performing ultrasound procedures to avoid these negative effects [46].

Ultrasound is able to produce images at speeds of over 100 frames per second due to the development of fast-switching transducers. When compared to traditional X-ray or MRI imaging techniques, this is a significant improvement over their typical multiple minute speeds [47]. Additionally, unlike X-ray or computed tomography scans which rely on ionizing radiation, ultrasound only utilizes sound waves within the body. The cumulative dosage effect of ionizing radiation requires additional precautions to be taken for sensitive organs and pregnancies [48] which are not needed for ultrasound. Compromises between attaining a suitable resolution and achieving appropriate penetration depth limits ultrasound to a maximum depth of approximately 25cm [47].

1) ULTRASOUND IMAGING

An early implementation of ultrasound, known as Amplitude mode (A-mode) ultrasonography, used a single transducer, which would transmit a short burst of energy and then listen for the resulting reflections. The reflected intensity over time can be interpreted by a physician to discern the boundary between different materials at varying depths [44].

Brightness mode (B-mode) ultrasonography can be seen as an extension of A-mode and is often used to generate a two-dimensional image. The method differs from an A-mode scan due to the use of a phased linear array of transducers and the presentation of the reflected intensity for each transducer as greyscale brightness spots rather than graphical peaks [44], [47]. Highly reflective material is seen as bright white, while absorptive material such as fluids are black [49]. The phased linear array will generate an image radiating from the transducer source extending into the body [50]. Modern equipment can exploit B-mode based equipment to provide either moving images or three dimensional images [51]. A specialized method of producing moving images is motion mode (M-mode) which is used in the analysis of rapid movements such as heart function [52].

Obstetric ultrasound can be performed either transabdominally or transvaginally [42]. For a transabdominal obstetric ultrasound the operator will apply a conductive gel and scan the desired area taking note of the relevant features for diagnosis of known conditions or issues [47]. When performing an obstetric ultrasound, the frequency of the device should be set to the maximum that will still achieve the desired tissue penetration to providing a better resolution image [53]. Depending on the specific procedure requirements, the operator will select the appropriate ultrasound mode, such as M-mode for analyzing cardiac rhythm, ventricular function and myocardial wall thickness [54] or B-mode for assessing pregnancy features and viability [55]. Both of these modes allow the operator to monitor fetal movements, though only for short term measurements, as exposure should be minimized [55].

Throughout a healthy pregnancy, ultrasound is performed two or three times. Routine obstetric ultrasound procedures do not include observation of fetal movement [56]–[58], but can occur at the discretion of the operator. Such assessments involve either a frequency or span count [59]. Ultrasound scanning is often used to assess fetal compromise. Maternal concerns of decreased fetal movement may be assessed using ultrasound, to either confirm absence of fetal movement (an ominous sign) or to assess possible fetal growth restriction, which is associated with reduced fetal movement. Ultrasound is also used to determine fetal wellbeing by conducting a fetal biophysical profile (BPP) that combines an assessment of amniotic fluid levels, fetal muscle tone, breathing, gross body movement, and fetal heart rate [5].

2) DOPPLER ULTRASOUND

The images produced from any ultrasound technique can be augmented by analyzing the Doppler shift of the resulting wave; the change in frequency resulting from the motion of the reflecting interface [60]. The mechanism for this analysis can utilize either continuous or pulsed wave transmission and reception, or a combination of the two. If pulsed waves are used the returning signal, which is recognised based on timing, can measure the depth of the motion [60]. Use of a continuous wave is used only when necessary due to increased exposure. With this it is possible to analyze the returning signal to measure sound and high velocity motion [61] such as in cases where the fetus has a very high velocity blood flow [62]. Due to timing constraints aliasing may occur if the motion being inspected is faster than the maximum implied by the sampling frequency [47]. It should also be noted that Doppler effects occur when the angle of the ultrasound beam closely aligns with the direction of motion.

As noted above, along with manual palpation and auscultation, the use of Doppler ultrasound to detect fetal movement does not form part of any formal clinical practice assessment. However, hand-held Doppler devices used for assessing fetal heart rate can also translate fetal movement into sound and can be used as a proxy for detecting fetal distress. Recording of these observations are at the discretion of the operator.

3) OTHER METHODS

Less common methods of identifying fetal movement have been explored in the literature but do not appear to be widely used in routine maternity care. These include: adaption of electric impedance [64], [65]; adaption of magnetic resonance imaging (MRI) [66]; electromyography (EMG) [67].

Electrical impedance exploits the interaction between water and electric fields, establishing an oscillating electric field in the human body and recording oscillation variations. Such variations can be correlated to fetal movement, for example signals increase with movements towards the sensor and decrease with movements away [64]. The use of a very low strength electric field was claimed to be proven safe to both mother and fetus [64].

MRI uses oscillation in very high strength magnetic fields (approximately 1.5T) to produce spin changes in hydrogen atoms and measure the resulting emitted radio frequency signal. The strength of the magnetic field required, limits MRI use to tertiary clinical services due to cost and size. In one pregnancy study MRI imaging was restricted to a lower power range [66], and determining suitable scan parameters was challenging due to variations in maternal and fetal sizes and orientations. Multiple short scans to achieve correct configuration was required making the procedure impractical for routine use although the researchers were able to achieve 3 frames per second, which was sufficient to identify most fetal movement [66].

EMG uses electrodes (such as silver-chloride) to pick up electrical signals produced by nerve and muscle tissue in the body. Typically these signals are produced when muscles are in motion. It appears that the involuntary responses of maternal abdominal wall that occurs in response to fetal movement generates signals suitable to detect such events.

Isolating other maternal movements was addressed by including electrodes on the inner thigh [67]. Mothers were stationary throughout the process [67].

All three methods were reported to be suitable for short duration observation similar to obstetric ultrasound, although EMG could be adapted to extended duration observation. All methods produced frequency counts and required interpretation by clinical personnel. Without further work these methods are unlikely to find application in practice.

E. AUTOMATED TECHNOLOGY MEASUREMENT

The primary requirement for these methods is a technological aid that can directly assess fetal movement without clinician input. These methods include transducer based devices such as actographs and cardiotocography.

1) ACTOGRAPHY

The anterior abdominal wall is thin enough to be deflected, allowing any impact between the fetus and the anterior wall with sufficient force to result in a deflection that could be measured on the surface of the abdomen. As soft tissue has damping properties, there will be a required force threshold that must be exceeded to detect a deflection. This force threshold may be similar to that required for maternal perception, as correlation between detection in both methods has been demonstrated [34]. When compared to ultrasound observation it has been found that some fetal movement is too slow, too weak or too deep to propagate with sufficient amplitude through the abdominal wall, making complete detection challenging [68].

There is a range of transducer types that can be used to detect motion in the abdominal wall. Examples are strain gauges for force [69], piezoelectric films for pressure [38], accelerometers for motion [68] and capacitive [40] or inductive [70] moving elements for deflection. These sensors are placed on the mother's abdominal wall, such as the transducer used by the tocodynamometer that is part of a CTG machine. All these measurements immediately face the challenge of eliminating signal noise from maternal artefacts. Non-fetal sources of motion in the abdominal wall can come from maternal breathing, blood flow, gross body motion and other abdominal sounds. If care is not taken, these maternal artefacts can create a signal noise floor orders of magnitude larger than the desired signal, making detection challenging [38].

To facilitate good coupling with the abdominal surface, pressure or tape is used to hold these transducers in place [40]. Care must be taken as this coupling can substantially impair the measurement due to the low compliance of the abdominal wall [70]. Compliance matching of the transducer to the abdominal wall is vital to obtain usable signals. This can be challenging as many traditional transducers for measuring movement are designed for use with hard surfaces in a civil or mechanical engineering context [38].

To cope with the large noise floor there are two common methods used. First is to use multiple transducers, such as multiple accelerometers [68], and use multichannel signal processing to eliminate noise [39]. Second, is to use a secondary transducer (often placed on the chest or thigh) to detect and compensate for maternal artefacts [40]. Despite this, in order to obtain usable measurements, most proposed methods require the mother to be stationary and breathing quietly [38], [40], [68]. Once a usable signal is obtained it can be processed using an algorithm to identify fetal movement in an automated, repeatable fashion [39]. These algorithms often include a range of signal filters (bandpass, notch, low and high filters) between 0.3 and 60 Hz depending on the specific fetal motion of interest [38]–[40].

The studies discussed above all report noise to exceed the desired signal at higher frequencies. The elastic and fluid nature of the abdominal wall likely limits transmission to low frequency deflections ($<$200 Hz). This reduces the set of ideal transducers, as those that are intrinsic high pass filters (i.e. moving coil, ceramic piezoelectric) will minimise the desired signal while maximizing high frequency noise [69]. The maternal artefacts that must be excluded are often much higher amplitude compared to the desired signal [38]. This requires complex signal processing to compensate for the maternal artefacts. The added complexity may become sufficient to prevent the device from being built as a portable unit. A related limitation is that fetal movements must be strong enough to produce deflections that can be measured and isolated on the external surface of the abdominal wall for detection to be possible [38]. Similar to ultrasound, care must be taken when coupling the transducer to the abdominal wall otherwise the signal can quickly become unusable [38].

The recorded fetal movement outcome can be a continuous timestamped event record, a count per fixed time period or a time per fixed count number. Measurement by actograph is intrinsically passive allowing the method to be safely used for extended durations. Therefore, the method can either be used on demand or for a period limited only by the devices power supply or maternal acceptance. As this is within the automated technology category, every method will produce a digital record of the fetal movement that will be stored for immediate or later review.

2) CARDIOTOCOGRAPHY

A commonly used extension of diagnostic ultrasound is the CTG or electronic fetal monitor. This technique can either be performed externally or, when required, internally using various transducer types to continuously monitor and record the fetal heart rate and mother's uterine contractions or deflections [71]. This technique is commonly performed during both antepartum and intrapartum periods [72], [73].

For external cardiotocography, two transducers are placed on the mother's abdomen. An ultrasound transducer is placed in a position that will allow it to detect the fetal heartbeat and another transducer, usually a tocodynamometer, is placed over the uterine fundus to detect pressure related to uterine contractions or deflection [35], [72]. As stated previously, CTG machines record fetal movement, but are not considered reliable due to confounding noise [38]. CTG is frequently used to assess maternal report of decreased fetal movements to exclude fetal death, and severe fetal compromise. Maternally perceived fetal movements that occur in association with a fetal heart acceleration (recorded by CTG) are considered reassuring.

Modern CTG machines are able to identify fetal movements automatically by analysis of the two transducer signals. This is then provided to clinical personnel as an ongoing digital record. CTG is most commonly performed in high risk pregnancies antenatally and during labor, as it gives a continuous assessment of fetal well-being, intended to improve the outcomes for infants by reducing morbidity or mortality. Though it is routinely performed, recent studies have concluded that there is no clear evidence to the method's benefit, stating that further studies are warranted [72], [73].

A CTG machine will report an outcome of a continuous timestamped event record, a count per fixed time period or a time per fixed count number depending on the machine and configuration. Again, by the nature of automation a record will be produced for immediate or later review by clinical personnel.

IV. DISCUSSION

This review has developed a descriptive taxonomy to categorise the methods currently used to assess fetal movements. Such a taxonomy offers a number of advantages. The taxonomy brings order to a complex field by providing a systematic approach to the categorisation of fetal movement measurement methods. The taxonomy allows comparison of the different methods of assessing fetal movement and highlights similarities and differences between different measurement methods and their shared properties. The taxonomy also draws attention to the diversity of the methods and count metrics used in this field and in related research. This will be useful in developing and planning future research in new ways to assess fetal movement. The taxonomy uses the essential components required for each type of assessment method: *maternal involvement; clinician involvement; technology assisted; and automated technology*. These categories reflect the technical evolution of monitoring fetal movement and the historical development of awareness of its importance. No comparable taxonomy was identified in the comprehensive search undertaken in the review process, indicating that this may be the first taxonomy developed to describe fetal movement assessments.

The combination of ultrasound and maternal perception has become accepted practice but has failed to reduce the incidence of stillbirth [11]. New approaches are needed and novel methods have been proposed but have not yet found wide acceptance in clinical practice [10]–[14]. The taxonomy highlights an important barrier to development. There are significant challenges in comparing the different methods currently available because of the different approaches taken.

Several comparisons in the literature focus on the accuracy of maternal involvement methods to correlate count metrics, usually with technology assisted approaches [34], [74], [75]. The value of the described taxonomy is demonstrated through the insight it provides that such comparisons involve a shift from the continuous observation of maternal perception to point-in-time measures- both for those with maternal involvement, for example count to ten [1], and technology assisted methods, such as ultrasound or Doppler [76]. This shift raises several questions including: the point-in-time chosen for measurement, which some studies have sought to address by using multiple time points in the fetal activity cycle [40]; the reference point used for comparison, which could be self-comparisons [17] or population-norms [26]; and the appropriate threshold for when further investigations should be triggered [9], [17], [28]. There is a lack of evidence to guide clinicians in the best methods to assess decreased fetal movements; CTG continues to have an important place in assessment of mothers' concerns about decreased fetal movements, despite its limitations [5]. More accurate methods of fetal movement assessment, such as ultrasound, also have limitations including the wide range of normal fetal movement and fetal behavioral states and safety concerns associated with extended scanning times. Consequently, new technologies are needed to improve assessment of fetal movement.

One way the taxonomy points to potential future development is the recognition that automated technology methods are typically used for extended durations and more closely replicate the feedback produced in maternal involvement methods associated with continuous measurements. Broader acceptance of new technologies is likely to require adapting any technology to augment existing clinical practice, rather than attempt to provide a replacement solution. There are significant secondary benefits to maternal fetal movement observation such as an increased feeling of control and a deeper connection to the fetus [16]. By augmenting this process it would be possible for future clinical practice to increase early detection accuracy, while retaining the valuable maternal instinct which has been demonstrated to impact on the stillbirth rate [5].

Ethical and practical barriers to the adoption of automated technologies must be addressed before such technologies can be used in routine practice. The most challenging of these are ethical. It is imperative that the potential harms that can follow false negative and false positive measurements are minimized. The long-term goal is prevention of stillbirth, not simply to achieve high precision measurement. There can be a fine balance between too much intervention and intervention that occurs too late. In addition concerns about excessive surveillance and the possibility of data theft [77] need to be considered particularly in regard to remote observation in antenatal care.

The biggest practical barriers are maternal discomfort and movement restriction that could occur with technology used over extended durations. The timing of the use of automated technologies may ameliorate some concerns. For example, automated technology used in the first stage of labor could avoid some ethical issues while retaining benefits of continuous fetal assessment with low cost, portable devices. Such developments would have the greatest impact where access to health care is limited.

This review has a number of strengths. It is based on a comprehensive overview of the field. The broad scope for inclusion identified a wide range of studies and multidisciplinary perspectives. A particular strength of the review is the descriptive taxonomy that was developed. There are also a number of limitations. While the search was comprehensive it was not systematic, did not include any appraisal and only included papers published in English. Consequently, some studies using less common methods of fetal movement measurement may have been overlooked.

V. CONCLUSION

The described taxonomy highlights that no current, ideal option exists when considering the most appropriate method for fetal movement assessment. Each assessment method had disadvantages depending on the conditions of use. The accuracy of maternal perception is reliant on adherence to recording and the ability to recall past events under stress. Ultrasound, as an active measurement method, is not recommended for extended periods of time or without definite medical need.

The taxonomy identifies that current challenges in fetal movement assessment are greater than current technological capability and that there is a need to consider how novel and existing technologies could be applied. It is uncertain if further refinement in detection accuracy in existing technologies will decrease the stillbirth rate. The challenge of using technologies to reduce stillbirth rates is compounded by a lack of standardization in reported data metrics. Novel approaches to fetal movement assessment that aims to better replicate maternal intuition may have greater impact.

Current technology has not produced data of sufficient breadth and depth to enable the development of universal guidelines on treatment and intervention. Actography offers a valuable middle ground to the techniques of maternal perception and ultrasound, particularly if it can augment existing standard practice.

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