Foetal movement detection and characterization based on force sensing

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This study presents a detection system for foetal movement classification based on the magnitude of force exerted on a pregnant woman's abdominal wall. Despite the effectiveness of ultrasound method in foetal monitoring, the characterization of movement depends on an expert's skill. A detection system was developed by incorporating force-sensitive resistor array into a wearable belt for pregnant women. The system characterized hand, leg and trunk movement with accuracy ranging from 75% to 93% with an accuracy of 98% on single movement detections compared to accelerometer performance. The system is thus a promising technique for low cost foetal movement detection.

Different foetal movement types reflect the neurobehaviour and maturation of the foetus[1,2]. Detection and management of foetal condition may influence the pregnancy outcome[3]. However, some of the current foetal movement monitoring methods only detect the foetal movement in general without details of the type of movement[3].

Currently, there are passive and active methods for measuring foetal movement. Passive methods, such as accelerometry, phonography and tocodynamometry measure the foetal vibration incident on the maternal abdomen while active methods such as ultrasound direct a high frequency sound wave to the foetus to create an image[4]. Foetal movement can also be monitored using mother perception registered on a 'kick-chart', but this method has been shown to be unreliable in terms of accuracy[5]. Ultrasound techniques are accurate in identifying foetal movement, but there are a few arguments for its usage in long-term foetal monitoring. Ultrasounds are also expensive and require a skilled operator to periodically reposition the transducer at the foetus to identify movements. Various attempts at classifying types of foetal movements have been performed before, but only for general movements[6]. As the gestational age increases, the movements that involve superior members such as hands, legs and head increase[7]. Vries *et al.*[2] classified these movements into sixteen distinct movement patterns, and of these, flexing-extension of the extremities may reach the uterine wall and cause an observable movement on the maternal abdomen[2].

In this study we demonstrate a foetal movement detection technique based on force sensing on the mother's abdominal wall. Force sensors have been used in medical application such as patient monitoring and as an implant[8]. Their property of detecting force is useful due to the fact that human body will always generate force, be it on the heartbeat or blood flow[9]. Foetal movements usually generate a force on the pregnant abdominal wall, which can be detected and measured by sensors[10].

Materials and methods

Sensors

FSR model 402 was used as the sensing element with force sensitivity ranging from 0.2 N to 20 N. Its nominal thickness of 0.5 mm helps in easier integration to the belt. The specification was selected based on the study by Hollinger and Wanderley[11]. The sensor was calibrated by statically placing a known weight over the active sensing area, to obtain the relation between the applied force and output voltage from the circuit. A set of different masses in increments were so chosen as to remain between the sensor range limitations. Voltage signals from the circuit, when each mass was applied, were acquired to plot force versus voltage graph and its function. The function obtained was

$$\text{Force} = 1.3508 \times \text{Voltage} + 0.0185, \quad (1)$$

and was used to correlate force and FSR voltage. This correlation will be the basis for determining and classifying the foetal movements. Figure 1 shows the FSR used as the sensor in the system and its configurations on the belt.

Microcontroller

In this study, we used Arduino Mega 2560 for processing signals from FSR, which provides 16 analog input pins operating at 16 MHz clock speed. Amounts on I/O pins are paramount in this work as we use 9 FSRs simultaneously for foetal movement detection and classification. The other feature of Arduino Mega 2560 includes 256 KB of flash memory, allowing long and complex programming and it also operates at 5 V. Analog-to-digital converter (ADC) built-in the Arduino to amplify miniscule reading from sensors eliminates the need for external ADC and simplifies the system design. The microcontroller reads the analog voltage from the voltage divider directly connected to the FSR. Then the microcontroller classifies all readings based on force and position according to its programming. The processed reading was then displayed on a 20 × 4 LCD display. To make the system usable to all pregnant women, the data is interpreted into a simpler term, allowing easier understanding on the type and strength of foetal movement to the mothers.

Foetal movement characterization method

The sensor array was connected to the Arduino in a voltage divider configuration. Variation of force magnitude detected and its position reflects the foetal movement. Due to the FSR property of changing its resistance inversely to the amount of force applied, the strength of the movement can be specified and used predictively to determine the health of the foetus depending on its strength. The movements are then classified into upper-limb movement, lower-limb movement, rolling or general movement based on the combination of strength of force and which sensors give out the reading. An algorithm was developed for the Arduino system for classifying the type of movements based on the magnitude of force and the sensors' position.

Experimental set-up

Experimental testing on volunteer

In this study we have tested the accuracy of the developed system on non-pregnant women volunteers as the control group to ensure that the system only detects foetal movements and not maternal movement. The error rate is calculated by dividing the movement detected by the number of subjects. Monitoring of foetal movement was typically conducted while the mother was sitting down during the testing period, so as to safely eliminate the error caused by moments due to sitting up and down.

We asked volunteers to wear the belt on their abdomen for a given period of time and perform various movements such as breathing heavily, talking, laughing, bending and sitting up and down that were suspected to cause a reading. The control group was selected among a group of non-pregnant women with a body physique similar to pregnant women, by considering their body mass index (BMI). The inclusion criteria of the control subjects were an age of 24–28 years and normal BMI (< 25 kg/m^2). Unhealthy women with any prior complications regarding pregnancy and obese women were excluded.

Testing using mechanical simulator

We compared the performance of our sensor against the accelerometer by testing both systems on the foetal simulator (device developed by the research team using servo motors). The foetal movement simulator and its internal working components is shown in Figure 2. The comparison was done to gain an insight into how the performance of FSR-based foetal movement detector is, when tested into real pregnant woman. The sensitivity of the accelerometer used in the experiment was 300 mV/g and the sampling rate was set at 40 Hz to match the sampling rate of FSR at 50 Hz. Foetal simulator simulated 50 single movements to be detected by both systems to measure their sensitivity and performance.

Data obtained from testing the system with the simulator was evaluated with performance metrics of sensitivity, specificity and accuracy. Sensitivity refers to the ability of the system to correctly read the movement by the simulator. The equation for sensitivity in percentage value was given as

$$\text{sensitivity} = 100\,[\text{TP}/(\text{TP} + \text{FN})], \quad (2)$$

where TP is true-positive and FN is false-negative. In this experiment, TP stands for the correctly detected movement by the sensor based on the movement produced by the simulator and FN stands for undetected movements on the sensors even though there is actually a movement present. Specificity test was done to test the ability of the system to correctly identify different movements.

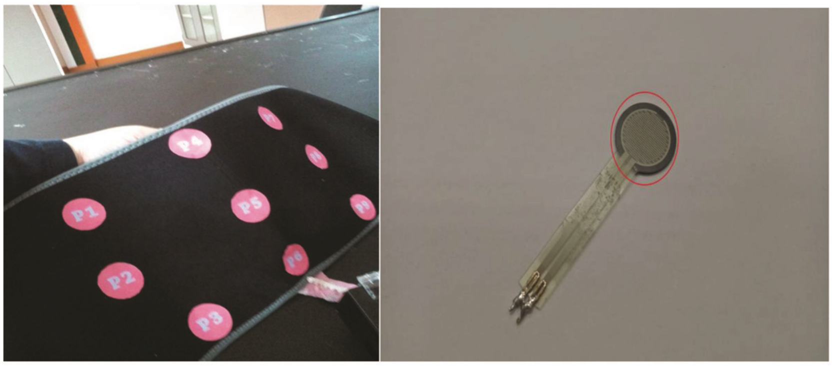

Figure 1. Sensor positioning on the belt and the sensor used. The positions represents abdominal regions, right hypochondriac, right lumbar, right iliac, epigastria, umbilical, hypo gastric, left iliac, left lumbar and left hypochondriac.

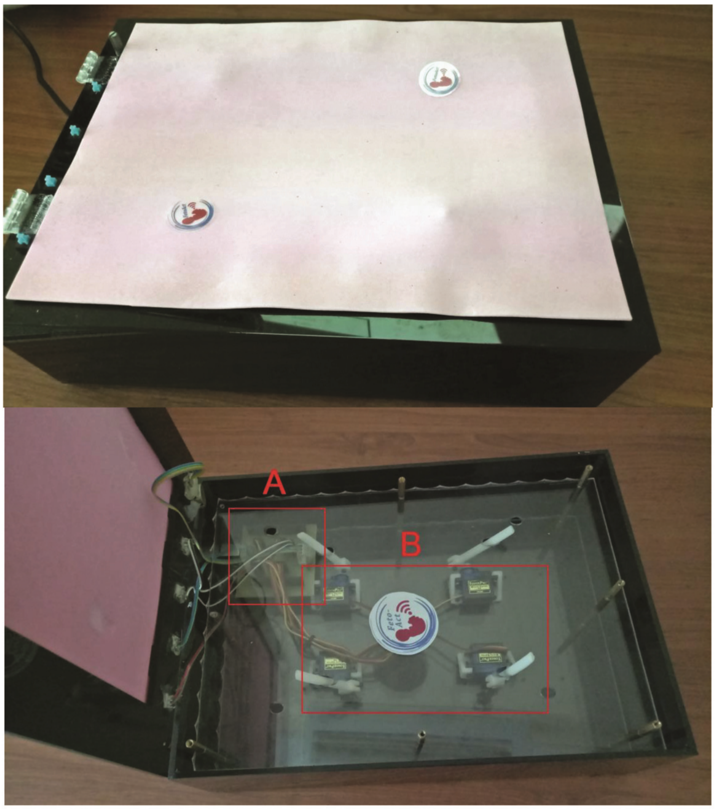

Figure 2. Foetal movement simulator. A marks the electronic control board made using Arduino while B is the servo motors used to simulate the foetal movements.

Table 1. Control group test results

Control subject	Activities						
	Breathing	Bending forward	Bending backward	Sit up	Sit down	Talking	Laughing
1	N	N	N	Y	Y	N	N
2	N	N	N	Y	Y	N	N
3	N	Y	N	N	Y	N	N
4	N	N	N	Y	Y	N	N
5	N	N	N	Y	Y	N	N
6	N	N	N	N	Y	N	N

N, No reading on FSR; Y, Movement detected by FSR.

Table 2. Statistical parameter of system performance

Movements types	Sensitivity (%)	TP	FN	Specificity (%)	TN	FP	Accuracy (%)
Hand	90	45	5	88	44	6	89
Leg	92	46	4	94	47	3	93
Trunk	74	37	13	76	38	12	75

For example, during hand testing, movements from leg and trunk were also triggered to determine if the system correctly registered those extra movements. Equation for it was given as

$$\text{specificity} = 100\ [TN/(TN + FP)], \quad (3)$$

where TN is true negative, which is when the system detects a leg or trunk as not a hand movement and vice versa. FP means false-positive which is when the system detects other movements such as hand movements. Lastly, accuracy can be calculated using

$$\text{accuracy} = 100\ [(TP + TN)/(TP + TN + FP + FN)], \quad (4)$$

where the accuracy represents the overall performance of the system.

Experimental findings and preliminary results

Data recorded from the control group is presented in Table 1. From the test, it was found that the sensors detected at least one activity from each subject. However, if the reading from sitting up and down is eliminated, only bending forward of subject 3 caused sensor detection out of 6 control subjects. Test on control subjects showed that the overall error rate caused by various movements was only 3%. The source of error has been considered to be controlled in future testing.

The data obtained from testing the device with a foetal kicking simulator is presented in Table 2. The accuracy of classification by the system from 50 simulated movements of hand, leg and trunk were 89%, 93% and 75% respectively. The majority of foetal movements generated by the simulator was detected by the sensor.

Table 3 shows the epoch-based performance parameter of both FSR and accelerometer. Accelerometer recorded higher sensitivity of 100% detection rate against 96% of FSR. However, FSR shows a better specificity. Overall, both systems showed comparable performance with FSR-based detection system which recorded 98% accuracy while accelerometer-based detection system which recorded 95% accuracy in detecting single movements from the foetal movement simulator.

Discussion

From the findings of the experimental testing on volunteer non-pregnant women as control subjects, the FSR-based foetal movement detector had low sensitivity to maternal movement. When the foetus was normally monitored (sitting down on a chair), the sensor only gave a false positive reading, detected by the bending forward movement from the control subject 3.

However, the detector showed low accuracy detection on trunk movements. This is due to the nature of how the trunk movement is programmed on the simulator and the detection algorithm. The predicted position for limbs, head and trunk was assigned around the abdominal surface area covering nine positions. This enabled the system to detect full movement on the torso and classify the foetal movements accordingly. Three FSRs needed to be triggered simultaneously in the central position of the belt, for them to classify the movement as a trunk movement. However, mismatches in the timing of the motors in the simulator and the detection on each FSR caused high false-negative recording. Additionally, the central position of the trunk is near enough to the side sensors responsible for detecting hand and leg movements, causing them to incorrectly trigger and give a high false positive reading and lower specificity.

According to Verbruggen[10], the leg of the foetus may produce a maximum force of approximately 21 N. Therefore, the proposed kick counting system classifies the type of movements based on the amount of force detected by the sensor. Translating force into voltage through FSR determined that, extension of the leg recorded an 800 mV reading on the FSR. On the other hand, voltage of less than 150 mV may indicate weak, flurry movements of the foetus. Comparing the magnitude of force detected and the position of sensor that produces the reading, the position of the foetus can be estimated.

Accelerometer has gained popularity recently as a passive approach in foetal movement detection[12–14]. From the test on the foetal simulator, the FSR-based detector was capable of achieving 96% sensitivity against 100% sensitivity of the accelerometer. However, our system shows a better performance in terms of

Table 3. Epoch-based performance of accelerometer against force sensitive resistance

Sensor	TP	FN	Sensitivity	TN	FP	Specificity	Accuracy
Force sensitive resistor	48	2	96	50	0	100	98
Accelerometer	50	0	100	45	5	90	95

specificity with 100% recorded specificity against 90% of the accelerometer. The high specificity value of our system is because of the nature of FSR which only detects a movement that is directly applied on the sensing area. On the other hand, the sensitivity of the accelerometer to small movements causes it to detect a false positive movement more frequently, resulting in a drop in specificity performance. Overall, the performance of FSR-based indicator is considered slightly better than accelerometer in terms of accuracy in detecting single movement on the foetal simulator. In perspective, Mesbah *et al*.[6] reported 59% accuracy in detecting foetal movement on comparing accelerometer to real time ultrasound machine and Nishihara *et al*.[4] reported 87.7% agreement between accelerometer and maternal perception.

The low cost, lightweight and non-intrusive system which is sensitive to small movements constitutes a viable alternative to ultrasound and may ultimately identify the at-risk foetus to allow timely clinical intervention.

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