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Neonatal Seizure Detection with Wearable Sensor System

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Abstract. Seizures in neonates, the most common sign of neurological dysfunction, require immediate medical attention. A new system for the detection of neonatal seizures using the wearable sensor is presented. The system including smart vest and system software aims for providing reliable continuous monitoring as well as a comfortable clinical environment for neonatal seizure and giving an alarm when seizure occurs on the basis of Electrocardiogram (ECG) and motion sensing techniques. We present the concept of the neonatal vest that enables ECG measurement by textile and motion measurement by Inertial Measurement Units (IMU). Furthermore, we explore a new software system for receiving, displaying and analyzing data based on android system. An iterative design process in close contact with experts and designers leads to a balanced integration of technology and aesthetics. We demonstrate the design process and the work in progress on the prototype.

Keywords. Infant, seizure, wearable sensor, detection, monitoring

1. Introduction

Seizures in neonates are the most common sign of neurological dysfunction and require immediate medical attention [1,2]. Clinical evidence shows that newborns with seizure have poor health outcomes, with a morbidity 50% of survivors, and a high probability of 30% to death [3,4]. The research shows that 1%-5% of newborn infants and 6%-13% of low birth weight infants suffer from seizure symptom [5,6,7]. Therefore, it is increasingly important to detect neonatal seizure. However, only approximately 2% of newborns admitted to a Neonatal Intensive Care Unit (NICU) [1] where vital signs monitoring 24 hours a day [8] can detect neonatal seizures.

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Seizure is difficult to be perceived and diagnosed, particularly after the medical treatment, which could disturb the clinical signs during observation [1,3,9]. The signals that are used presently to detect neonatal seizure in NICU is Electroencephalography (EEG) [1,2,10]. Electrocardiogram (ECG) offers additional parameters for neonatal seizure detection [3]. Those measurements require a highly structured environment in clinical laboratories. Neonatal seizures can also be diagnosed clinically as abnormal movements of limbs and eyes. The occurrence and type of seizure can be analyzed by observing the nature, speed and amplitude of the movements [7,11]. Experience is required to recognize seizures and it is obvious that seizures may pass unnoticed when infants are not closely surveyed. In [1] a video-based method was reported to distinguish myoclonic from focal clonic seizures and separate these related types from normal behaviors of infants [1]. But in fact, this method is inconclusive since some types of seizures occur without any abnormal movements.

Long term monitoring to detect seizures in NICU is performed by EEG, a derivate of the EEG that is obtained by 3 - 5 needle electrodes or adhesive electrodes. Through many wires running to external monitors, the key parameters are acquired with adhesive sensors on the fragile skin. Large amount of tangling wires can cause discomfort, skin irritation and interruption of neonates' sleep [12].

Furthermore, parents can hardly recognize seizure occurring when they are looking after their baby without a doctor. Thus, the design of non-intrusive alternatives for monitoring of neonatal seizure is urgently needed.

In recent years, with the development of wearable devices and sensors including accelerometers, gyroscopes, smart fabrics, actuators, wireless communication networks and power supplies and data capture technology for processing and decision support [13], the creation of a new seizure detection system with wearable sensors becomes a feasible alternative. Smart textiles have already been integrated into a garment for electrocardiogram (ECG) and respiration monitoring with the wireless transmission [12,14,15]. On the other hand, a recent development is the use of wearable motion-sensing technology for studying infant movement. Based on the use of miniaturized motion sensors, techniques are available for long term monitoring of daily activities and assessment of motor functioning in infants. These methods are highly relevant for studying the motor pattern of infants. These techniques provide a new way for the detection of seizure in infants.

In this study, a wearable sensor system for neonatal seizure detection was designed, based on ECG [8] and motion sensing techniques. The system consists of an infant smart vest and a software system. The vision of the smart vest enables ECG measurement by textile and motion measurement by IMU, and the software presented for receiving, displaying and analyzing data. This wearable sensor system provides a new method to detect the neonatal seizure with highly improved comfort and enhanced interaction between infants, medical staffs and parents. The prototype is partly implemented and we are working on the transmission unit from sensors to the monitoring PC.

2. Design process and design concept

The neonatal seizure detection with wearable sensor system aims to provide continuous monitoring of neonatal seizure and give an alarm when seizure occurs. The major challenge is that design issues are highly interdisciplinary with a diverse range of areas, including medical science, sensor behavior, infant body and motion, networking, power consumption, software execution and interaction design [16,10,17].

The process is presented based on our previous research and experience on neonatal monitoring [18,19,20,21,22,23,24,25]. With consideration of both user aspects and technical functions, table 1 shows the requirements for the full design of the neonatal seizure detection system. Because the existing baby's vest and diaper cannot meet the design requirements, so we decided to design a baby's vest from the beginning.

Table 1. Requirements for the design of the neonatal seizure detection system

Smart Vest	
Functionality	Motion data collection
	ECG data collection
	Wireless communication and local signal processing
Usability	Look friendly and familiar
	Be non-intrusive
	Shape comfortable
	Easy to remove needless-washing parts
	Easy to wear and remove from baby
	Security (in data transmission and usage)
	Dimensional/shape stability during repeated use
	Ease of mending
	Ease of diagnosing problems
	Launderability
	Ease of connect to power source (battery charging and replacement), processors (computing, wireless communication)
	Elastic Materials
	The placement of sensors should be stable.
System Software	
Function	Support data storage
	Support multiple users simultaneously
	Support data display
	Support to add new users
	Support to edit user's information
	Support seizure alarming
Interaction	Easy to operate
	Easy to understand data information

3. Prototype

A smart vest prototype system integrated with the sensors for neonatal ECG and motion monitoring has been developed as shown in Figure 2, Figure 3 and Figure 6. Data collection, data transmission and data display were focused in this stage. Figure 1 illustrates the system flowchart. The first iteration of a smart vest is the result of smaller design cycles in which numerous explorations have been made of materials, structure and shape, see Figure 2. Data analysis will be researched in the next iteration. One video camera is considered in this system, according to the expert advice that it is necessary to have a simultaneous video for the doctor to monitor the condition of the patient. In the first iteration, the proposed vest is made of soft cotton material (Figure 3). Two Inertial Measurement Units (IMU) and textile electrodes are incorporated into this vest. According to the information obtained from previous literature reviews and experts, the motion sensors are located on the infant's wrists and placed forefront arms, which were reported as one of the best ways to monitor related motion when seizure occurs [26].

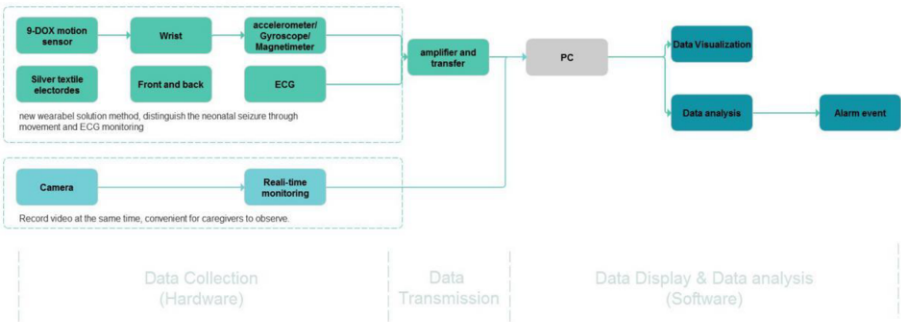

Figure 1. Overall block diagram of the prototype system.

For the sensors of ECG monitoring, Silver textile electrodes were selected and located the three positions:

- Two sets of textile electrodes on the wrists
- One set of textile electrodes on the belly

System software includes three main parts:

- Time Line, display real-time data and historical data
- Video, display-simulated video
- User profile, display and edit user's information

Figure 2. The iteration of prototype.

a b

Figure 3. Final version of prototype

3.1. Vest design

The final prototype vest is made of soft solid color cotton fabric. For the fragile and delicate infants' skin, the requirements on moisture absorption, smooth and comfort are pretty higher than other applications. Compared with cotton fabric, materials such as wool, chemical fiber, and nylon may rub babies' skin and cause static electricity, and they may stimulate the skin and reduce human skin' s moisture, thus leading to itching of the skin. In addition, some man-made fibers are in poor permeability. Therefore, it's difficult for them to volatilize sweat. So pure cotton fabric material is a wonderful choice for babies, which suits their skin well for its soft, smooth and flexibility. Solid color such as pink and blue was chosen because it looks clean and affinity. The outfits are designed to appear as regular baby clothing aesthetically. The structure of vest is open at front including the part of sleeve and body, see Figure 3-b. This structure is easy to wear and remove from a baby. For the sensor's stability, the Velcro at the bottom of the sleeves and chest is used to fix the sensors' position. Its shape is a combination of a vest and diaper which is designed because it is simple to fix the whole clothes comparing with the non-diaper vest.

3.2. Sensor selection and placement

Like all wearable systems, the system present in this paper has many sensor issues that must be explored, including sensor's size, placement, accuracy and selection.

3.2.1 Motion sensor

Recently, the use of inertial sensors has become a prevalent practice in ambulatory motion analysis [27], for epileptic seizure analysis, Babak Kamalizonouzi et al. Summarized the various types of inertial sensors have been used for seizure analysis [28]. To gain accurate results, IMU, integrating the accelerometers, gyroscopes and magnetometers are often employed by the researchers [28]. According to the design requirements and previous research, LSM9DSO sensor was selected. There are three sensors in the LSM9DSO; one is a classic 3-axis accelerometer, which can tell you which direction is down towards the Earth (by measuring gravity) or how fast the board is accelerating in 3D space. The other is a 3-axis magnetometer that can offer stability in the horizontal plane by measuring and controlling the direction of the earth magnetic field. The third one is a 3-axis gyroscope that can measure its spin and twist. Through the data combination, more accurate data to monitor neonatal movement can be gained. In addition, we chose LSM9DSO because it has a small size (diameter of 16mm) and easy to integrate into comfortable fabrics.

To detect the epileptic seizure, the motion sensors to apply on the body such as wrist, forearm and arm was often used by researchers. Sándor Beniczky et al. (28) Carried out an objective research to assess the clinical reliability of a wrist-worn, wireless accelerometer sensor for detecting generalized tonic–clonic seizures (GTCS). The mean of the sensitivity calculated for each patient was 91%. However, it has not been applied to infants yet. Therefore, based on previous research on adults and children, we placed LSM9FSO on the infants' wrist in the prototype, see Figure 4.

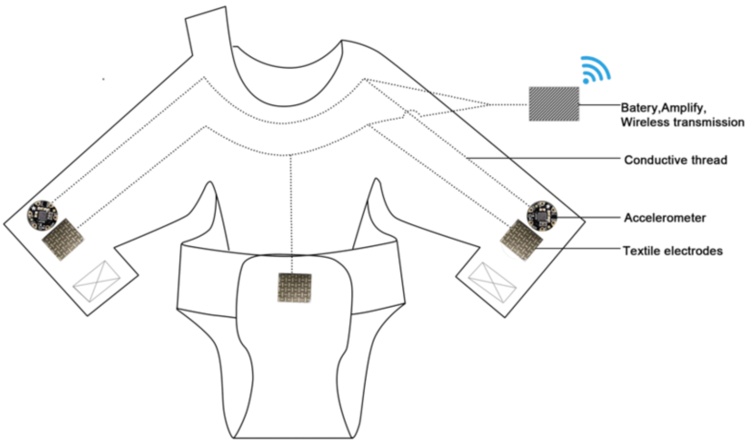

Figure 4. Sensors' placement in prototype.

3.2.2 ECG sensor

According to the design requirements and previous review, the ECG sensor should be capable of non-invasion, comfortable material and small size for integration. We chose textile electrodes called 'Shieldex BONN' to obtain ECG signal based on the previous requirements. The Shieldex Bonn is Sliver plated non-woven fabric made by Shieldex (Figure4). These are flexible, non-irritating, lightweight (54 g/sq.M), thin (0.28mm nominal), low resistance (< 0.5 ohms/sq) and convenient to integrated into the side of the vest. Based on the research on ECG signal acquisition through textile electrodes done by Sibrecht Bouwstra and other scholars, three textile electrodes were chosen to put on the wrists and belly, because these parts are easier to be fixed. With the design techniques, this prototype may solve the problems of poor contact between sensors and skin appearing in the previous studies.

3.3. Sewing with Stainless Medium Conductive Thread

Currently, neonatal seizure detection system often uses hard wires that can cause discomfort when the infant is lying on the wire. Conductive thread is suitable for the non-invasive health monitoring system, cause it is lightweight, flexible, nonirritating. This allows the users to sew a circuit together, creating flexible circuits that require no soldering. In some textile-based projects, this is the most practical tool to maintain the hang of the fabric. For the prototype, we used the stainless medium conductive thread instead of the hard wires for improving babies' comfort. Stainless medium conductive thread as shown in Figure5, is thicker than every day polyester or cotton thread but still thin enough to be sewn by hand in medium-eye needles or with a sewing machine that can handle 'heavy' thread. Because it is strong and smooth, it is ideal for any wearable/e-textile project. It also has fairly low resistivity (0.83 ohms per inch). Besides, as it is made of stainless steel fibers, it will not oxidize like silver does. The material will not 'stop working' because of oxidation after a few months and it's safe to wash. Therefore, we chose it in the prototype.

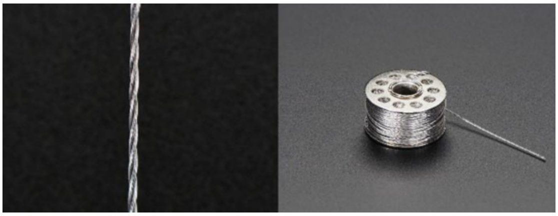

Figure 5. Stainless conductive thread.

3.4. System Software

After the data collection of the smart vest, we will transfer them to the computer software to display and analyze them. Based on the design requirements, we set up the function abstract of software, see table 2.

Table 2. Introduction of pivotal function modules of software.

Function Module	Function Point	Details
Overview	Brief introduction of users	Displaying brief information of patients
	Adding users	Adding new patients
Timeline	Devices Connection	Connecting hardware devices
	Displaying ECG Data	Displaying a single user's ECG data
	Displaying Movement Data	Displaying a single user's movement data
	Alarming event (next stage)	Marking and alarming when seizure occurs
	Timeline	Including historical data
Video	Displaying Videos	Displaying recorded videos
	Displaying ECG Data	Displaying corresponding ECG date
	Displaying Movement Data	Displaying Movement Data
User profile	Modifying/ displaying user's profile	Displaying user's profile/ accepting modification

We classify the software into four main functional modules: Overview (Figure 6-a), Timeline (Figure 6-b), Video (Figure 6-c) and User profile (Figure 6-d). The 'Overview' is the home page of the software, and it is set up to be compatible with multiple users, a caregiver needs to take care of several patients in the hospital. The ‘Overview’ covers “Presentation of Patient lists”, “Patients hardware connection status” and “Button for Adding Patients. Press the button for detailed information in Module “Overview” and go to the Module “Timeline”. It mainly contains displaying real-time data and viewing historical data. The data includes the motion and ECG. At this stage, we mainly focus on data collection and data presentation, so the function of alarming seizure occurring will be added at the next stage. This function is designed because the caregivers have to ensure the surroundings of patients and make some arrangements when emergencies happen. Besides, synchronous video recording can help doctors to examine epilepsy. “User profile” is mainly used to display and modify users’ information, which is convenient for doctors to manage patients.

a b c d

Figure 6. Interface design of software’s function modules.

4. Conclusion

Non-invasive neonatal seizure detection system is important for the development of the neonates and their life later on. In this paper, we present our iterative design process and demonstrate the design of seizure detection system for neonates using wearable sensors. The design aims to provide accuracy as well as comfort for neonates and provide efficient system software for doctors. The prototype ‘smart vest’ is developed with LSM9FSO motion sensor, textile ECG sensor and conductive thread embedded in cotton fabric. The garment integrating with diaper and baby vest creates a stable platform for sensor placement. The demo software is developed to display data in this stage. Simple functional division and interface design aims to improve the efficiency of medical intervention. The whole system is implemented to demonstrate the possibilities for the freedom of movement, the aesthetic design and the stress-free dressing process. For further development of the neonatal seizure detection system, we will focus on data analysis, clinical tests and evaluating the accuracy of the neonatal seizure detection system.

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