Review Article

Artificial Intelligence-Driven Wearable Technologies for Neonatal Cardiorespiratory Monitoring: Part 1 Wearable Technology

***Ethan Grooby[1], *Chiranjibi Sitaula[1], T'ng Chang Kwok[2], Don Sharkey[2], Faezeh Marzbanrad[1], Atul Malhotra[3,4]**

*Equal contribution

[1]Department of Electrical and Computer Systems Engineering, Monash University, Melbourne, Australia
[2]Centre for Perinatal Research, School of Medicine, University of Nottingham, Nottingham, United Kingdom
[3]Department of Paediatrics, Monash University, Melbourne, Australia
[4]Monash Newborn, Monash Children's Hospital, Melbourne, Australia

Corresponding author:
A/Prof Atul Malhotra (ORCID: 0000-0001-9664-4182)
Department of Paediatrics, Monash University,
246 Clayton Road, Clayton, Melbourne,
VIC 3168, Australia
T: +61 3 8572 3650
E: atul.malhotra@monash.edu

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Impact Statement

- State-of-the-art review of sensor technology for wearable neonatal cardiorespiratory monitoring
- Review of the designs for wearable neonatal cardiorespiratory monitoring
- Use of multi-sensor information to improve physiological data quality has been limited in past research
- There are several sensor technologies which have been implemented and tested on adults that have yet to be explored in the newborn population

Abstract

Background

With the development of Artificial Intelligence (AI) techniques, smart health monitoring, particularly neonatal cardiorespiratory monitoring with wearable devices, is becoming more popular. To this end, it is crucial to investigate the trend of wearable sensors being adopted and developed in this domain.

Methods

In this study, we performed a review of papers published in IEEE Xplore, Scopus, and PubMed from the year 2000 onwards, to understand the use of wearable technologies for neonatal cardiorespiratory monitoring. We reviewed the advances in sensor technologies and wearable technology design for this application, as well as potential future directions.

Results

The most common wearable sensors included sensor-integrated clothing (39%); chest and abdominal belts (25%); and adhesive patches (15%). We further categorised and analysed the wearable sensors based on the information they provide from the human body. Popular singular physiological information from wearable sensors included electrocardiography (ECG) (15%), breathing (24%), oxygen saturation and photoplethysmography (PPG) (13%). Many studies also incorporated a combination of these signals (46%).

Conclusion

There has been extensive research completed in neonatal cardiorespiratory monitoring using both single and multi-parameter systems. Poor data quality is a common issue for wearable systems and further research into combining multi-sensor information to alleviate this issue should be investigated.

1. Introduction

The neonatal period is the most vulnerable time for a child's survival, with 2.4 million deaths globally in 2020 alone (1). The major causes of neonatal mortality are infections, birth asphyxia, and preterm birth (1-3). For infections and birth asphyxia, cardiorespiratory monitoring is crucial for the early detection, prediction of prognosis, and continued monitoring of these conditions to assist clinicians in minimising morbidity and mortality (4). Preterm births account for around 10% of live births and are associated with the underdevelopment of the newborn's lungs (5). Respiratory support and cardiorespiratory monitoring are therefore needed to provide the best possible care for these babies.

Wearable technology for newborns offers the convenience and potential of continuous cardiorespiratory monitoring in both hospital and home environments. These technologies have come in the form of adhesive patches; chest and abdominal belts to measure breathing; and wrist and ankle bands to measure heart rate and oxygen saturation. Additionally, many wearable devices have been integrated into clothing such as a newborn's onesie, diaper, and socks. Most of these systems integrate multiple sensors that work together to obtain more accurate measurements, and enable sufficient information for both clinical and artificial intelligence-driven decision making for cardiorespiratory conditions.

The objective of this study is to review artificial intelligence-driven wearable technologies for neonatal cardiorespiratory monitoring. This is achieved in a two-part review. In this Part 1: Wearable Technology, we reviewed the current state-of-the-art in sensor types and designs of wearable technology being used for neonatal cardiorespiratory monitoring (**Section 2**). Additionally, we identified research gaps and potential future directions in wearable sensor technology (**Sections 4-7**). In Part 2: Artificial Intelligence, machine learning techniques suitable for analysis of cardiorespiratory monitoring are reviewed and developments specifically for wearable neonatal cardiorespiratory monitoring are examined.

2. Review Methodology

A query string was constructed with three components:

1. Restrict to neonatal population
    a. Search terms: "Neonatal", "Neonate", "Pediatric", "Paediatric", "Infant", "Baby", "Babies" and "NICU"
2. Restrict to wearable technology
    a. Search terms: "Wearable", "Textile", "Clothing", "Clothes", "Garment", "Vest", "Jacket", "Belt", "Diaper", "Sock", "Shoe", "Portable", "Wireless" and "Fabric"
3. Restrict to cardiorespiratory monitoring
    a. Search terms: "Cardi*", "Heart", "Respiratory", "Respiration", "Lung", "Breath", "Breathing", "ECG", "Pulse", "Oximeter", "Apnea", "Apnoea", "Blood Pressure", Vital", "Multi*", "SIDS", "Sudden Infant Death Syndrome", "SpO2", "Oxygen"

Based on this query string, three popular databases: PubMed, Scopus and IEEE Xplore were searched for articles published from the year 2000 onwards based on title, abstract and keywords on 09 March 2022.

The search resulted in 115, 1066 and 141 articles in PubMed, Scopus, and IEEE Xplore respectively. Articles were then removed based on the following criteria:

- Duplicate articles
- Not within the scope of the review
    - Neonatal population was not the target population or was not used for neonates
    - Not wearable devices e.g., other non-contact-based monitoring devices such as video and radar monitoring, and sensors integrated within neonate’s pillow, mattress and cot were common results excluded.
    - Not cardiorespiratory monitoring i.e., did not provide information on heart rate, cardiac cycle, breathing rate, breathing volume, work of breathing, or oxygen saturation
- Only abstract available
- Insufficient information provided on wearable technology
- Not in English or English language translation not available

In total 88 articles including 13 relevant review papers were obtained.

The reference list of the 88 included papers, including articles citing them were searched to find additional relevant articles. Additionally, two authors (CS and EG) independently searched for further articles, identifying an extra 32 papers. The detailed PRISMA flow diagram is presented in **Figure 1**. 13 review papers were excluded as relevant studies were already extracted from them.

All the selected manuscripts were then reviewed in detail by one author (EG), with the initial analysis plan to first categorise the papers based on:

- Sensors used
- Parameters/measurements obtained from the sensors
- The location of the sensors
- The type of wearable modality the sensor was integrated into
- If any machine learning algorithms were utilised

Once categorised, further information extracted when available from papers included:

- Sensor functionality and relationship to physiological parameter being monitored
- Cardiorespiratory conditions that are monitored
- Power consumption: passive, battery, external power supply
- Relevant discussions and results on:
    - Accuracy,
    - Ease-of-use
    - Robustness to noise
    - Advantages and disadvantages of the system

- Cost

Categorisation results are shown in **Table 1**. Once categorised, papers were then analysed in detail as presented in **Section 0**.

3. Wearable Technology

3.1. Sensor Types

Sensors are transducer devices that detect a physical parameter from the subject and convert it to a signal, typically an electrical signal that can be processed. For this section, sensors are classified based on the technical domain they detect, namely, mechanical, electrical, magnetic, thermal, and radiant sensors. A summary of the technical domain and location of sensors can be found in **Figure 2**.

3.1.1. Mechanical Transducers

Strain and pressure sensors are common types of mechanical-based transducers used for neonatal respiratory health assessment, such as breathing rate monitoring and apnoea detection. Dandekar and colleagues (6-8) utilised a mechanical strain gauge sensor in combination with passive radio-frequency identification (RFID). The mechanical strain gauge sensor was made from conductive and non-conductive threads to create an antenna, which was then inductively coupled to an RFID chip. The system was integrated into an elastic band, called Bellyband, which was then worn around the abdomen or chest of the infant. The Received Signal Strength Indicator (RSSI) of the returned signal from the RFID chip can then be continuously monitored by an external sensor. During inhalation, the Bellyband stretches, causing a decoupling of the antenna with the RFID chip that decreases the RSSI returned (6-8). The benefit of this system is being battery-less, which enables it to be small and flexible (6, 8). However, the RSSI is a weak signal prone to motion artefacts and temporal distortions. This makes signal processing and AI necessary to extract breathing and non-breathing periods (7, 9-11).

In more recent studies, a secondary strain-based RFID tag was placed on the upper shoulder of the infant (9, 10). The second RFID tag is not subject to respiratory motion and enables modelling and removal of noise artefacts present in the Bellyband signal (9, 10). Overall, signal quality improved by more than 17dB (10), and breathing/non-breathing detection by 7.7% (9) with the addition of the secondary sensor. However, weak signal remains an issue with breathing/non-breathing detection accuracy being 86% (9, 11).

Most recently, Bellypatch has been proposed to overcome the weak signal issue. Bellypatch is an abdominal belt that has a read range of 580 cm, nearly ten times more than Bellyband (11). An additional benefit of a larger read range is improved utility of the system and minimises radio-frequency exposure (8). Instead of sensing breathing through strain like Bellyband, the sensing property is compression. During inhalation, the expansion of the torso exerts pressure on the Bellypatch, which reduces its radiation efficiency, leading to a sharp decrease in RSSI (11). Further research is still required to determine the accuracy of breathing/non-breathing detection.

In similar research, chest or abdominal bands using strain sensors (12, 13) have been integrated into infant clothing to measure breathing. The strain sensors were made from electrically conductive strands that can be knitted into various patterns and change resistance when stretched (12, 13). The relationship between resistance and strain changes with knit patterns, therefore careful selection is required to ensure a repeatable linear relationship can be obtained (12). Additionally, conductive strand based sensors are prone to drift in recorded signal, which needs to be corrected (13).

Pressure sensors have been integrated into chest belts for monitoring breathing (14-16). Unlike RFID, these systems produce strong signals enabling high accuracy in breathing detection (99%), but require a battery system (14, 16). The sensors' resistance changes based on the amount of pressure applied to them. It was found that Velostat pressure sensor with Jersey knit exhibited the best resistance to pressure curve (16). With this system, breathing can be monitored, enabling respiration rate calculations and apnoea detection (14, 16).

Ballistocardiography (BCG) is the technique of monitoring the mechanical activity of the heart. BCG recordings are obtained using sensors that measure the mechanical forces on the surface of the body. The BCG signal is like ECG, with the added benefit of the sensor being small and not requiring skin contact. BCG sensors have been integrated into newborn clothing and used modified ECG code to determine the heart rate (17).

Accelerometers measure acceleration along a predefined axis (x, y, or z-axis) or a combination of axes for dual- and tri-axial accelerometers. Through the integration of the acceleration signal, velocity and displacement can also be provided. A common use of accelerometers is determining the breathing rate of neonates by placing the sensor(s) around the abdomen or sternum (13, 18-20). Although this method is susceptible to motion artefact (20), two dual-axis accelerometers around the abdomen alleviate this issue (18, 19). With multiple accelerometers, breathing volume can also be calculated, however, a look-up table with reference spirometer is required (19).

Accelerometers placed on the chest can also be used for seismocardiography (SCG) and vocal biomarkers (21, 22). SCG is produced from the small vibrations of the chest due to sounds, and can be used to obtain heart rate, systolic interval, pre-ejection period, and left-ventricular ejection times. It was found that heart rate estimation using SCG was within FDA regulation of ±5 beats per minute (21). Vocal biomarkers can be indicative of neurophysiological state (21). Crying was easily identified in the 400-500Hz frequency range. Crying detected using an accelerometer as opposed to a microphone, offers the benefit of being largely unaffected by the ambient environment (21).

Microphones convert sound waves to electrical signals and are usually of mechanical types. An omnidirectional microphone has been placed on either the neck or suprasternal notch with adhesive tape to monitor breathing (23). During breathing, the sound is created by turbulence in the respiratory system, enabling detection of inhalation and exhalation. It was also suggested breathing volume may be determined, however, the relationship between breathing sound power and breathing volume is questionable (23). A two-microphone system that was placed either on the chest, neck or wrist to obtain a phonocardiogram (PCG), also known as heart sounds has also been proposed (24). The benefits of PCG over ECG are no electrical contact is required and low-power consumption, making battery-free radio-frequency powered system possible (24).

3.1.2. Electrical Transducers

ECG records the heart's electrical activity and is achieved through the placement of electrode sensors around the heart. With the ECG signal, heart rate and cardiac abnormalities can be detected. For wearable technology, past work has used 2- (19, 25-27), 3- (28-30) and 6-electrode (31) ECG configurations integrated into the newborn's clothing or as a separate chest belt. Unlike traditional ECG electrodes that require the use of electrolytic paste or conductive adhesive, capacitive dry electrodes are used (29).

A downside to wearable capacitive electrodes is the higher impedance compared to gel electrodes, and the need to maintain sufficient pressure for skin-to-electrode coupling/contact. These result in greater sensitivity to motion artefacts from the baby and clothes, weaker signals and disconnection of a particular electrode (27, 29, 30, 32, 33). Additionally, to make the system more comfortable, newborn clothing is used as the insulator, as opposed to more ideal materials, making the detected waveforms more distorted (29). Due to these limitations, typically only heartbeat rhythm can be extracted and tight fitting clothing is required (19).

To address the issues of poor skin-to-electrode contact and disconnection, a smart algorithm for a 6-electrode jacket has been developed (31, 34). With the additional electrodes, the context-aware algorithm determines the optimal selection of electrodes to produce the best quality ECG signal. Therefore, the signal quality of the overall system is not affected by a single electrode source disruption (34).

A battery-free ECG wearable monitoring system using RFID embedded into clothing or a chest patch has also been made (8, 25). Using a heartbeat detection circuit, the RFID tag is turned off momentarily for each ECG spike detected. The downside with this system is that the ECG signal is not transmitted, except for the heartbeat information (8, 25).

Commercially, Laerdal Global Health has created NeoBeat (35), a belt that is placed around the abdomen of newborns. NeoBeat has 2-dry electrodes located on the lower back of the newborn for specifically heart rate monitoring (35).

With 2 electrodes placed around the diaphragm and one reference electrode placed at the sternum, this offers the possibility of monitoring both heart and lung health (36-40). The primary signal obtained is diaphragmatic electromyography (dEMG), a measure of the neural control of the diaphragm. The benefit of the system is it provides a direct measure of breathing and diaphragmatic work of breathing. ECG which is present as noise, can also be separated and extracted with signal processing (36, 38).

Another electrical-based sensor system is electrical impedance tomography (EIT). EIT utilises a belt containing multiple (16 (41, 42) or 32 (43)) active electrodes around the chest of the newborn to monitor lung volume changes in real-time. Active electrodes refer to the fact that they inject small alternative currents, which can then be measured as potentials at the same or other electrodes. Overall, this process enables the impedance of the chest to be calculated in real-time at up to 49Hz, providing useful information about lung aeration and ventilation (41). Whilst EIT provides real-time lung imaging, these images are of low resolution, and do not represent structural lung information. Due to these issues, these lung images are difficult to be interpreted by clinicians (43). The electrodes can be used to obtain an ECG (42).

3.1.3. Magnetic Transducers

A neonatal vest to measure volume changes when the neonate is breathing has been developed (44). The vest covers the entire chest and abdomen with two continuous wire coils sewn into it. Alternating current is passed through the coils and external magnetic field sensors detect this. During breathing, the volume contained within the coils changes, causing a proportional change in the magnetic field generated (44). The vest provides an accurate direct measurement of the respiratory volume changes and does not require prior calibration (44).

3.1.4. Thermal Transducers

Many studies have proposed a wearable respiratory monitoring system that can be placed under the nasal cavity or within a nasal cannula or breathing mask (45-49). The purpose of the system is to monitor breathing and apnoea. A polyvinylidene fluoride (PVDF) film-based sensor was utilised for this purpose. PVDF exhibits a pyroelectric property, where heat changes during breathing are transduced into an electric charge. As PVDF is an active sensor, a piezoelectric transducer for energy harvesting to make the overall system self-powered has been used (45-49). Overall, this is a simple system that integrates well with babies on respiratory support, when respiratory monitoring is most important (46, 48, 49).

3.1.5. Radiant Transducers

Optical based methods are typically used for two purposes, namely, pulse oximetry and PPG. Pulse oximetry is the measurement of blood oxygenation saturation, that is, the concentration of oxygenated haemoglobin in comparison to de-oxygenated haemoglobin (50, 51). Whereas PPG is the measurement of blood volume changes, which indicates blood perfusion to a particular area and can be used to derive heart rate. Both these methods utilise the same design, a combination of a light-emitting source e.g., light emitting diodes (LEDs) and a light detecting sensor e.g., a photodiode. For pulse oximetry, oxygenated and deoxygenated haemoglobin have differing light absorption spectrums, hence, the effective attenuation of light emitted to the light detectors can indicate the relative concentration of oxygenated to deoxygenated haemoglobin. For PPG, the presence of blood absorbs light more than the absence of blood. Hence the effective attenuation of light emitted to the light detectors can indicate the volume of blood flowing through a particular area.

There has been extensive research into the usage of wearable optical sensors for heart rate (52-55) and peripheral oxygen saturation (54, 56, 57). These sensors have been integrated into a sock (56), foot band (52, 57) and head cap (55, 58) for wearable purposes. Additionally, many have been proposed for home-based monitoring (53, 54, 56, 57).

Flexible silicone patches with LEDs and light sensors have been used on neonate’s forehead (50, 59-61). Utilising multiple near-infrared LEDs and light sensors, cerebral tissue oxygenation, peripheral oxygenation and heart rate can be obtained. The measurement of brain oxygenation is especially important for premature infants, who are vulnerable to hypoxic and ischemic cerebral insults that can lead to long-term morbidity. Whilst out of scope for cardiorespiratory monitoring, bilirubin levels have also been measured using these silicone patches, based on the difference in the absorbance of the blue and green lights emitted. Measuring bilirubin levels is useful for the early detection of neonatal jaundice (60, 61).

Commercially, a Bluetooth wireless cap with forehead-mounted sensor that uses reflectance-mode optimised 525nm green light PPG to measure heart rate has been developed (55, 58, 62). By capturing blood flow at the forehead which shares arterial pathways for brain perfusion via the carotid artery, it is less susceptible to poor peripheral perfusion (63, 64). The cap developed is compatible with respiratory equipment fittings including endotracheal tube and non-invasive ventilation attachments, making it suitable with neonatal care (55).

Other commercially available devices, Baby Vida and Owlet Smart Sock, integrate the optical-based sensor into a sock to obtain oxygen saturation and heart rate information (65, 66). Owlet Smart Sock has been a popular consumer device, offering an alarm system for when oxygen saturation is too low or heart rate is too high, which has been positively received to reduce the anxiety of parents and prevention of critical events (65, 67). However, these two baby monitors are not FDA-regulated, and with the lack of research, there are accuracy concerns with the risk of creating a false sense of security (67). It was found that Baby Vida never correctly detected hypoxemia and displayed falsely low pulse rates, whereas Owlet Smart Socket detected hypoxemia but performed inconsistently (66).

The combination of fibre optics and photodiode sensors can be used for monitoring breathing (68). Optical fibres arranged in a sinusoidal pattern were integrated into an elastic material and attached to the outside of an infant's diaper. During inhalation, the diameter of the optical fibre bend increases, which causes the intensity of the light-emitting from the optical fibre to increase, which is detected by the photodiode (68). A limitation of this system is that careful design of the diameter and curvature of the optical fibres is required to ensure a sufficient linear relationship between power output and strain is obtained (68).

3.2. Integrated Wearable Sensors

3.2.1. Clothing

Infant sensor integrated clothing has come in the form of attachments or fully integrated sensors in onesies/vests/jackets, diapers, socks, and shoes. Most common sensors in clothing have included inertial, optical and temperature sensors, as well as electrodes for the purposes of breathing movements, oxygen saturation, temperature, and ECG.

Chen and Bouwstra et al. have been developing a smart neonatal jacket that integrates 6-electrode ECG (31, 69), pulse oximeter (51) and temperature sensors (70) with wireless power supply and transmission (71-73). Similarly, baby vests to monitor respiration using resistive strain sensors around the chest and abdomen, as well as heart rate from a 3-4 electrode ECG are common (32, 74, 75). Linti et al.'s (74) vest also measured temperature from two thermistors around the armpit and humidity using electrodes that measure moisture-dependent resistance on the back. On the other hand, Mastro et al.'s (75) vest contained optical sensors in the sleeves. With regards to power supply, some have been wired systems (74, 75), wireless (32) or accompanied by a plush toy to supply power (71-73).

More recently, Chen and colleagues (76, 77) designed a smart vest. Within the vest are two textile-based dry ECG electrodes on the chest, a strain sensor around the abdomen for respiration measurement and two inertial sensors (accelerometer, gyroscope, and magnetometer) on the wrists for movement information. The textile-based electrodes are designed to be disposable and replaceable to ensure optimal ECG signals. Additionally, the electrode is designed such that a cotton component is sandwiched between two electronic-textile components. The proposed sandwiched electrode provides a cushioning effect that improves electrode-to-skin contact during movement, overall improving the robustness of the ECG signal (76, 77).

Smart jackets have also been designed for blood pressure monitoring (78). With an expandable arm cuff within the jacket, the newborn's brachial artery can be semi-occluded and detected by the PPG sensor. Using the combination of pressure measurements from the capacitive force sensor and the PPG signal, blood pressure can be calculated (78). Further testing is required to determine the accuracy of this system. There are also potential safety concerns with ensuring semi-occlusion is occurring in the right location and is not cutting off blood supply for a prolonged period.

Baker (79) designed a swaddle that covers the baby. Within the swaddle are two integrated sensors that each contain a thermistor and electrode and are placed on the posterior and anterior of the infant's torso. The thermistor was used to measure temperature, the electrodes obtained ECG for heart rate and hydration based on resistivity measurements between them (79).

Commercially, the Goldilocks Suit and MonBaby Smart Button have been developed for home monitoring (80, 81). These devices are not designed for clinical use and instead are provided to parents to aid in monitoring their baby. The Goldilocks Suit is a baby onesie that contains sensors to monitor temperature, breathing and various movement activities (80). Whereas, MonBaby Smart Button attaches to an article of clothing to monitor breathing and various movement activities (81).

Many devices have been developed to place on the infant's foot in the form of a sock or shoe (82-86). All devices utilised a pulse oximeter for heart rate and oxygen saturation. A temperature sensor was used for instantaneous peripheral temperature measurement (82, 83, 85-87). A tri-axial accelerometer was used for position and activity monitoring and to reduce motion artefacts in PPG (84-86). Finally, pulse oximeter signals and galvanic skin response were obtained in a subset of the devices (87). With regards to design, InfaWrap (82, 83) and Leier and Jervan's (85, 86) device are comparatively bulky and have hard outer casings, whereas BBA bootee's (84) sensors are encapsulated in a soft fabric and are appropriately sized.

Sensors have been designed to attach to the infant's diaper (88, 89). Mahmud et al.'s (88) diaper attachment had two capacitive electrodes for non-contact ECG and an accelerometer. The accelerometer was used as a reference signal in the adaptive filter to remove motion artefact and interference present in the ECG signal (88). NAPPA (89), a diaper cover, contained accelerometer and gyroscope sensors, collecting respiration rate and body posture data.

Xu et al. (90) developed a reusable system using a laser-induced graphene-based integrated flexible sensor system that is placed within the front side of a diaper. The electrodes were used in three configurations for tilt, strain, and humidity sensors. The tilt sensor was used to determine the rotation of the baby, strain sensor for breathing rate and humidity sensor for wetness monitoring (90).

Commercially for home monitoring, Snuza Hero and Levana oma sense are two diaper clip-based sensors (91, 92). Both sensors monitor the baby's abdominal movement for breathing and gently vibrate to rouse the baby if no breathing movement is detected for 15 seconds (91, 92).

3.2.2. Patch

Roger and colleagues have undertaken extensive work on soft and flexible 2-patch system for neonatal monitoring (21, 93-95). One patch is placed on the neonate's hand or foot for PPG and oxygen saturation from optical-based sensors (21, 93) and peripheral temperature measurement (21). The other patch is placed either on the neonate's back or chest and contains 2-electrodes for ECG (21, 93), tri-axial accelerometer, and temperature measurement unit (21). The two patches are time synchronised such that the pulse transit time can be calculated from the time difference between the R-peak of the ECG chest unit and the valley regions of the PPGs on the limb unit. This pulse transit time can then be used as a surrogate measure of systolic blood pressure (21, 93, 94). Preliminary results show the surrogate measure is has mean error <5mmHg and standard deviation 8.7mmHg (21). The tri-axial accelerometer is used for respiratory rate, posture and movement measurements, and SCG (21). In one such patch design, no batteries were required (21, 93). Instead, radio-frequency power transfer was supplied from an antenna placed underneath the neonate's mattress, to the antenna on the patch (21, 93).

The work done in Rodger's lab has been translated to a start-up, Sibel Health (96), offering the neonatal monitoring device commercially. Overall product was positively received due to its non-invasiveness, portability, ease of use and ability to measure multiple vital signs in hospitals in Nairobi, Kenya (97, 98). However, there were concerns related to cost, maintenance, lack of reliable access to electricity and overcrowding in NICU (97, 98).

De Clercq and Puers (99) proposed a three node system that was attached to the chest and abdomen of the newborn. Two nodes were utilised for respiration measurement based on inertial measurements from accelerometer and gyroscope, and one node was used for heart rate measurement based on ECG (99).

3.2.3. Band

Bands suitable for placement on the infant's ankle or wrist have been developed (100). The band contained optical sensors for oxygen saturation and heart rate, and a temperature sensor (100).

3.2.4. Belt

Belts have been placed either around the chest/thoracic wall (101-103) or abdomen (33, 104-106) of neonates. A combination of ECG textile electrodes and inertial sensors for monitoring heart and breathing rate respectively has been common (101, 103, 104). Actidiaper, an elastic waistband, is placed over the newborn's abdomen (104). Actidiaper contained two textile electrodes at the back, which were used in combination with a commercial inertial sensor, Movesense, that clipped onto the front of the belt (107). Movesense sensor contained a tri-axial accelerometer, gyroscope, and magnetometer, each of which was tested for respiratory rate detection. It was found that gyroscope y-channel produced the best results (104).

In other abdominal belts, they have contained a thermistor and inertial sensors for hypothermia detection and breathing rate measurement respectively (102, 105). Additionally, Lin et al.'s (102) belt contained a carbon monoxide sensor to monitor the environment. For one belt, accelerometer was wrapped around NeoBeat for breathing and ECG monitoring (33, 35, 106). For belts wrapped around the chest of the baby, they contained ECG electrodes for heart rate, accelerometer for posture and breathing rate, and temperature monitoring capabilities (101, 103).

4. Discussion

With regards to determining the most suitable sensor type and wearable modality, there are several considerations that should be made, namely: power system, energy consumption, physiological information provided, accuracy, robustness to noise, ease of use and cost. **Tables 2 and 3** compare sensor types and wearable modalities.

For power system, battery, battery with wireless charging, batteryless with wireless power, and passive batteryless systems have been proposed. Batteryless systems reduce the size of the system, improve flexibility, and are not constrained by battery life. However, portability of these systems is constrained either by the wireless power unit range or wireless reader. Additionally, a passive system results in a weaker signal that is more prone to noise, typically resulting in only vital sign (heart and breathing rate) information only being feasible to extract.

For energy consumption, all mechanical sensors, PVDF thermal sensor and ECG monitoring have been shown to be capable of low-power consumption and application in a passive system. On the other end of the spectrum, the magnetic field sensor and EIT system would require the most energy for usage.

For physiological information provided, in the cardiac space, sensors have been used to provide BCG, SCG, PCG, ECG and PPG information. ECG is widely considered the gold standard, providing typically the highest quality signal enabling the most accurate heart rate estimation and extraction of information on the cardiac cycle. Similarly, PCG, SCG, BCG, and PPG can provide electrical or mechanical cardiac time intervals, however, are more susceptible to noise. For neonatal wearable devices, so far PCG, SCG, and BCG have been constrained to just heartbeat detection for heart rate estimation. Therefore, further research in the potential usage of these systems for electrical or mechanical cardiac time intervals and the quality of these signals in the neonatal wearable space is required. In terms of unique information provided, LED with optical sensor provides both PPG and pulse oximetry, where oxygen saturation from pulse oximetry being an important vital sign not obtained by other sensor types.

In respiratory space, most of the sensors only provide basic breathing monitoring enabling breathing rate calculations and apnoea detection. Multi-accelerometer setup, magnetic field sensor, and electrode system for EIT have been shown to provide more detailed information on breathing volume and work of breathing. In particular, the magnetic field sensor being the only system directly measuring lung volume. Both accelerometers and microphones can also be used for vocal biomarkers such as adventitious lung sounds such as wheezes, crackles, and rhonchi. Microphones are designed more appropriate to collect these lung sounds due to frequency range and accuracy. However, accelerometers offer the benefit of not being affected by background noise, though are affected by motion artefact.

All wearable modalities of belt, band, patch, and various forms of clothing have been shown to integrate multiple sensors to successfully monitor numerous cardiorespiratory parameters. For a single location, placement of sensors around the chest is the most suitable for cardiovascular monitoring. This is because it maximises the types of sensors that can be used, the proximity to the heart and lungs, and related chest movements during breathing. Similarly for cardiac monitoring, placement around the chest is optimal. Whereas systems placed around the abdomen or back are prone to picking up motion artefacts or EMG noise.

Adhesive patches provide the benefit of direct skin contact, which allows higher quality signals due to reduced motion artefacts, closer to the source of the physiological signal, and better contact for electrodes. As adhesive patches can be disposable, this increases costs and is more suitable for shorter term monitoring within a hospital environment as opposed to home monitoring. Additionally, adhesive patches carry the risk of skin damage to the newborns, which is especially of concern for premature neonates that have fragile skin. However, there have been many advances in adhesive technology, which have minimised neonatal skin damage after removal of the patches.

Integration into clothing is the most suitable with regards to ease of use in both clinical and home environments. However, integration of sensors within clothing places the further requirement of being washable. Additionally, the ability of the clothing to appropriately fit to provide sufficient contact and reduced motion artefact for good quality signals for different sized neonates, and if used for long-term monitoring, be suitable as a neonate grows from 0 to 1 month old, raises questions. Swaddle offers the potential benefit of minimising motion artefact as the baby's movement is restricted and is tight fitting, however, the sensors are placed further away in comparison to other clothing integrated sensors.

Overall, cost is difficult to determine and compare as most of the wearable technology reviewed are in research stage and costing is multifactorial. In general, all sensor types are relatively low-cost as they typically aim for home and rural usage. As highlighted previously, disposable modalities such as patches would increase costs. **Supplementary Table 1** shows the cost of existing commercial infant cardiorespiratory wearable technology.

5. Future Directions

Many newborn wearable technologies offer the possibility of an integrated system of multiple sensors. Besides the benefit of multiple physiological signals for a clinician or machine-learning algorithm to interpret, it also offers the ability to combine the information for new health information and improved signal quality and accuracy, which are challenging with wearable systems. In the current literature, this has been achieved through utilising accelerometer signals to remove motion artefacts in PPG, oxygen saturation and ECG signals (84, 85, 88), multi-electrode systems to improve ECG signal quality (31, 34) and using the combination of ECG and PPG signal to determine systolic blood pressure (21). In future, additional benefits can be seen in utilising the multiple sensors to more accurately extract and separate heart and lung signals. For instance, ECG monitoring is contaminated with EMG signals from breathing and vice versa (36, 38, 108), audio signals contain both heart and lung sounds (109-111), and accelerometer data contain both SCG and chest movement data (21).

With these multiple inputs, heart and breathing cycles can be more readily and accurately identified, enabling correct segmentation and separation of these data sources.

For sensor technology specifically, four gaps and possible future directions are presented. Firstly, existing pressure-based sensors can also be used for heart monitoring (112). Apexcardiogram can be obtained with pressure sensors, providing information on the changing volume of the left ventricle, and is a commonly used technique for obtaining cardiac function information (112). Secondly, microphone sensors have been used for either heart or lung information (23, 24). With more suitable housing of the microphone within a diaphragm structure, like stethoscopes, both heart and lung sounds can be obtained simultaneously and more accurately (113). Thirdly, there is research into flexible and wearable ultrasound transducers (114). Ultrasound transducers offer the possibility of echocardiography, which is a commonly used approach for more detailed information on newborn cardiac function such as blood pressure and cardiac output (114, 115). However, this is still an emerging technology with issues around image resolution and long-term flexibility of the material (114). Finally, there are existing chemical sensors that can provide useful information about expiratory gas content (116). Whilst this sensor has not yet been implemented as a wearable technology, it has been proposed to be suitable to integrate as a badge to attach to clothing.

6. Limitations and Future Work

This study has only focused on wearable technology for cardiorespiratory monitoring. In the future, review of non-contact cardiorespiratory methods such as video and radar monitoring that offer similar benefits to wearable technology should be completed. Similarly, a review of technology integrated within the newborn’s pillow, mattress and cot should also be completed.

7. Conclusions

In this study, we reviewed wearable technologies for neonatal cardiorespiratory monitoring. We found there has been a large body of research in both single-parameter and multi-parameter sensing. In particular, multi-parameter sensors offer the possibility of improved accuracy in the acquisition of physiological signals and subsequent training accuracy due to the variety of heart and lung information provided to machine learning models.

In Part 2: Artificial Intelligence, the developments of the machine learning techniques used for these wearable neonatal cardiorespiratory monitoring devices is explored. Additionally, machine learning techniques suitable for neonatal cardiorespiratory monitoring are examined.

Data Availability Statement

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

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