Joey: Supporting Kangaroo Mother Care with Computational Fabrics

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ABSTRACT

Kangaroo Mother Care (KMC), involving chest-to-chest skin contact between an infant and caregiver, is proven to be an effective intervention for preterm and full-term infants. Accurate monitoring of KMC duration and infant's vital signs during KMC is clinically important. Existing monitoring methods, however, rely on manual efforts and require rigid sensors or wires/electrodes on the infant's body. We propose Joey, a fabric-based approach to continuously monitor KMC duration and two vital signs essential to an infant's well-being: heart rate and respiration rate. Joey is a soft fabric necklace worn by the caregiver. It leverages the transmission of electrocardiogram (ECG) signals across individuals during skin-to-skin contact. With a minimalist fabric sensor structure, Joey measures KMC duration via the presence of mixed ECG signals. It then isolates the infant's ECG from this mixture with a proposed signal extraction algorithm and employs a diffusion-based denoising model to mitigate motion artifacts, enabling reliable inference of infant's vital signs. We fabricate Joey prototypes with off-the-shelf hardware and evaluate its performance with user studies. Results demonstrate that Joey achieves an average F1 score of 96% for KMC duration measurement, and clinically-acceptable accuracy in infant's vital sign estimation with a mean absolute error of 2.3 beats per minute and 2.9 breaths per minute in estimating heart rate and respiration rate. Clinical interviews further confirm the usability of Joey's sensing fabric for infant skin. A demonstration video of Joey is available at:

`mobilex.cs.columbia.edu/joey`

CCS CONCEPTS

• Hardware → Sensor devices and platforms; **• Human-centered computing → Ubiquitous and mobile computing systems and tools**; **• Applied computing → Health care information systems**.

KEYWORDS

Computational Fabrics, Kangaroo Mother Care, Electrocardiogram, Vital Sign Monitoring

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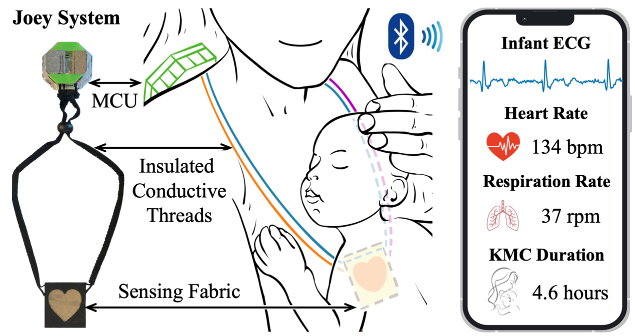

Figure 1: Practicing KMC with the Joey system. Joey is a fabric necklace worn by the caregiver. Joey senses the ECG signals of the caregiver and infant. Raw ECG signals are transmitted to a Joey app on a smartphone, which computes the KMC duration, infant's heart rate, and respiration rate in real time.

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1 INTRODUCTION

Kangaroo Mother Care (KMC) is a low-cost, evidence-based intervention with proven benefits to both infants and their families. It refers to holding the infant with the infant's chest skin against the caregiver's chest skin in an upright position [49]. The skin-to-skin contact provides warmth and protection, and promotes bonding between the caregiver and infant [22, 28, 33, 41, 67, 70, 103]. KMC should be initiated immediately after birth and continued for as long as the caregiver and infant desire [33, 49, 90, 102]. KMC improves infant's thermal regulation, enhances breastfeeding rates [10, 87], reduces the risk of infections, and promotes cognitive and behavioral development in infants [10, 28, 33, 103]. Based on a report from the World Health Organization (WHO) [90], KMC benefits are evidenced by a 32% reduction in neonatal mortality, a 68% reduction in hypothermia at discharge or by 28 days after birth, a 15% reduction in severe infections or sepsis, and a 48% increase in the duration of exclusive breastfeeding at facility discharge. More importantly, KMC can be performed in diverse healthcare settings including resource-constrained environments. It has been adopted as a standard of care for infants with low birth weights worldwide [90].

Continuous monitoring of KMC practices is clinically important. In particular, the duration of KMC sessions and infant's vital signs during KMC hold significant clinical values, as highlighted by prior studies [49, 90] and reinforced through our clinical surveys with pediatricians (§5.4). Accurate tracking of KMC duration allows pediatricians to better understand the correlation between KMC duration and the infant's recovery (e.g., weight gain [47]), which then facilitates the adjustment of subsequent care plans [24]. Additionally, for ongoing research studying KMC's impact (e.g., heart rate regulation during KMC [92]), it is essential to precisely quantify the duration of each KMC session and its distribution throughout the day. Furthermore, regular assessment of infant's vital signs during KMC is critical for nursing care. It enables early identification and management of potential life-threatening issues for infants and indicates if the KMC practice is performed effectively [118].

Systematic KMC monitoring, however, faces multiple practical barriers. First, KMC duration is currently measured manually through an independent observer (e.g., a caregiver or nurse). Such manual efforts not only are susceptible to errors and may be biased by the Hawthorn effect [24], but also impose additional burdens on caregivers and healthcare providers. Second, existing methods of measuring infant's vital signs require placing rigid sensors, wires, and electrodes on the infant's body [54, 98, 109]. This requirement limits the caregiver's activities and is highly undesirable considering the delicate nature of infant skin.

In this paper, we introduce Joey, a fabric-based approach to continuous and accurate monitoring of KMC duration and two important vital signs (i.e., heart rate and respiration rate) of the infant. As depicted in Figure 1, Joey eliminates the need for additional infrastructure or rigid electrical sensors on either the infant or the caregiver. Instead, it leverages a small necklace made of conductive fabrics as a soft and natural sensing layer between the caregiver's and the infant's chest. By exploiting the observation that electrocardiogram (ECG) signals can transmit between individuals under specific skin-to-skin contact conditions, Joey senses mixed ECG signals of the caregiver and infant. The mixed signals form the basis for monitoring KMC duration and the infant's vital signs.

Realizing this concept as a practical system poses several challenges. These challenges include the complex characteristics of mixed ECG signals, the need of minimal/zero wiring given the fragile skin of infants, as well as motion-induced noise that adversely affects the quality of sensed ECG signals and degrades the accuracy of vital sign inference. To address these challenges, we propose a dual-sided design for Joey's necklace pendant, where sensing fabrics are embedded in each side the pendant. This design leverages the inherent skin contact between the infant's and the caregiver's chests during KMC, eliminating direct sensor attachment to the infant while ensuring optimal sensor-skin contact and KMC skin-to-skin contact. Additionally, we incorporate another sensing fabric on the caregiver's neck to create two sensing channels, where one channel senses caregiver's ECG and the other senses the mixed ECG from the caregiver and infant. We design an ECG separation algorithm based on human body's impedance properties to extract infant's ECG. We mitigate the impact of motion noise by adding a noise-monitoring channel based on a conductive thread to detect motion noise and employing a diffusion-based model for denoising in the presence of motion.

To evaluate the performance of Joey, we fabricate prototypes using off-the-shelf hardware and conduct a user study with 11 infant-adult pairs and 10 adult-adult pairs. We also conduct clinical interviews with pediatricians to examine Joey's clinical usability. Overall Joey achieves an average F1 score of 96.4% for KMC duration estimation and a mean absolute error of 2.3 beats per minute and 2.9 breaths per minute in inferring the infant's heart rate and respiration rate. Furthermore, Joey is robust against washing/drying (>50 cycles), various skin conditions (e.g., sweating), and motion noise. Pediatricians concur with the clinical usability of Joey's fabric pendant for infant skin. Participants also highlight Joey's ease of use and comfort to wear.

We summarize our contributions as follows:

- To the best of our knowledge, Joey is the *first system* capable of simultaneously monitoring KMC duration, infant's heart and respiration rate, while maintaining comfort.
- Leveraging the observation that ECG signals can transmit between individuals, we propose a fabric-based physiological sensing methodology to capture both the caregiver's ECG and its mixture with the infant's ECG.
- We design and implement a signal separation algorithm using discrete wavelet transform and adaptive filtering techniques, effectively extracting the infant's ECG signals from the mixed ECG signals.
- We leverage a conductive thread to detect motion-induced noise, alongside a deep diffusion denoising model. This hardware-software co-design effectively mitigates motion noise while ensuring minimal computational overhead.
- We build a Joey prototype and validate its sensing performance with both infant-adult and adult-adult pairs, its clinical usability with clinical interviews, and its robustness under practical factors, such as washing, different skin conditions, and motion noise.

More broadly, while prior works of fabric sensing focus on sensing a single user [13, 53, 62, 63, 65, 71, 114, 119, 121], this work pushes the envelope of fabric-based human sensing by extending it to multi-user scenarios and enabling the detection of human contact. Joey's sensing rationale of ECG transmission between humans paves the way for the development of novel applications in multi-user fabric sensing and interaction.

2 JOEY SENSING PRINCIPLE

An effective KMC monitoring system needs to meet three goals. (1) It should place no rigid or adhesive sensors on infant's body given the dedicate nature of infant skin. Medical devices and adhesives are a major iatrogenic cause of skin breakdown in hospitalized neonates [74, 80, 108]. Up to 15% of a neonate's skin surface area can be traumatized daily, increasing with greater prematurity [99]. (2) Given the intimate nature of KMC, the system needs to protect user privacy. Traditional vision-based approaches [51] are inappropriate for this context. (3) The system should entail minimal operation overhead to enable continuous monitoring of KMC.

To meet above goals, we propose a fabric-based approach – Joey – to monitor KMC duration and infant vital signs. Joey achieves these goals by sensing ECG signals of the caregiver and infant using conductive fabrics. Joey's sensing principle stems from the fact that ECG signals transmit over human skin when the sensing path passes through the heart. As such, chest-to-chest skin contact between two individuals leads to the observation of mixed ECG signals of the persons in contact. Joey exploits the observation to

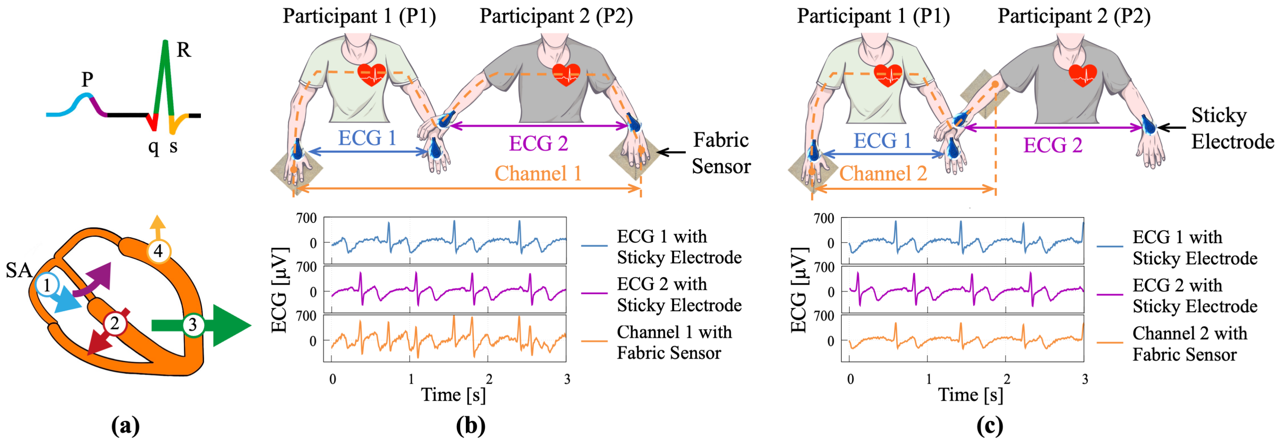


Figure 2: (a) The QRS complex and the ECG depolarization direction (the numbers represent the depolarization sequence) (b) The study setup and measured ECGs, when the path passes through two hearts or (c) passes through only one heart.

detect chest-to-chest skin contact. The mixed ECG signals also form the basis for inferring an infant's vital signs.

The fabric approach presents the following benefits. (1) Conductive fabrics are comfortable to wear and skin-friendly, posing no harm to the delicate skin of infants, compared to rigid or adhesive sensors. As the ECG signal is naturally generated by the human body, our approach is passive and introduces no active current or voltage to the infant, ensuring their safety. (2) The fabric sensor exclusively collects ECG signals, preserving the privacy of both the infant and the caregiver during KMC practice. (3) The fabric sensor is durable (i.e., washable for repeated use) and easy to maintain, introducing minimal operation overhead.

ECG Primer. ECG is a graphical representation of the electrical potentials occurring between different sites on the skin in response to cardiac activity [2, 82]. The fundamental electrical event within the heart is the depolarization and repolarization of cardiac cells. Depolarization occurs when electrically polarized cardiac cells lose their internal negativity, leading to a wave of depolarization that spreads across the myocardium and encompasses the entire cardiac muscle. This wave represents the flow of electric current, which can be detected through electrodes placed on the skin. As shown in Figure 2(a), the primary origin of this current is the sinoatrial (SA) node located in the right atrium, and it spreads in various directions through the heart to the atrioventricular node [34, 40]. To measure ECG, *the electrode path needs to pass through the heart.* A 12-lead ECG configuration is commonly used in clinical practice, providing different "views" of the heart by measuring electrical potentials between different electrode combinations [40, 81]. However, this configuration is challenging to set up due to the large number of channels/wires needed. The QRS complex (Figure 2(a)) is typically the largest amplitude waveform observed in an ECG. In most cases, the QRS complex can be measured regardless of the lead used and is directly related to the heart rate.

Body Transmission of ECG. ECG transmission within a human body has been extensively explored [4, 16, 40]. Prior examples demonstrated that the human body can act as a conductor for ECG transmission from the heart to the hands [40]. Leveraging this effect, an increasing number of wearable devices (e.g., Apple Watch [9], KardiaMobile [58]) offer one-lead ECG measurement.[1]

In this work, we are motivated by a novel observation that the transmission of ECG signals can actually go beyond a single user. When two users are in skin-to-skin contact, their mixed ECG signals can be observed when the sensing path passes through their hearts. A similar phenomenon was observed in a medical report [64], where it was characterized as a "mysterious ECG" and the report offered limited explanation. In the KMC context, this observation naturally allows the detection of direct skin-to-skin contact on the chest. It eliminates false positives that can occur with distance-based sensing methods (e.g., acoustic or computer vision-based methods [61]), as these methods have to assume spatial proximity equals actual contact. Furthermore, the ECG transmission makes it possible to sense an infant's ECG signals with sensors on the caregiver's body. It *eliminates the need for any sensor or hardware on the infant*, which is commonly required by previous ECG sensing methods [23, 31].

Experimental Validation. We conduct a controlled experiment with two participants to validate this rationale and the use of conductive fabrics to sense ECG signals. We fabricate two fabric sensors as electrodes for a one-lead OpenBCI ECG sensing system [89]. We test two setups to verify the condition of observing mixed ECG signals. In the first setup (Figure 2(b) top), two participants (P1, P2) each touch a fabric sensor with one hand while touching the other participant with the other hand. In this case, two fabric sensors form a sensing path (channel 1) passing through the hearts of P1 and P2. We also add conventional sticky electrodes to each participant's hands to collect individual lead-I ECG signals as the ground truth. We plot sensed ECG signals at the bottom of Figure 2(b). We observe that at channel 1, fabric sensors sense a weighted summation of P1's and P2's individual ECG signals. When P1 and P2 are not touching hands or not in direct skin-to-skin contact, we observe that channel 1 remains at zero due to the infinite impedance of the open circuit. In the second setup, we move the fabric sensor to P2's hand that is touching P1 (Figure 2(c) top). As such, the resulting channel (channel 2) passes through only P1's heart. As shown in the

[1]These devices require the user to wear the device firmly on one wrist, establishing contact with *one hand* as one electrode side. The other electrode side is created by placing a finger from *the other hand* onto the device.

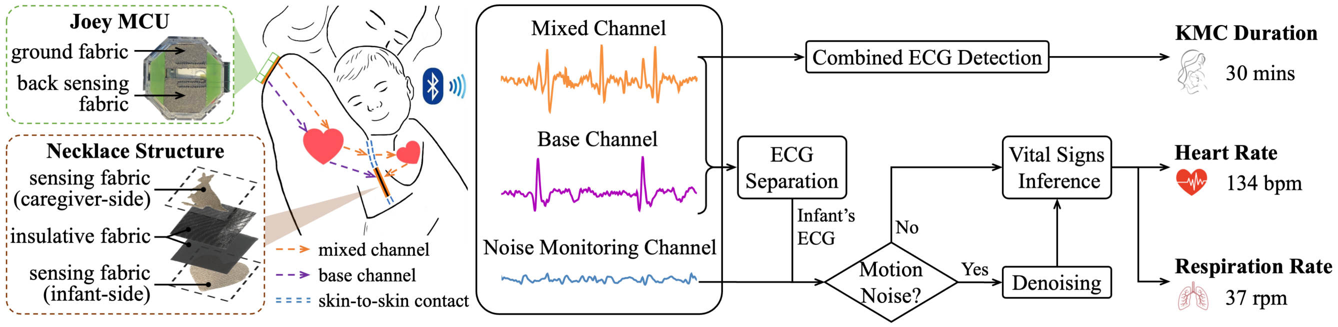


Figure 3: Joey system overview. The mixed channel is established exclusively through skin-to-skin contact. The initial step is the detection of mixed ECG to obtain the KMC duration. Subsequently, utilizing both the mixed and base channels, an adaptive filter-based algorithm is employed to extract the infant's ECGs. In instances of motion noise identified by our noise monitoring channel, we apply a deep diffusion model for denoising the infant's ECG. The resulting clean ECGs allow for accurate inference of the infant's heart and respiration rates.

bottom of Figure 2(c), signals sensed by fabric sensors at channel 2 now contain only P1's ECG.

Overall our experiment validates the ECG transmission across humans. When the sensing path goes through the hearts of two persons in skin-to-skin contact, the sensed ECG signals exhibit a combination of both individuals' cardiac activities. This experiment also confirms that fabric sensors can replace sticky electrodes due to their high conductivity as mentioned in prior work [23, 72, 116]. We have further verified experimentally that the size and shape of the fabric sensor do not affect the quality of sensed ECG signals.

Challenges. To apply this rationale to KMC monitoring, a major challenge lies in the handling of mixed ECG signals. Infants and caregivers have distinct and dynamic characteristics in their ECG signals due to differences in heart rate. Conventional approaches to extracting individual ECG signals from mixtures require multiple measurement paths [12, 37, 117], which adds complexity to the device and compromises wearability. Another challenge is to avoid sensor attachment and wires to the infant and maintain good contact between the fabric sensor and human skin. Obtaining the mixed ECG signal of two individuals requires at least one fabric sensing node to be in firm contact with each individual. This leads to complex wiring between the individuals, limiting the activities of the caregiver. Additionally, ensuring contact between the fabric sensor and human skin is also challenging, as the common skin-tight fabric sensing design is unsuitable for the fragile skin of infants. Finally, fabric sensors are prone to motion interference. Fabric sensors are formed of flexible and stretchable conductive threads, providing comfort. However, this flexibility can also lead to mechanical deformations and movements of the conductive threads. These deformations can cause changes in the electrical properties of the conductive fabric [68], resulting in motion noise.

3 JOEY DESIGN

Joey addresses the above challenges via (1) a minimalist structural design of fabric sensors that do not require any sensors worn by the infant and enable multiple sensing channels, (2) an effective filtering algorithm to extract the infant's ECG signals from the mixture, and (3) a hardware-software co-design to enable motion noise detection and removal to address motion interference for accurate vital signs estimation. Figure 3 illustrates the fabric sensor design and the system flow. Overall, Joey consists of a fabric pendant, a fabric band, and a micro-controller (MCU) attached to the back of the caregiver's neck. The MCU transmits signals from three sensing channels to a Joey app on a smartphone, which computes KMC duration and the infant's vital signs in real time. Next we describe each design component in detail.

3.1 KMC Duration Estimation

Necklace Design. We propose a minimalist structural design of the fabric sensor to enable two ECG sensing channels. The primary fabric sensor is the fabric pendant worn on the caregiver's chest, along with a sensing fabric and ground fabric attached to the MCU in contact with the back of the caregiver's neck. In particular, the fabric pendant is dual-sided, with conductive sensing fabrics on each side. During a KMC session, one sensing fabric layer contacts the caregiver's chest skin, while the other side contacts the baby's chest skin. These two sensing fabric layers are separated with an insulation fabric in the middle. As such, the design enables two ECG sensing channels (Figure 3):

- *The mixed channel* originates from the back fabric sensor on the MCU, traverses caregiver's heart, continues through skin-to-skin contact to reach the infant's heart, and finally ends at the infant-side sensing fabric on the pendant. By passing through both the caregiver's and infant's hearts, it senses the mixed ECG signals of the caregiver and infant.
- *The base channel* is formed from the back fabric sensor on the MCU to the caregiver-side sensing fabric on the pendant, passing through the caregiver's heart. Hence it senses the caregiver's ECG signal alone, providing essential information to facilitate the extraction of the infant's ECG signals for vital sign inference.

It is important to note three key aspects of this design: First, the mixed channel can only be established when there is chest-to-chest skin contact between the caregiver and the infant. Second, the sensing path of the base channel is part of the path of the mixed channel. This ensures that ECG signals of the base channel align with the caregiver's ECG signals of the mixed channel, facilitating subsequent extraction of the infant's signals. Third, this design capitalizes on the inherent chest-to-chest skin contact in KMC to guarantee optimal contact between the human skin and the sensing fabric, which constitutes the foundation of fabric-based sensing and is often challenging to ensure.

Estimating KMC Duration. With the fabric sensor design, KMC sessions can be detected by monitoring the signals of the mixed channel. When the caregiver and the infant establish a chest-to-chest skin contact, signals from the mixed channel exhibit a combination of two persons' ECGs. Otherwise the mixed channel will have no readings due to the open circuit. To detect the presence of mixed ECGs, we continuously monitor signals from the mixed channel, segmenting the signals into discrete two-second segments. For each segment k, its power E_k is computed as the summation of the squared ECGs. E_k is then compared to a predefined threshold ϵ to detect the skin-to-skin contact during a KMC session. ϵ is empirically configured to avoid random circuit noise. Based on the detection results of all segments, KMC duration T_{KMC} (in seconds) with N segments can be computed as below:

$$T_{KMC} = \sum_{k=1}^{N} 2 * \delta(E_k), \text{ where } \delta(E_k) = \begin{cases} 0 & \text{if } E_k \le \epsilon \\ 1 & \text{else} \end{cases} \tag{1}$$

Here $\delta(E_k)$ denotes the KMC detection result for segment k.

3.2 ECG Separation

The second key design element of Joey is its algorithm to extract the infant's ECG signals from the mixed channel for later vital signs inference. The hardware design ensures that the sensing path of the base channel is part of that of the mixed channel, providing a consistent view of the caregiver's heart. This guarantees that the caregiver's ECG signals in both channels have the same shape and are synchronized. However, due to the impedance difference between the base channel (caregiver's body impedance) and the mixed channel (caregiver's body impedance + infant's body impedance + contact impedance), the resulting signal strengths of the caregiver's ECG sensed at these two channels are different. Consequently, a simple subtraction of the base channel signal from the mixed channel is not sufficient.

To address this issue in ECG separation, we apply an online learning method called adaptive filter [11, 113], which suppresses the interference based on the input signals and the reference signals. In contrast to batch learning methods that train models offline using a fixed dataset, adaptive filter updates its parameters incrementally and continuously adapt to changes in input signals or the environment. Additionally, adaptive filter does not require multiple mixed ECG channels [12, 37, 117] or accurate R-peak locations information for template construction [57, 76, 110]. These make it well-suited for our applications where (1) the statistical properties of the mixed ECG signals vary over time due to the fluctuation of two people's heart rates and the mismatch between their heart rates (2) the two channels of ECG can be utilized as the input and reference signals, with the caregiver's ECG component in the mixed signal serving as the interference. Consequently, the adaptive filter's objective is to determine optimal weights that effectively eliminate interference and ensure accurate signal separation.

We model the mixed signal $y(t)$ as a combination of infant's ECGs $s(t)$ and caregiver's ECGs $\eta(t)$, expressed as $y(t) = s(t)+\eta(t)$. Due to the impedance difference, the caregiver ECGs in the mixed channel are typically modeled as a scaled version of the caregiver

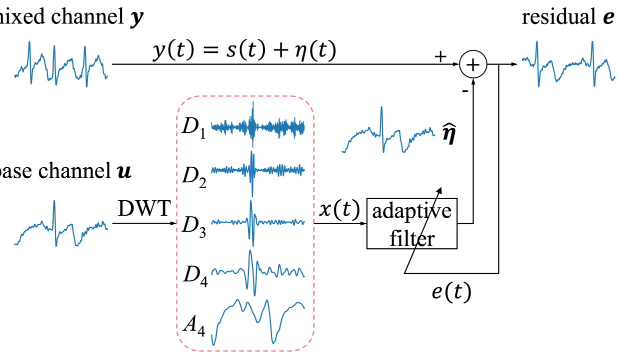


Figure 4: Visualization of the ECG separation process.

ECGs $u(t)$ from the base channel, formulated as $\eta(t) = w \cdot u(t)$. With $u(t)$ as the reference signal, the adaptive filter estimates the infant's ECGs $s\hat{(t)}$ by optimizing the weight w:

$$\hat{s}(t) = y(t) - w \cdot u(t) \tag{2}$$

Equation (2) assumes a uniform level of attenuation for all frequency components of the caregiver's ECG, represented by a single weight w. However, the disparity between the caregiver's ECG signals in the base and mixed channels is primarily caused by the addition of infant body impedance and contact impedance. In general, the human body impedance exhibits frequency-dependent behavior, which typically decreases with increasing frequency due to the capacitive properties of cell membranes and interstitial fluid [30, 42]. Consequently, a single weight w cannot effectively capture this frequency-dependent behavior of impedance.

Based on the above analysis, we propose to employ discrete wavelet transform (DWT) [83, 94] to decompose the caregiver's ECG signals into five signals in different frequency bands and then apply non-uniform weights across frequency bands. Specifically, DWT decomposes the caregiver's ECG signal into a high-frequency and a low-frequency signal, which are known as the detail (D) and approximation components (A), respectively [94]. In the first-level decomposition, the caregiver's ECG signal $u(t)$ undergoes sub-band filtering and sub-sampling, yielding detail coefficient and approximation coefficient vectors. These vectors are subsequently employed to reconstruct the first-level detail (D_1) and approximation components (A_1), which are constituents of the original signal [79]. For multi-level decomposition, this procedure iterates on the approximation component. Our study reveals that a four-level decomposition of the caregiver's ECG signal achieves an optimal balance between performance and complexity. Crucially, the DWT preserves the linear relationship property, allowing the original signal to be expressed as the sum of detail components and the fourth-level approximation component:

$$\begin{aligned} u(t) &= D_1(t) + A_1(t) \\ &= D_1(t) + D_2(t) + A_2(t) \\ &= \ldots \\ &= D_1(t) + D_2(t) + D_3(t) + D_4(t) + A_4(t) \end{aligned} \tag{3}$$

Here D_i and A_i denote the i-th level detail and approximation component at level i, respectively. Figure 4 demonstrates the whole separation pipeline. Following the DWT, we define the reference input

$x(t)$ for the adaptive filter as $\boldsymbol{x}(t) = [D_1(t), D_2(t), D_3(t), D_4(t), A_4(t)]^T$. Using the reference signal $x(t)$, we approximate the caregiver's ECG signals along with other noise components as:

$$\hat{\eta}(t) = \boldsymbol{w}^T(t-1) \cdot \boldsymbol{x}(t) \tag{4}$$

Here, $\boldsymbol{w}$ represents the weight vector updated through the Least Mean Squares (LMS) algorithm [113] , which updates the weights using the gradient of the MSE with respect to the weights. The weight update process is given by:

$$e^2(t) = [y(t) - \hat{\eta}(t)]^2 \tag{5}$$

$$\boldsymbol{w}(t) = \boldsymbol{w}(t-1) - \frac{\mu}{2} \cdot \nabla e^2(t) \tag{6}$$

Here, μ is the step size, and $e(t)$ is the residual signal representing the estimation of the infant's ECG signal. The algorithm proceeds through two distinct phases. During the initialization phase, which typically occurs within the first 20 seconds of the user wearing Joey, the weight vector undergoes significant alterations due to the initial random weights. In the second phase after initialization, the weight vector is stabilized but still updated and used in real-time to output the infant's ECGs, represented as $\hat{s}(t) = e(t)$.

3.3 Vital Sign Inference

Based on the extracted infant ECG signals, we infer infant's two vital signs. Since motion-induced noise (e.g., user accidentally moving necklace bands) affects ECG signal quality, we add a denoising module before vital sign inference to improve inference accuracy. We leverage a noise monitoring channel to detect motion noise, and apply a deep diffusion model to mitigate the effect of motion noise. We next elaborate on each component.

Deep Diffusion Model for Denoising. Motion-induced noises usually appear as high-amplitude peaks that cannot be fully removed by the ECG separation module due to its different presences on both channels. We set out to test several deep learning methods recently proposed for ECG denoising. Among different types of network structures (e.g., LSTM [50], autoencoder [107], conditional generative adversarial net [111]) we tested, a conditional diffusion model (DeScoD-ECG [69]) works the best due to its ability to handle severe motion distortion. Diffusion models function by deliberately introducing noise into training data and subsequently learning to reverse this process. A well-trained diffusion model can generate data from random noise by iteratively removing the predicted noise. Embeddings, such as text descriptions for image generation, can be added to guide the content generation process.

In our scenario, we aim to recover clean ECG signals given the noisy ECG observation as the embedding. The DeScoD-ECG model, originally designed for ECG baseline wander and noise reduction and trained with the QT database [66] (geared towards adult ECGs), needs adaptation due to the distinct characteristics of infant ECGs (e.g., higher heart rates). To this end, we retrain the model using the PICS [45] database, which includes ECGs from 10 infants, and the MIT-BIH NST database [46, 85], including various types of motion-induced noise in ECG recordings. An illustration of the denoising effect is shown in Figure 5(a). The refined model comprises 1.2 million parameters and achieves an average inference time of 0.5 seconds for a 2-second ECG recording, tested on a MacBook Pro 2022 (M2 Max, 64GB). In our current implementation, this model is deployed on a computer, and the reconstructed signal is transmitted to the Joey App on a smartphone via WiFi. This setup, while functional, introduces additional power consumption and latency due to both the inference process and data transmission. To mitigate these issues, we integrate a noise monitoring channel to trigger the denoising module only when motion-induced noise is detected. Next we will describe the design of the noise-monitoring channel.

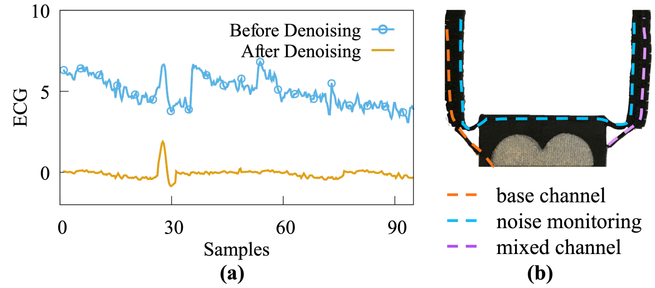


Figure 5: (a) ECG before and after the deep diffusion model. (b) The conductive thread acts as the noise monitoring channel, capturing the noise whenever the necklace bands and pendant are moved.

Noise Monitoring Channel. Given the infrequency of significant motion noise during KMC, constant activation of the diffusion denoising model is unnecessary. To activate denoising only upon the presence of motion noise, we incorporate an additional conductive thread into the necklace bands, which serves as a dedicated noise monitoring channel. This conductive thread as shown in Figure 5(b), strategically placed alongside the signal transmission threads but not connected to the sensing pendant, is exclusively dedicated to detecting noise signals caused by the movement of the necklace bands and pendant. §4 describes the implementation details of this noise monitoring channel. The diffusion model is activated only when the signal power from the noise monitoring channel exceeds a predefined threshold, otherwise the signal after the ECG separation module is utilized directly for vital signs inference. The reading of the conductive thread channel is approximately zero upon the absence of motion noise. Thus, the threshold is set empirically to half of the average noise power. This hardware-software co-design approach not only addresses motion noise challenges effectively but also significantly reduces required computational power and data transmission bandwidth.

Vital Sign Inference. After denoising, we next infer infant's two vital signs as below.

(1) Heart Rate. To compute infant's heart rate, we employ the Pan-Tompkins algorithm [91] to identify R-peak locations in infant's ECGs. This involves filtering the ECGs to emphasize the QRS complex, differentiating and squaring the signal to enhance the peaks, and integrating with a moving window to capture the full QRS complex. Finally adaptive thresholding and decision rules are applied for R-peak detection [91]. By measuring the time interval between consecutive R-peaks, we calculate the instantaneous heart rate (H) in beats per minute as below:

$$H = \frac{1}{\sum_{i=1}^{5} d_i / 5}, \tag{7}$$

where d is the consecutive R-peak-to-R-peak intervals and 5 is the empirical window size for averaging.

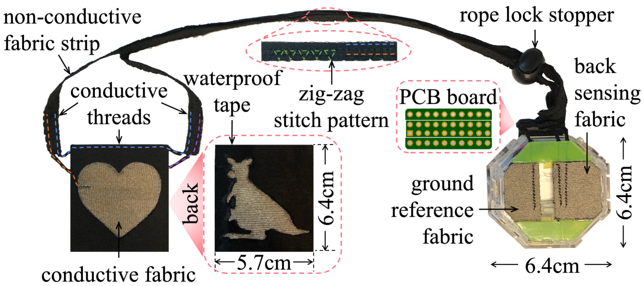


Figure 6: Joey prototype. Four conductive fabrics are connected to the MCU with conductive threads. The conductive threads are embedded into the non-conductive fabric strip to form the necklace band, whose length is adjustable through the rope lock stopper.

(2) Respiration Rate. Estimating the respiration rate from ECG signals has been investigated in previous studies [27, 55, 93]. The rationale is that ECG signals are influenced by respiratory modulations [25, 26], including baseline wander, amplitude modulation, and frequency modulation (FM). Due to the sensitivity of the ECG signal baseline and amplitude to factors such as sensor location and individual differences, we leverage the FM property to estimate the respiration rate. The physiological mechanism underlying FM is the manifestation of spontaneous variations in heart rate during the respiratory cycle, known as respiratory sinus arrhythmia [17, 25]. Specifically, heart rate increases during inhalation and decreases during exhalation [59, 106]. Based on this FM mechanism, we utilize the heart rate inferred in the previous step to compute the Heart Rate Variability (HRV), which is the variation of time intervals between successive heartbeats. We then apply Fast Fourier Transform to the HRV data. In the HRV frequency spectrum, we identify the peak frequency within the frequency range corresponding to an infant's respiration rate, typically 20-60 breaths per minute. The peak frequency is the estimated respiration rate.

4 JOEY IMPLEMENTATION

We have fabricated multiple Joey prototypes/necklaces using off-the-shelf hardware (Figure 6) and implemented the algorithms for ECG separation and vital sign inference as an Android App. While aiming to optimize sensing performance, we also guarantee that the prototype is comfortable to wear, skin-friendly to infants, and washable. Overall the Joey necklace is compact and lightweight, measuring 6.4cm by 6.4cm for the MCU, 5.7cm by 6.4cm for the pendant, and weighing 65 grams, of which 2.1 grams is the fabric and 62.9 grams is the combined weight of the board, case and battery. Instead of inventing new high-cost materials, all the components in the system are off-the-shelf and at low prices (<$5), except the computing unit ($499). The potential of optimizing the computing unit for a more cost-effective implementation is discussed in §6.

Necklace Pendant. The pendant consist of conductive fabrics [5] at each side as conducting electrodes, and an insulation middle layer using two water-proof non-conductive fabric tapes [7] and silk fabrics [6]. We cut the conductive fabric facing the baby into a heart shape and that facing the caregiver into a kangaroo shape using the Cricut smart cutting machine [36]. To prevent curling and isolate the two sensing fabric layers, we glue them with waterproof fabric tapes [7], and sew a 0.3cm overlock pattern along the edges of the two layers to secure them (Figure 6).

Necklace Bands. Necklace bands connect the pendant to the MCU on the back of the caregiver's neck. The band wraps conductive threads [3] with non-conductive fabric strips. We sew the noise-monitoring conductive threads in parallel to the conductive threads connecting the pendant and the MCU, maintaining a 0.7cm gap between them. The strips are then folded along the middle line, and the folded edges are stitched using a 5mm wide overlock pattern. The necklace bands go into a Cord Rope Lock Stopper [8] for adjusting the band length to a given user (Figure 6).

MCU. We use the commercially available OpenBCI Cyton Board [88] as the MCU. Sensed signals sampled at 250 Hz are transmitted via BLE to a phone for further processing and visualization. Channel 1, 4, 8 are dedicated to mixed ECGs, caregiver's ECGs, and noise monitoring, respectively and channel GND serves as the ground reference. To establish a stable connection between the conductive threads and the board's pins, we designed a small printed circuit board (PCB) with four rows of holes. The upper two rows are connected, as are the lower two rows. We can connect the conductive threads to MCU by tying them to the corresponding holes in the first and last rows. To ensure insulation between the threads, we carefully wrap the exposed sections with waterproof tape. The MCU is glued to the caregiver's neck skin via two pieces of skin-friendly hypoallergenic adhesives [105]. We utilize a 3D-printed case, to hold the MCU, a Lipo battery, and accommodate the attachment of the back patches.

Joey App. The Joey App is an Android application that receives ECG signals from the MCU, processes them, and visualizes KMC monitoring results. The app is implemented in Java and establishes a connection between the smartphone and the OpenBCI board using the OpenBCI Cyton Dongle [88], utilizing the Gazell high-speed link layer protocol [100]. The data processing pipeline is implemented in Python and is accessed through the Chaquopy Software Development Kit [73]. Lastly, the calculated heart rate, breathing rate, and the extracted infant ECG signal are presented on the user interface, as depicted in Figure 1.

5 SYSTEM EVALUATION

We evaluate Joey with user studies and clinical interviews after obtaining the approval of our institution's Institutional Review Board. We aim to examine Joey's sensing functionally, clinical usability, and practical robustness.

5.1 Study Setup

Participants. We recruit participants in pairs (as the KMC practice involves two persons), through flyers distributed within our institution. Each participant was compensated at the rate of $15 per hour. A total of 4 newborns and 11 adults are recruited, forming 11 infant-adult pairs. The pairs include four newborns (a 30-day-old male, a 34-day-old female, a 59-day-old female, and a 6-month male) with 11 caregivers (5 males and 6 females; 8 in the age group of 25-40 and 3 in the age group of 55-64). Given the difficulty in recruiting newborns, we also recruit 20 additional adults to form

(a) KMC (b) Clothes-on Session

Figure 7: (a) The caregiver and infant wear clothes for privacy while leaving their chests bare for KMC. (b) Caregiver holds an infant where both chests are covered in clothes.

10 adult-adult pairs (9 male-female pairs and 1 male-male pair; 4 in the age group of 18-24 and 16 in the age group of 25-34), where one acts as the infant while the other acts as the caregiver. It is important to note that the adult-adult pairs present a more challenging scenario for the ECG separation algorithm because measured ECGs of newborns exhibit higher amplitudes than that of adults based on our experiments[2]. Including both infant-adult and adult-adult pairs allows us to comprehensively demonstrate the feasibility and effectiveness of Joey. All participants are healthy with no reported heart or breathing-related health issues.

Procedure. Before each study session, participant pairs receive a comprehensive overview of the study, coupled with detailed instructions on how to wear the prototype device and use the Joey app for data collection. It is important to note that the positioning of the pendant on the caregiver's chest is flexible; there is no requirement for it to be in any specific location, ensuring ease of use and comfort. After signing a consent form, participants are allowed to take a Joey device home for the study. A study comprises three types of sessions totaling 60-100 minutes:

- KMC session (>30 mins), where participants have chest-to-chest skin contact. As shown in Figure 7a, caregivers practice KMC with the infant while wearing Joey. Adult pairs mimic the same practice, with one adult acting as the caregiver and embracing the other, maintaining chest-to-chest skin contact. KMC is suggested to be 30 minutes at minimum, but the actual duration depends on participant conditions, especially for infants. Both participants can move freely during the KMC session although infant mobility is limited due to their age.
- Clothes-on session (5-10 mins), where participant's chest is covered by clothes while having chest-to-chest contact with the other, hence there is no skin contact on the chest (Figure 7b). This session represents scenarios where infants are in a similar posture as during KMC, but with clothing, such as breastfeeding or sleeping, aiming to verify that Joey detects only chest-to-chest skin contact and does not produce false positives when two users in contact have clothes on the chest. In comparison, it is hard for distance-based methods to differentiate these two scenarios.
- Play session (5-10 mins), where participants have skin contact (e.g., touching hands) but no chest-to-chest skin contact. This scenario can happen when the caregiver and infant interact with each other.

[2]Based on our consultation with pediatricians, this is potentially because newborns have a larger heart size relative to the chest cavity than adults.

Table 1: User Study Session Duration

Session Type		KMC	Clothes-on	Play	Total
Duration (minutes)	Infant-Adult	413	116	100	629
	Adult-Adult	382	97	94	573

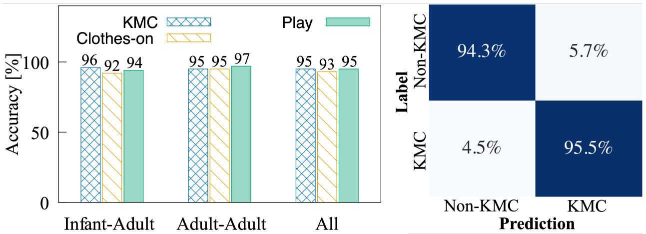
Participants participate in multiple sessions (at least one for each session). All raw ECG data along with inferred vital signs and KMC duration are collected by the Joey app and transmitted to a database. In total, we have collected 1202 minutes of data from all participants, corresponding to 36060 samples, where a sample is a two-second data segment. The duration breakdown for each session type is in Table 1.

Ground Truth. We collect ground truth for KMC duration and infant's vital signs. (1) The ground truth of KMC duration is collected manually via the Joey app. Recognizing potential inaccuracies in manual recordings, we have developed the Joey app to include buttons to click at the beginning and end of KMC sessions. In all user studies, we ensure that a third person is nearby to click the buttons to record KMC duration. The timestamps of these actions are recorded and used to compute KMC duration. (2) The ground truth of heart rate (HR) and respiration rate (RR) are collected by an FDA-approved pulse oximeter [78] for adult pairs. The device's accuracy [77], as quantified by the Root Mean Square (RMS) error, is reported to be 3 beats per minute (bpm) for HR and 2-4 respirations per minute (rpm) for RR. This device, however, is not applicable for infants whose fingers are too short. Thus, we opt for wrapping an Apple Watch [9] around the infant's ankle. We do not consider medical-grade adhesive sensors because of their potential harm to an infant's dedicated skin. We validate the use of the Apple Watch by conducting a separate study, where we apply both an Apple Watch and the FDA-approved pulse oximeter on a user for vital sign measurements. Results reveal that measurements from these two devices differ by less than 1%. It aligns with previous studies comparing Apple Watches and medical-grade devices [44].

Evaluation Metrics. Joey estimates KMC duration by checking whether each two-second segment is in a KMC session. Thus, duration estimation can be framed as a binary classification problem. Using the self-reported session types as the ground truth labels, we assess the accuracy of KMC duration estimation via measures of recall, precision, and F1 score. Additionally, we present a detailed analysis of the actual duration error measured in seconds. We evaluate the sensing accuracy of HR and RR using the mean absolute error (MAE). As our estimated HR and RR have a higher sampling rate than ground truth devices, we align each estimation to the ground truth value with the closest timestamp.

5.2 Sensing Performance

KMC Duration Estimation. We assess the accuracy of KMC duration estimation across participant pairs and individual sessions. As shown in Figure 8(a), Joey achieves an F1-score of 96% for infant-adult pairs and 95% for adult pairs in detecting each two-second segment as KMC or not. Out of 795 minutes of labeled KMC sessions,



(a) (b)

Figure 8: (a) The KMC duration detection performance across different sessions. (b) The confusion matrix.

Table 2: Vital Signs Estimation Results

	Heart Rate [bpm]		**Respiratory Rate** [rpm]	
	Range	**MAE**	Range	**MAE**
Infant	92-169	2.3	23-57	2.9
Adult	65-98	1.6	13-19	2.6
Overall	65-168	1.9	13-57	2.8

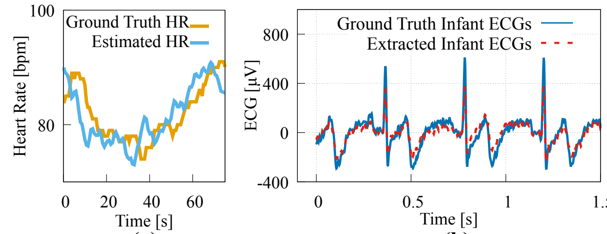
35.6 minutes are detected as non-KMC, and 22.1 minutes labeled as non-KMC sessions are detected as KMC. Figure 8(b) shows the confusion matrix.

Upon closer examination, segments of the 4.5% false negatives predominantly occur around the start and end of each session. Signal analysis reveal that during these segments, there are indeed no ECG signals present (and mostly no signals on the mixed ECG channel), indicating potential human labeling errors during the study. Further interviews with participants confirm that the need to press a start and end button in the app often introduces a few minutes of offsets. Consequently, it underscores the necessity of an automated KMC monitoring system such as Joey.

On the other hand, the 5.7% false positives primarily come from two pairs. In one adult-infant pair, they recall that during the last session labeled as KMC with clothes, the caregiver's chest (along with the sensing patch) likely touched the infant's head, resulting in signals similar to a KMC session. The false positives observed in another adult-adult pair are attributed to signals that appear similar to tapping on the sensing patch, causing peaks similar to the ECG readings. While this constitutes an edge case that the current KMC detection algorithm cannot handle, it is also highly unlikely to occur in actual KMC practices. Overall, these findings demonstrate the reliability and accuracy of Joey in estimating KMC duration.

Vital Signs Inference. We notice that the ground truth device and Joey employ different time window lengths for data processing. As such, the ground truth HR measurements exhibit a delay compared to that in Joey. Figure 9(a) shows an example of the delay (mean 6.8 seconds across the study) between the inferred and ground truth HR. We compensate for this delay by shifting the inferred HR by a fixed delay specific to each participant. Table 2 presents the MAE for inferred HR and RR after the compensation[3], which are 2.3 bpm and 2.9 rpm, respectively. The accuracy levels are comparable to those

[3]Without compensation for the delay, the MAE for HR and RR are 2.9 bpm and 3.3 rpm, respectively.



(a) (b)

Figure 9: (a) The estimated HR is always ahead of the ground truth HR measurement. (b) The extracted (acted) infant ECGs align well with the ground truth (acted) infant ECGs.

of FDA-approved clinical devices [1, 78]. Throughout the analysis of 1202 minutes of data, our diffusion-based denoising module is activated 1770 times, each for a two-second segment. This amounts to an activation duration of 59 minutes, accounting for 5% of the total processing time. Focusing specifically on these 59 minutes, we observe a notable improvement in inference accuracy, where the HR MAE decreases from 5.2 bpm to 3.1 bpm, and the RR MAE reduces from 5.1 rpm to 3.3 rpm. These improvements highlight the efficacy of the denoising module in mitigating the impact of motion noise on HR and RR inference.

It is noteworthy to mention that within our study involving adult pairs, some scenarios featured an adult-acted infant with weaker heartbeats compared to the adult acting as the caregiver. Remarkably, we did not detect any degradation in accuracy under these conditions. This observation can be attributed to the fact that R-peaks, crucial for ECG analysis, remain prominent even in ECG traces with lower amplitude.

Motion Tolerance. We also conduct a detailed study to examine Joey's tolerance of motion noise. We instruct an infant-adult pair to practice KMC in four scenarios: (1) the caregiver and infant staying stationary, (2) the caregiver moving and performing daily tasks with a sleeping infant on the chest, (3) the caregiver staying stationary with an active, moving infant on the chest, and (4) both the caregiver and infant moving during KMC. Each scenario is roughly 20 minutes. Analysis of the collected data shows that the activation rate of the denoising module is 2.2%, 4.2%, 40.2%, and 51.2%, respectively in each scenario. The resulting F1 score of KMC duration estimation is 96.1%, 96.5%, 92.1%, and 92.9%, respectively. The MAE (bpm/rpm) of HR/RR inference is 1.9/2.2, 2.1/2.4, 2.5/2.7, and 2.5/2.8, respectively. Overall, caregiver's movement has minimal impact on Joey's performance. However, infant movement causing pendant shifts leads to slight degradation of accuracy as the denoising module is unable to completely counteract the induced spikes. It is worth noting though that significant infant movement is less likely during KMC, particularly with preterm infants.

5.3 Sensing Micro-benchmarks

ECG Validity. To demonstrate the validity of the ECGs measured by the Cyton board in conjunction with Joey's fabric sensors, we conduct simultaneous measurements of lead-I ECGs from a participant using both a clinical ECG device (COSMED Quark C12x[35]) and the Joey prototype for 30 minutes. These two devices are synchronized by an injected small current that induces a synchronized

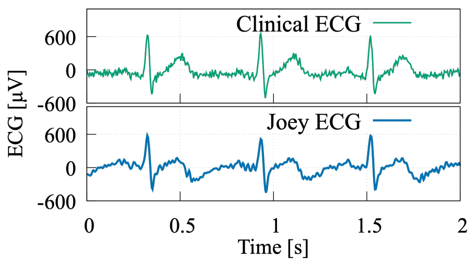


Figure 10: ECG signals from the clinical device and Joey.

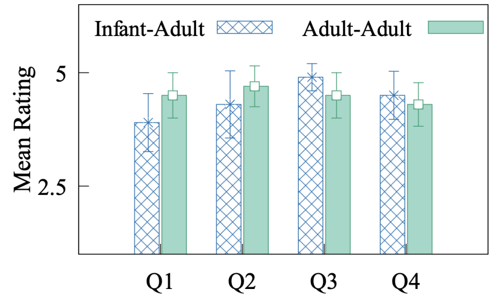


Figure 11: Users' ratings on the usability and comfort level.

fluctuation in both recordings. The COSMED data is downsampled from 1000Hz to 250Hz to match Joey's sampling rate. Figure 10 plots ECGs measured by both devices for an example two-second segment. The average HR inferences from the COSMED and Joey are found to be 91.15 and 90.99 bpm, respectively. Additionally, a t-test ($t(998) = -0.0096, p = 0.992$) conducted on the R-peak locations from these two measurements reveal no statistically significant difference. These findings indicate that Joey is capable of providing ECG recordings that are statistically consistent with those from a medical-grade ECG monitoring device. These results are consistent with the literature on Cyton board's ECG sensing validity [21].

Separation Accuracy. Due to concerns about attaching adhesive electrodes on infants' skin, measuring ground truth ECG signals of the infant is not feasible. To evaluate our ECG separation algorithm (§3.2), we conduct additional experiments with 3 adult pairs, where one adult wears Joey as the caregiver, while the other acts as the infant. We utilize an additional channel on the Cyton board, along with adhesive electrodes, to measure the ECG of the adult-acted infant as the ground truth. Figure 9(a) plots the extracted infant's ECGs and the ground truth ECGs. We evaluate the separation accuracy by comparing the detected peak locations of the ground truth ECGs and extracted ECGs. We consider peak locations within 5 samples as correct detections since they correspond to a window of 20 ms, which is smaller than the threshold in prior work (e.g., 50ms [48] and 30ms [84, 120]). The measured F-1 score for peak detection with extracted ECGs is 98.2%. The observed errors are primarily false negatives, occurring when the peaks of the infant overlapped with those of the caregiver and the adaptive filter fails to learn appropriate weights in the previous iteration. Overall, the ECG separation algorithm performs exceptionally well, establishing a reliable foundation for HR and RR inferences.

5.4 System Usability

We conduct interviews with pediatricians for clinical feedback and with users for system general usability.

Clinical Interview. To examine Joey's clinical usability with infants, we conduct clinical interviews with eight pediatricians. In each interview, a Joey prototype is demonstrated with adult participants. Pediatricians touch the necklace pendant to assess the softness and smoothness of the fabrics and stitches. They also examine other parts of the prototype and interact with the Joey app. Based on their evaluation, they later complete a questionnaire, where they are asked to provide clinical feedback on the necklace's usability on the infant's skin, comparing Joey to the fabrics of hospital swaddles, infant clothes, and standard medical-grade vital sign sensors. Pediatricians are also asked to answer open-ended questions on the clinical significance of KMC, the need and clinical uses of KMC duration and infant vital signs. In summary, they all conclude that Joey's sensing fabrics are clinically usable for infants (including preterm) who can wear clothes. The comfort level of Joey's fabrics matches or surpasses that of the newborn fabric cover and is substantially better than existing medical sensors. Regarding potential allergy concerns, pediatricians emphasize the importance of fabric's washability. This requirement is crucial for ensuring hygiene and reducing the risk of allergic reactions. §5.5 systematically evaluates Joey's washability.

User Interview. We also ask participants of our user study to evaluate Joey's usability and comfort level using a short questionnaire. The questionnaire asks participants to rate on the standard 5-point Likert scale (i.e., 1: Strongly Disagree, 2: Disagree, 3: Neutral, 4: Agree, 5: Strongly Agree) to the following statements:

- Q1: I found the system was easy to use.
- Q2: I thought the system was comfortable to wear.
- Q3: I thought this system would be helpful for supporting infants' development.
- Q4: I like the experience of the device overall.

Participants also write down their comments and suggestions. Figure 11 presents the mean scores from all participants, indicating a positive user experience overall. Caregivers in the infant-adult group have a lower rating on ease of use and comfort level than adult groups. Analysis of written comments reveal two main reasons. First, both groups mention that the MCU attached to the caregiver's back tends to fall during vigorous movements, which is more problematic in the infant-adult group due to the need for soothing a crying infant. Solutions to address this limitation will be discussed in §6. Second, half the caregivers in the infant-adult group find it inconvenient to press buttons in the Joey app for ground truth during KMC. It is important to note that the ground truth labeling is for performance analysis and does not occur in actual use cases. Despite these challenges, both groups report high levels of comfort. They also highly rate the system's effectiveness in supporting infant development, with the infant-adult group assigning almost the full score.

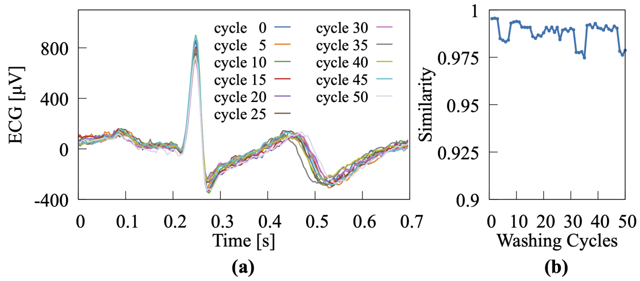


Figure 12: (a) The ECGs after different washing cycles. (b) The similarity to the unwashed fabric measured ECGs.

5.5 Practical Considerations

Durability over Washing. Washability is a critical factor to consider when designing fabric sensors [15]. To evaluate the washability of Joey, we prepare four identical fabric pendants of Joey. A pendant serves as the control with no washing/drying, while the other three undergo 50 washing and drying cycles. These pendants are washed in a washer [95] (medium-soil, hot-temperature, perm-press cycle) for 34 minutes/cycle and then dried in a dryer [96] (high-temperature mode) for 45 minutes/cycle. After each washing and drying cycle, we measured the resistance changes of these three fabric pendants compared to the control/unwashed pendant.

We observe that even after 50 washing and drying cycles, fabric resistance change is minimal, ranging from an average of 1.9 Ω to 11.7 Ω. We also measure the same participant's (male, 24 years old) ECG signals for 10 minutes using the two sides of the fabric pendant. Since we cannot synchronize the 51 measurements (they are not measured at the same time), to assess the variation in sensed ECG signals, we calculate the Pearson correlation coefficient [32] between average ECG cycles obtained from the control pendant and other washed pendants. The average cycle, similar to that in [12], is determined as the median of all ECG cycles within the recording. Figure 12a illustrates the average ECGs obtained after 0 to 50 washing cycles. Visually, there is no discernible difference in these measured ECGs. Figure 12b plots the computed similarity for all 50 cycles. All similarity scores are above 96%. These results demonstrate the superior durability of our fabric sensors. The tight adherence of the sensing fabric to the adhesive tape prevents stretching of the conductive threading during washing and drying, thereby minimizing the degradation of sensing performance. We acknowledge that this study is conducted with a single user. Future research involving a larger set of participants will further strengthen and validate these conclusions.

Skin Conditions. To evaluate Joey's robustness across different skin conditions, we conduct a study with a single participant (male, 24 years old). The participant wears Joey in the same location to measure ECG signals under three skin conditions: normal skin without preparation, sweating skin after running, and prepared skin following scraping and cleansing with a lotion cleaner (i.e., after a shower). Each skin condition is measured for ten minutes. An FDA-approved Pulse Oximeter [78] is used concurrently to obtain the ground truth HR and RR. The average peak-to-peak ECG amplitudes are 2.0 mV, 2.1 mV, and 1.9 mV for these three skin conditions, respectively. Fabric resistance slightly decreases on sweating skin, leading to slightly higher ECG signals. However, MAEs of HR and RR inferences are comparable in these three conditions. Specifically, the MAEs for HR are 1.9, 1.6, and 1.8 bpm, while the MAEs for RR are 2.4, 2.4, and 2.6 rpm for three skin conditions, respectively. These outcomes affirm Joey's reliability across varying skin conditions without necessitating prior skin cleaning. Given the limitation of the study with one user, broader participant involvement in future research will reinforce and confirm these findings.

Power Consumption. We measured the power consumption of Joey prototype using a Monsoon Power Monitor [39]. Overall the MCU consumes 170.2 mW power with a 3.6-V voltage. Joey app can run for approximately 26 hours on a 3.7-V 1200-mAh lithium-ion battery. It implies that the system can continuously monitor KMC for a day and require a daily change of battery. To further reduce power consumption, we can replace the current 8-channel ADC with a 4-channel model [52], since the system only needs data from three channels. It can reduce ADC power consumption from 41 mW to 5 mW. We can also replace the current processor with a lower-power version. We defer power optimization to future work.

6 DISCUSSIONS AND FUTURE WORK

User Study. We recognize that our current user study is limited by the small user group and short-term user experiences because of the difficulty of recruiting newborn participants. We are establishing collaborations with hospitals to expand our user group and include more newborns and real preterm infants through clinical studies. Additionally, our current ground truth device for collecting infant's vital signs is not medical grade given its potential harm to delicate infant skin. Upcoming clinical studies will address this issue, as preterm infants involved in these studies will already be using medical-grade devices. We also value the importance of collecting a more extensive and longer-term ground truth dataset. By refining our ground truth collection procedure, we hope to obtain accurate and reliable measurements of KMC duration and infant vital signs over an extended time period.

Hardware and Denoising Module Optimization. Feedback from participants highlighted the need for hardware optimization to reduce MCU size and improve the comfort and reliability of MCU attachment on the neck. A customized MCU can address this concern by eliminating unnecessary channels and modules from the OpenBCI board. This optimization will result in a significantly smaller and cheaper MCU, improving the overall ergonomics and affordability of the system. Furthermore, the use of a flexible PCB can be explored to enhance comfort and flexibility, allowing the MCU to conform better to the caregiver's neck. Secure neck attachment of the MCU will also ease continuous, long-time wear of Joey and allow us to conduct longer-term user study. Additionally, the current denoising module necessitates the use of a dedicated laptop, which may not be feasible for all users. Future research can consider the development of lightweight models capable of operating on resource-constrained MCUs or smartphones.

Continuous Temperature and Oxygen Saturation Sensing. Temperature and oxygen saturation measurements during KMC are also clinically valuable [49]. While it is not mandated to monitor temperature continuously according to the WHO guidelines [49], continuous temperature and oxygen saturation sensing will provide insights into the efficacy of KMC practices [14, 19, 38, 118]. Unobtrusive temperature measurement can be achieved using infrared thermometers. Integrating this technology into KMC practices needs to be explored further to avoid burdening the infant and caregiver. Monitoring oxygen saturation generally involves contact sensors, which are not suitable for infants' sensitive skin. Recent advances have suggested the possibility of using camera-based, remote photoplethysmography for non-contact measurement of SpO2 levels [101, 122], representing a promising direction. However, significant challenges remain in addressing issues related to motion interference and privacy concerns specific to the KMC context.

Other Applications. While Joey design has been tailored to the KMC application, Joey's sensing principle can be explored to enhance the monitoring of physiological synchronization, which is essential for examining interactions and dynamics in fields requiring collaboration and communication (e.g., dance performances [56, 86]). Additionally, Joey design can be simplified to enable continuous ECG monitoring for a single user. Specifically, Joey's necklace pendant can be simplified to a single-side sensing fabric to establish the base channel (§3.1) and monitor wearer's QRS waves. In comparison, current wearable ECG sensors (e.g., Apple Watch) require user cooperation and consequently cannot provide continuous monitoring. QRS detection is critical as it yields key metrics like QRS duration, essential for the diagnosis and management of various cardiac conditions, including coronary artery disease, bundle branch block, and cardiac hypertrophy [60, 75].

7 RELATED WORK

KMC Monitoring. Prior studies on KMC monitoring have primarily focused on sensing vital signs [20, 31, 54, 98, 115]. Bouwstra et al.[20] incorporated textile electrodes into a jacket to monitor the neonate's ECG during KMC. Rao et al.[98] focused on the development of wearable sensors capable of measuring the skin temperature of both infants and caregivers. Joglekar et al. [54] utilized capacitive electrodes to sense skin contact between the caregiver and the device, facilitating temperature sensing. However, it requires a rigid device directly against the infant's chest, undermining its suitability for long-term wear. Furthermore, this device cannot monitor the heart rate and respiration rate. Chung et al. [31] devised a binodal, wireless system to record infants' ECGs and PPGs. The binodal and wireless nature of the system effectively supported KMC. Xu et al. [115] developed wireless, skin-like sensors to monitor the physiological signs of infants, including heart rate via ECG, respiratory rate, and chest temperature. Although above works show promise in monitoring infant's vital signs, they cannot sense KMC duration. To sense KMC sessions, prior studies have examined infant's body position for KMC inference, using either accelerometer [109] or gyroscope [98]. However, these approaches require placing a rigid sensor on the infant skin. Weber et al. [112] developed a proof-of-concept conductive thread stitch sensor coupled with a pair of magnets functioning as a switch. However, no user study was conducted with caregiver-infant pairs and this approach is prone to false positives. In comparison, Joey detects both KMC duration and infant vital signs without rigid sensors on the infant and is evaluated with infant-adult pairs.

Textile-based ECG Sensing. Textile ECG electrodes offer several advantages over wet electrodes (e.g., Ag/AgCl electrodes [72, 116]), such as suitability for long-term monitoring [18] and prevention of skin irritation caused by adhesive materials [29]. Textile-based ECG sensing systems can be divided into two main categories: contact-based and non-direct contact approaches. Contact-based systems employ highly conductive fabric materials to acquire ECG signals [23, 97]. Conversely, non-direct contact systems [43, 97, 104] utilize variations in capacitance between the textile electrodes and the skin to ascertain ECG signals, thereby negating the necessity for direct skin engagement. This approach eliminates the need for direct skin contact, enabling non-contact measurements. However, capacitance-based ECG sensing necessitates specific conditions regarding insulating layers (for example, thickness and moisture levels), which complicates its practical application. Since our goal is to detect the skin-to-skin contact between the caregivers and the infant during KMC, capacitance sensing can trigger false positives. Therefore, we apply the contact-based sensing rationale in our design. Previous fabric-based physiological sensing techniques have primarily focused on monitoring the physiological signals of an individual user. To the best of our knowledge, our study represents the first attempt to sense and analyze physiological signals between individuals using fabric sensors.

8 CONCLUSION

We designed, implemented, and evaluated Joey, a fabric-based wearable system for KMC monitoring. Exploiting the ECG transmission across human bodies, it effectively monitors KMC duration and the infant's heart rate and respiration rate. Prototype experiments with 35 participants demonstrated its accuracy in estimating KMC duration with an average F1-score of 96% and vital sign inference with clinically acceptable accuracy. Clinical interviews further confirm the usability of Joey's sensing fabric for infant skin. This work extends the application of fabric-based sensing to multi-user scenarios and opens possibilities for new developments in multi-user fabric sensing and interaction.

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ARTIFACT APPENDIX

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