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Empowering Maternal Healthcare through IoT- Driven Long-Term Monitoring: System Architecture and Assessment

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ABSTRACT

During pregnancy, it is crucial to monitor maternal health to ensure the well-being of both the mother and the unborn baby. Numerous studies conducted thus far have presented a range of maternal health monitoring systems. However, these studies tend to concentrate on particular health concerns and frequently depend on limited-term data- gathering approaches like questionnaires. Furthermore, there is a lack of long-term studies evaluating the requirements and challenges of continuous monitoring. Our team has successfully developed an advanced system that utilizes cutting-edge Inter- net-of-Things (IoT) technology to continuously monitor maternal health both before and after childbirth. This cutting-edge system integrates various data collection mechanisms to precisely record crucial health metrics, including stress levels, sleep pat- terns, and physical activity. We conducted a comprehensive study with actual pregnant women from the Vadodara region of Gujarat State, India, to validate the effectiveness of our system.

Our extensive research has unequivocally demonstrated the practicality, energy efficiency, and the data reliability of this system we have established. This system has been proven to be highly effective in monitoring the health of expectant mothers for the entire duration of their nine-month pregnancy. Our maternal health monitoring system, utilizing IoT technology, offers an exceptional framework for ongoing monitoring throughout both pregnancy and the postpartum period. Rest assured that our system is the ultimate solution for monitoring maternal health. It has been implemented and evaluated, providing valuable insights into its feasibility, energy efficiency, and data reliability. This positions it as a strong candidate for improving maternal care and seamless integration with existing healthcare systems.

Keywords: *Maternal Health Monitoring, Pregnancy Monitoring, Postpartum Monitoring, Internet of Things (IoT), Wearable Sensors, Continuous Monitoring, Healthcare Systems Integration.*

1. INTRODUCTION

In maternal Health care, a remarkable duality takes center stage: fostering the inter- twined health and well-being of both mother and fetus. This dual focus demands a delicate equilibrium, navigating every step of pregnancy to safeguard both lives. Rec- ognizing the profound influence of the mother's prenatal health on the infant's imme- diate and long-term health

necessitates prioritizing her comprehensive care. It is crucial to acknowledge that health issues that arise during pregnancy, like hypertension or gestational diabetes, carry the potential to lead to subsequent health complications for the mother [1-3]. Therefore, maternal care plays a much-needed role in promoting the general health of the population in the long run and averting immediate complications during pregnan- cy.

Regular check-ups during pregnancy are essential for detecting any abnormalities and preventing complications, injuries, or fatalities [4]. Safeguarding a healthy pregnancy hinges on meticulous monitoring by healthcare professionals. They employ a battery of essential metrics, including blood pressure, blood glucose levels, and urine analy- sis, alongside close observation of uterine development and maternal weight gain to ensure optimal maternal and fatal well-being.

While these measurements are essential, it is also important to address other lifestyle factors and provide counseling on self-management practices, including physical ac- tivity and sleep. However, the systematic monitoring of these aspects is currently lacking [5].

Ongoing surveillance of pregnant women's health is vital for early detection of poten- tial complications, contributing to enhanced overall health outcomes [6-8]. By collect- ing valuable quantitative data through the continuous monitoring of various health parameters, we can enhance our understanding of pregnancy.

Fueled by advancements in ICT, particularly the burgeoning Internet of Things (IoT), the healthcare industry has embarked on a profound transformation. IoT is obtained with sensing, communication, and computational infrastructure, establishing a net- work of interconnected objects that enable the provision of advanced healthcare ser- vices regardless of time and location. Through the combination of big data analytics and artificial intelligence, the IoT seamlessly integrates into healthcare systems, fa- cilitating continuous remote monitoring of individuals. These monitoring systems gather data from users and their environments, transmit it to remote servers, employ advanced algorithms for analysis, and deliver personalized recommendations and feedback. Research findings suggest that systems incorporating the Internet of Things (IoT) hold significant promise as a cost-effective solution for delivering daily health monitoring services to pregnant women. Considerable evidence underscores the noteworthy enhancement in health results for both mothers and infants

During pregnancy and postpartum phases through the implementation of remote health monitoring systems.

Numerous endeavours have been undertaken to establish remote health monitoring systems for expecting mothers.

Several research studies have employed subjective methods, relying on mothers to self-report their health and well-being [15-17]. However, these approaches often in- volve scheduled phone interviews or online questionnaires, which may be prone to inaccuracies [18]. Certain research endeavors gather sporadic data on variables like blood pressure and weight from pregnant women in their homes, but the extent of data collection remains restricted [19, 20]. Mobile applications and wearable devices have emerged as tools for ongoing monitoring of health metrics throughout and post- preg- nancy, concentrating on aspects like sleep patterns, physical activity, and hyperten- sion [21-23].

Numerous studies have found the multifaceted applications of IoT for enabling re- mote monitoring the expectant mothers. But, these studies often have a limited scope, concentrating on specific health issues, possessing restricted sensing capabilities, and being confined to brief testing periods within pregnancy.

While the potential of long-term IoT systems in maternal care is promising, a detailed exploration of their implementation challenges remains absent. Existing research has primarily focused on the viability of mobile applications throughout pregnancy [20] and the application of wearables across pregnancy and postpartum [6].

To uphold consistent performance, an IoT monitoring system must confront essential implementation challenges. These challenges encompass feasibility and usability, energy consumption and efficiency, as well as reliability and accuracy. Failure to meet these requirements can have a detrimental impact on the user's overall experi- ence [6, 24-29].

We are thrilled to present a paper showcasing our state-of-the- art Internet of things- based health monitoring system tailored for extended use throughout pregnancy and the postpartum period. Our system incorporates various methods for collecting data to remotely access the health of pregnant women, encompassing both objective and sub- jective measures. The securely stored information is analysed from a distant location and seamlessly transmitted to healthcare providers. This study established a robust system for monitoring stress, sleep, and physical activity in pregnant women via AI- powered techniques like data quality assessment, personalized modeling, imputation, and anomaly detection. We also addressed challenges encountered during the imple- mentation and deployment of the remote maternal monitoring system, which are thor- oughly evaluated and discussed in this paper. Our team is confident that our findings will contribute significantly to enhancing the best way of care for pregnant women.

In conclusion, this paper offers the following contributions:

Our team has successfully designed and implemented an IoT- based system that effec- tively access the health pregnant women during and after birth of child. Our design meticulously balanced system efficiency and user needs, prioritizing practicality to deliver a truly exceptional user experience.

We have successfully developed a monitoring system that serves as a evidence-of- concept for the human subject study. The system employs a range of data collection methods, including cutting-edge AI-based and machine-learning techniques for data analysis.

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In this study, we Conclude a comprehensive analysis and evaluation of the implemen- tation challenges related to these monitoring systems. Our assessment covered areas such as feasibility, reliability, energy efficiency, and integration with the existing healthcare infrastructure.

In order to tackle these challenges, we seamlessly incorporated AI-based methodolo- gies into the system, as previously recommended by the authors. This holistic ap- proach enables effective data analysis and provision of monitoring services.

The paper is structured in a clear and concise manner. An overview of the latest ma- ternal monitoring techniques for the long term is presented in Section 2, Following a discussion of diverse monitoring services enabled by big-efficiency IoT-based sys- tems in Section 3, Section 4 implies for a high-risk pregnancy study and dissects the architectural intricacies. Technical challenges are evaluated and discussed in Section 6, offering a comprehensive analysis of the system. The paper concludes with Section 7, summarizing the key points presented throughout the paper.

2. RELATED WORK

This section provides a concise overview of the latest IoT- enabled systems developed for monitoring motherly health. Extensive research has been conducted on remote monitoring services for pregnancy, with some studies utilizing questionnaires to track maternal health [32], While promising research explores IoT-based monitoring for specific issues like hypertension [23, 33] and sleep disturbances [21], a crucial gap remains in understanding its potential for comprehensive, long-term monitoring throughout pregnancy and beyond.

There are various approaches for efficiently monitoring the health of pregnant women over a short period. For example, some studies employ a combination of self-reports and wearable devices. While Tsai et al. investigated sleep and life's quality using questionnaires and actigraphy, other studies prioritize monitoring diverse parameters like weight,B.P and glucose to manage conditions like hypertension and diabetes. One example involves equipping pregnant women with gestational hypertension with home blood pressure monitors.

Nowadays, smartphone applications are available to assist mothers in terrible situa- tions. For instance, Krapf et al. created a mobile application that records blood pres- sure and weight readings of mothers, issuing alerts when any deviations are detected. For high-risk pregnancies, Allahu et al. designed a pioneering framework. Their system uses a body sensor to collect uterine contraction data, allowing for personalized monitoring through a mobile app that alerts women when contractions exceed their individual thresholds.

Wearable devices have demonstrated great efficacy in the continuous collection of maternal health data. This study leverages a readily available wristband as a platform for a novel pregnancy hypertension monitoring model. By capturing continuous data on heart rate, activity levels, and sleep patterns, the model offers unique insights into maternal health beyond traditional blood pressure measurements. During a three- month evaluation at a healthcare center, pregnant women expressed their satisfaction with this non- invasive method of monitoring their health. An additional research study introduced an IoT rooted accessing system that employed a smart wristband to objectively evaluate sleep quality by gathering sleep information from mothers. By analyzing individual data, the system produced a personalized model that indicates the decline in sleep quality. In another research endeavor, Kumar et al. put forth a health monitoring architecture for pregnancy, emphasizing the crucial role of system adaptation in response to gathered health data.

Maternal health accessing systems rooted on the IoT frequently face limitations con- cerning the range of health concerns addressed, monitoring duration, and employed data collection methods. To address the need for sustained and extended monitoring of maternal health status, there is a requirement for an IoT-based system that provides a comprehensive perspective on maternal health. Such a system would encourage healthy lifestyles during pregnancy and mitigate risk factors, including the likelihood of premature birth.

Numerous studies have explored the possibility of implementing long-term monitor- ing systems for expectant mothers. Marko et al.'s research [20] successfully tested the feasibility of a six-month pregnancy monitoring system pairing a mobile app can measure digitally weight scale and B.P device in eight low-risk pregnancies. This study, along with Grym et al.'s work [6] develop a case study to assess the feasibility of employing a smart wristband for maternal health monitoring, involving the moni- toring of 20 pregnant women over a seven-month duration. These findings suggest promising developments in the field of maternal health monitoring.

Examining maternal health monitoring from various angles is crucial for its effective- ness [6,35,38,39]. To cater to long-term monitoring needs and enhance user satisfac- tion, practicality, dependability, and energy efficiency should be top-notch features of the monitoring systems utilized. It's important to assess technical and practical obsta- cles that come with monitoring outside clinical settings. The comprehensive integra- tion of AI and machine learning techniques is crucial for various aspects, including data quality assessment, missing data imputation, and personalized monitoring of ma- ternal health.

3. EXTENDED DURATION IOT-ENABLED MATERNAL MONITORING SERVICES

This section will investigate the capability of IoT-based systems in providing extend- ed maternity care through remote monitoring of maternal health. These services pro- vide continuous tracking of physical activity, sleep patterns, and stress levels.

3.1 Physical Activity Monitoring

Maintaining a good level of physical activity is crucial for the overall well-being and quality of life at the time of pregnancy [40]. Additionally, it significantly decreases the risk [41]. Nonetheless, physical activity levels often decline as pregnancy advanc- es [42], and self-reported measurements can exaggerate the sound and viewing of activity [43]. Continuous and objective monitoring provides uninterrupted and accu- rate data on a woman's physical activity, enabling personalized counseling tailored to her specific needs. This monitoring approach benefits both healthcare providers and pregnant women.

3.2 Sleep Monitoring

Sleep disturbances plague a significant portion of pregnant women, with the third trimester witnessing the highest incidence. This vulnerability often stems from factors like frequent urination and postural discomfort. Research said that sleep disturbances during pregnancy are linked to an elevated risk of premature delivery, gestational hyperglycemia, and mood disorders.

3.3 Stress Monitoring

Pregnancy can be a stressful time for women due to various factors such as physical symptoms, changes in the body, and concerns about the health of the fetus. Pregnan- cy, while a joyous occasion, can be overshadowed by stress, potentially culminating in detrimental consequences like depression, hypertensive disorders, and premature birth. As a result, it is crucial for maternity care providers to address these concerns and provide support to expectant mothers.

4. SYSTEM FOR MONITORING MATERNAL HEALTH AND WELL-BEING

Grettings! Breaking new ground in maternal health monitoring, we present our cut- ting-edge Internet of Things (IoT) system, meticulously crafted to provide a holistic picture of maternal well-being throughout pregnancy and postpartum.

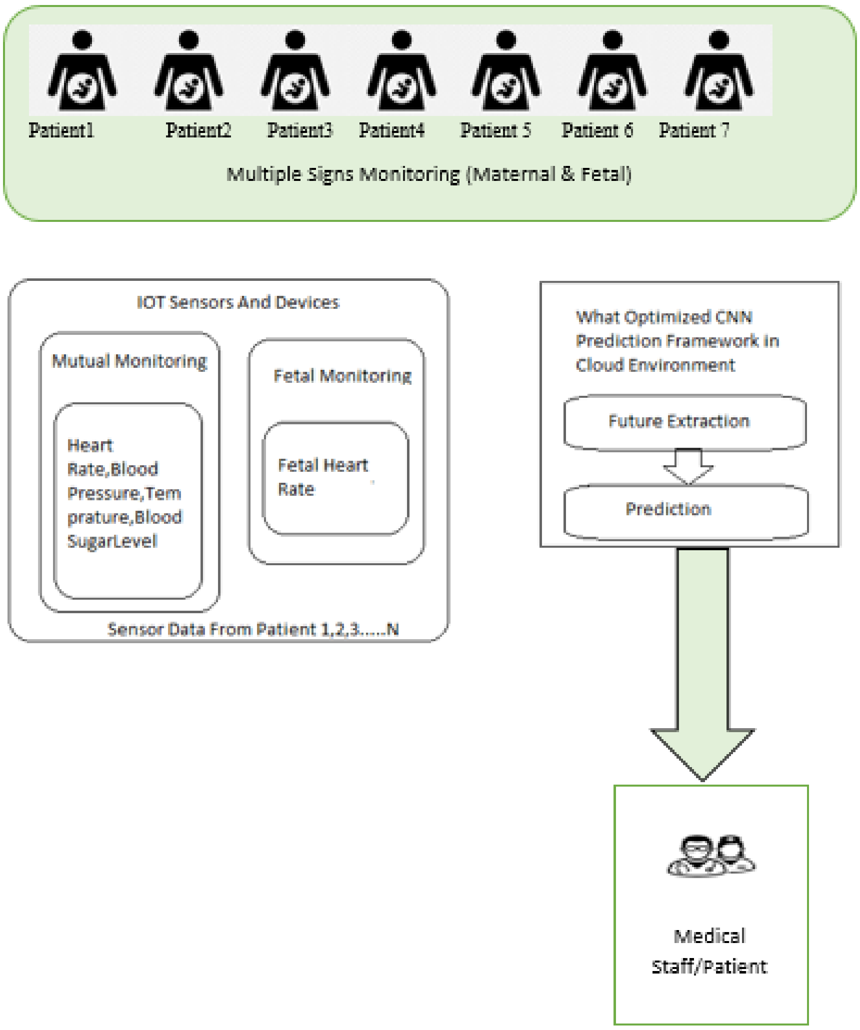


Fig 1. IoT-Enabled System for Monitoring the Health of Expectant Mothers.

As illustrated in Figure 1, our system seamlessly integrates both subjective and objec- tive data from mothers, empowering a comprehensive understanding of their health journey. To offer a brief overview, let's explore each layer.

4.1 Perception Layer

The perception layer plays a vital role in collecting physiological well-being infor- mation from pregnant women by utilizing a range of sensor types. These sensors may include wearable devices, such as smartwatches or fitness trackers, as well as other sensors capable of monitoring specific health parameters. The collected data from these sensors serve as input for the subsequent layers of the system.

4.2 Gateway layer:

The intermediary layer, alternatively referred to as the fog/edge layer, serves as a bridge connecting the perception layer and the cloud layer. Its pivotal function in- volves enabling a smooth transfer of sensor data to the cloud, facilitating advanced processing and analysis. To ensure the effectiveness of this process, the gateway layer employs edge computing techniques to conduct preliminary data filtration and pro- cessing before transmitting the data to the cloud.

4.3 Cloud Layer:

The cloud layer serves as the central storage and processing component of the sys- tem. It obtains data from the gateway layer and securely stores it in a scalable manner. Moreover, the cloud layer conducts data analysis, employing diverse algorithms and machine learning techniques to give meaningful insights from gathered data. These processed data can then be utilized for visualization, research purposes, and generat- ing personalized recommendations for pregnant women.

4.4 Application layer:

The application layer gives user-friendly interfaces and tools for both pregnant women and researchers. It visualizes the health information derived from the collect- ed data, enabling the users to monitor their own well-being and track their progress over time. The application layer also facilitates communication between the research- ers and the pregnant women, allowing for remote consultations and personalized guidance throughout the monitoring period.

In summary, the presented IoT-based system for maternal health monitoring incor- porates multiple layers to ensure continuous data collection, transmission, storage, analysis, and visualization. This all-encompassing strategy facilitates a complete comprehension of maternal health conditions. It encourages efficient communication between expectant mothers and the healthcare professionals or researchers overseeing their care, with information being provided to users at various intervals, such as daily or weekly. Furthermore, users have the capability to share diverse health- related de- tails, seek technical assistance related to the system, and connect with a qualified nurse or physician for any required support.

4.4.1 Periodic Monitoring with Portable Devices

To ensure accurate monitoring, it is necessary to utilize portable devices to meas- ure physiological parameters periodically. Some parameters, such as weight, undergo

gradual changes over time, while others, including blood pressure and blood glucose levels, require intermittent measurement due to the lack of a dependable non-invasive method [58,59]. These compact devices are employed to periodically assess such pa- rameters, and the captured values are either transmitted or manually inputted by users through the mobile application

4.4.2 Historical and demographic details

Our study hinges on a robust foundation—gathering essential background and de- mographic data like age, health history, and lifestyle choices. This detailed portrait of each mother unlocks the potential for insightful analysis and drives the development of actionable healthcare solutions throughout pregnancy and beyond. This data can aid in identifying any potential health risks during pregnancy and postpartum. Condi- tions like prior miscarriages or preterm births may elevate the likelihood of experienc- ing a preterm birth in subsequent pregnancies [60]. Personalization of pregnancy care is dependent on considering various factors that can increase the risk of complica- tions, including age, ethnicity, pre-pregnancy weight, diagnosed medical conditions, and lifestyle. These variables can be acquired through the mobile application or ac- cessed from hospital information systems, subject to the presence of appropriate agreements and consents.

4.5 Gateway Layer

The gateway element plays a crucial role as an essential intermediary, effectively connecting the perception layer with the cloud layer. Our system facilitates the secure and streamlined data transmission from the personal area network of the mother to the cloud server. Whether in the form of a router or smartphone, the gateway plays a vital role in ensuring secure and reliable communication. Advanced versions, like intelli- gent gateways, provide additional functionalities such as integrated data mining, lo- calized data analysis, data compression, and enhanced reliability and security features.

4.6 Cloud layer

The distant server constituting "the cloud" securely stores extensive health data and has the ability to employ big data analytics and M.L algorithms for the identification of patterns and anomalies within the data. Through personalized data analysis, pa- tients can receive tailored health monitoring and alarm notifications. Additionally, the cloud server can be integrated into a client-server setup, enabling caregivers and mothers to easily visualize the collected data.

4.7 Application layer

The application layer boasts user-friendly interfaces that seamlessly interact with the system. It encompasses both web and mobile applications that enable data moni-

toring and visualization across various platforms. These applications also facilitate effective communication between mothers and researchers. Healthcare providers can utilize a real-time monitoring dashboard to engage with mothers through the web ap- plication. Empowering mothers to be active partners in their healthcare, our cross- platform mobile app provides convenient access to their health data, fostering proac- tive self- management practices.

5. IMPLEMENTATION

In this segment, we present a thorough overview of the arrangement and delve into the intricate particulars of our case study, which revolves around an IoT-based system designed for effective access to maternal health.

5.1 Perception layer

Our implemented system adeptly integrates varied sources of data, encompassing a smart wristwatch, a multi-platform phone application, a B.P monitoring device, and comprehensive contextual info.

5.1.1 Wearable technology

For this study, the Samsung Gear Sport smartwatch [62] was chosen as the ideal wearable device. It offers access to raw data, ample built-in memory, configurable data collection, extended battery life, and waterproof capabilities. The smartwatch is equipped with one (IMU) as well as with one photoplethysmography sensor.

Tizen, an open-source operating system, powers the Gear Sport watch and allows for the creation of personalized smartwatch apps. The C programming language has been utilized to design data collection services that operate seamlessly without any user input. These services can be easily adapted to function on other smartwatches or wearables that run on Tizen OS, including the Samsung Galaxy, Active, and Active2 smartwatches.

In this study, Leveraging a battery-conscious approach (detailed in Section 6.3), we effectively monitor the photoplethysmogram (PPG) signal at regular intervals, ena- bling accurate extraction of heart rate variability (HRV) and heart rate parameters.

Moreover, we collect accelerometer data and daily activity information, like the num- ber of steps taken, to closely track the physical activity and sleep patterns of the sub- jects.An intuitive application has been developed to streamline data collection, allow- ing for effortless uploading to the server via Wi-Fi connectivity. Employing cutting- edge compression techniques, the data is optimized to reduce bandwidth consump- tion. It is strongly recommended that participants keep the device on and utilize the application frequently to ensure daily data uploads to the server.

5.1.2 Smartphone

A cutting-edge mobile application has been developed for smartphones that facilitates the collection of self-report data, which includes ecological assessments through vari- ous questionnaires. The app boasts an array of features such as health parameter mon- itoring, tech support request, background detail collection, reminders and push notifi- cations, and easy communication services for health- related concerns. It is a cross- platform application created using the state-of-the-art Angular 2 technology and the Cordova framework, both of which are open to use (anyone can use), and both are independent on platforms. The app ensures top-notch security through token-based authentication, and access is granted only to authenticated participants. In Figure 2, the app's interface is displayed.

5.1.3 Wearable technology for continuous health monitoring

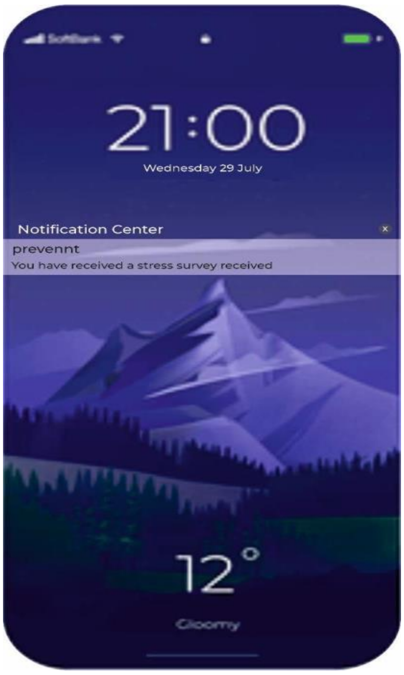
To initiate home blood pressure monitoring, participants were equipped with the clinically validated OMRON M3 Intelligence device [67]. They received instructions to self- measure at least once weekly, utilizing the user-friendly 360 accuracy feature for precise readings regardless of cuff placement [68]. Following the recording of measurements, participants can easily transmit the collected blood pressure data via the Smartphone app communicating with the server, as depicted in Figure 2c. This straightforward and uncomplicated process ensures that users can swiftly and effort- lessly acquire accurate blood pressure readings

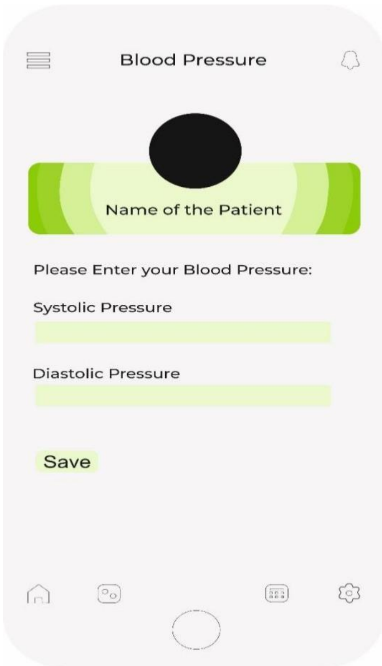
5.1.4 Historical and demographic details

The self-report questionnaire, available on multiple platforms, enables users to eas- ily submit their background information.

This structured questionnaire gathers exten- sive data on participants' medical backgrounds, including diagnosed conditions, preg- nancy experiences (miscarriages/preterm births), lifestyle habits, and subjective stress levels.

Main page





(b) Notification **(c) Blood Pressure**

Fig 2 Our monitoring system utilizes various interfaces within the cross-platform mo- bile application.

5.2 Gateway Layer

The monitoring system incorporates two separate gateway devices. Data from the smartphone application flows seamlessly to the server via internet connectivity, thanks to its client-server functionality. A dedicated Wi-Fi router further ensures un- interrupted data transmission from the smartwatches throughout the monitoring peri- od.

5.3 Cloud layer

We chose Apache 2 [69] with confidence as our open to use and cross-platform-web server for the server implementation, considering its reliability and robustness. Addi- tionally, we relied on Flask [70], an open to use Python WSGI framework known for its excellent scalability, flexibility, and support for rapid development. For data stor-

age, we confidently chose MongoDB [71], a NoSQL database, due to its exceptional ability to handle diverse data types. To ensure secure communication, we confidently leveraged an SSL API, which is a trusted and proven method.

The server's role in managing users, data, and analysis is absolutely crucial. User management, for instance, covers a range of tasks including creating new accounts, modifying existing information, assigning access levels, and allocating sets of ques- tions to users. Authorized users have the power to add, modify, or delete questions, as well as schedule notifications and reminders All data is securely stored on the server in an anonymous manner to prioritize user privacy.

Mothers can easily submit data to the data management module using the mobile ap- plication and wristbands. The system ensures accuracy through its authentication mechanism and data validity checks. In case of any errors, users receive notifications to re-upload the data. Rest assured, no personal information that could jeopardize user privacy is transmitted to the server. To access the data, authentication, and authoriza- tion are required, guaranteeing maximum security.

At the heart of our system lies the data analysis module, a comprehensive engine dissecting both subjective and objective data collected from mothers. Equipped with dedicated features for tracking stress, activity, and sleep, it meticulously peels back the layers of information, empowering exceptional monitoring of these crucial health aspects

The precise monitoring of stress levels in this system involves measuring heart rate variability (HRV) and heart rate parameters. Recent research indicates that parameters related to Heart Rate Variability (HRV) are strong indicators of changes in autonomic nervous system activity, directly associated with stress levels [72]. During mental stress, low-frequency (LF) power increases, while high-frequency (HF) power de- creases, and the LF/HF ratio significantly rises during psychological stress. SDNN (standard deviation of inter-beat intervals) reflects the body's ability to endure stress. Brief HRV assessments often reveal a decrease in RMSSD, AVNN, and LF/HF ratios during stress, accompanied by an increase in HF [72, 73]. Table 1 outlines the specific HRV parameters employed in the IoT system's stress monitoring, calculated from inter-beat intervals (IBI) extracted from the PPG signal. This analysis utilizes heart rate, computed as the number of heartbeats in the signal, and IBI, represented by the time between successive peak values.

Harnessing the combined power of hand movement and step count data from smart- watches, Our advanced sleep monitoring service delves deep into your slumber, me- ticulously using sophisticated algorithms for utmost accuracy. This data-driven ap- proach unlocks a nuanced understanding of sleep patterns, empowering both re- searchers and individuals to gain valuable insights. Utilizing this information, our system can precisely estimate the duration of total sleep time, evaluate sleep efficien- cy, and identify the duration of wakefulness after sleep onset. This ensures the provi- sion of precise and valuable insights into the quality of your sleep. The monitoring service accurately computes the daily sedentary time and physical activity by analyz- ing the step counts and covering time data collected from participants. This data of-

fers valuable insights into the activity levels of participants throughout the day, con- tributing to the assessment of their overall physical well-being. Figure 3: In this sec- tion, The graph illustrates the recorded data over time, facilitating visual analysis and observation of patterns in sleep and physical activity.

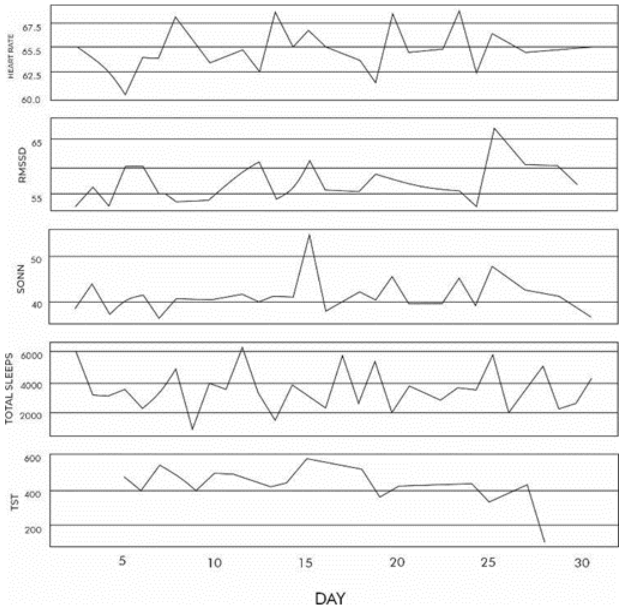


Fig 3. A sample of data was collected over a month from a single pregnant

In the domain of data analysis, a multitude of sophisticated AI and ML advanced al- gorithms are employed, enabling the execution of a broad spectrum of functions. in- cluding assessing data quality, detecting anomalies, identifying trends, and establish- ing personalized models [21, 30, 31]. Data is gathered during the mother's everyday activities, which include different physical activities. It should be noted that the data collected, particularly PPG, may be influenced by environmental noise and motion artefacts. Please rewrite the plagiarism-free content in your own words for a research paper. Leveraging the magic of machine learning, we unveil personalized models for each patient, empowering them to track evolving trends and predict potential changes throughout pregnancy and postpartum [21]. These dynamic models act as watchful companions, offering valuable insights into individual health journeys. Our compre- hensive data processing pipeline incorporates techniques suggested by the authors, including a deep learning-based evaluation for Photoplethysmogram (PPG) quality [30], M.L-based imputation for missing data [31], personalized modeling, and anoma- ly detection [21]. For further details, please refer to Figure 4.including a deep learn- ing-based evaluation for Photoplethysmogram (PPG) quality [30], M.L-based imputa- tion for missing data [31], personalized modeling, and anomaly detection [21]. For further details, please refer to Figure 4.

6. APPLICATION LAYER

We leveraged the power of Angular 2 to develop a highly efficient web application that allowed us to seamlessly reuse components from our mobile app. Our cutting- edge web application empowers researchers to effortlessly monitor and analyze col- lected data while keeping track of trends and changes over time through detailed daily and weekly plots. For a sneak peek of our web application's sleek and user- friendly interface, be sure to check out Figure 5.

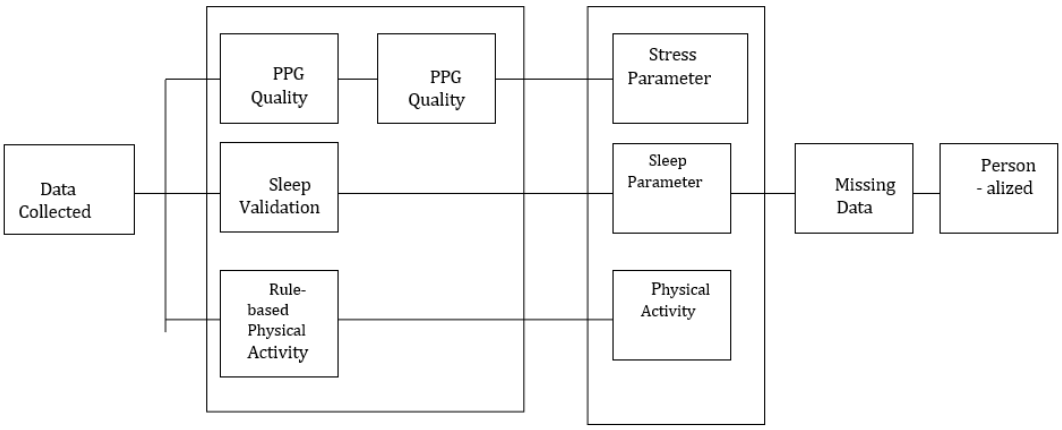


Fig 4. Data processing pipeline

Fig 5. An illustration of web application displaying the participant's deep sleep patterns.

7. EVALUATION AND DISCUSSION

Our study triumphantly demonstrates the feasibility of an IoT- based system for high- risk pregnancies, successfully monitoring a cohort of 35 women throughout their pregnancy and for 3 months postpartum. This system's feasibility, measurement relia- bility, and energy consumption were thoroughly assessed, revealing its potential, limi- tations, and practical challenges. Additionally, the researchers explored the system's compatibility with the existing healthcare system, further proving its value in improv- ing patient care.

Eligibility criteria were strictly adhered to the inclusion criteria for participants in- volved factors like age, gestational weeks, history of previous late miscarriage or pre- term birth, and proficiency in the Finnish language. Eligible participants, possessing either an Android or iOS smartphone, were directed to wear a smartwatch from the moment of enrollment until three months after giving birth. Researchers were con- tacted via email by interested participants.

The investigators organized a face-to-face session where they comprehensively eluci- dated the study protocols and acquired written consent from the volunteers. The par- ticipants received vital instruments, comprising a smart wristwatch and a blood pres- sure measuring device, along with a custom-designed mobile application installed on their smartphones. The study initially recruited 32 expectant mothers with high-risk pregnancies, but the final sample size included 35 pregnant women with a median gestational age of 13.4 weeks at the start of the monitoring period, as four participants withdrew during data collection.

7.1 Feasibility

Throughout our research, we thoroughly evaluated the practicality of implementing an IoT-based system over an extended duration of nine months. Simultaneously, we evaluated the user-friendliness of data collectors designed for participating mothers. We conducted a meticulous assessment of the average daily wearing time of the smartwatch to ascertain its feasibility during both pregnancy and the postpartum peri- od. Despite encountering challenges like six preterm births and one participant's work restrictions, we were able to gather valuable data from the participants. However, we did experience server failures that resulted in the unfortunate loss of data for twelve participants, lasting an average of four days.

Participants wore the smartwatch less on average during pregnancy, but most in- creased their wearing time in the weeks following childbirth. Regrettably, two partici- pants faced constraints in utilizing the device post-delivery, attributable to restrictions within the NICU. During the gestation phase, the mean daily wearing time was calcu- lated to be 17.01 ± 4.20 hours, which subsequently diminished to 13.72 ± 5.71 hours per day after childbirth.

Fig 6. To assess smartwatch adherence in high-risk pregnancies

Figure 6. To assess smartwatch adherence in high-risk pregnancies, we tracked usage patterns for 35 women throughout their pregnancy and postpartum journey, providing a comprehensive view of smartwatch integration across these critical stages.

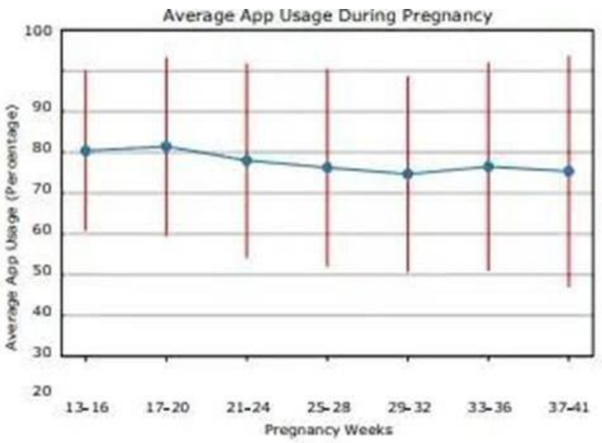
Building upon the findings of Grim et al. [6], who observed an average pregnancy- time smartwatch wearing time of 17.3 hours, our study with high-risk pregnancies yielded similar results with a slight decrease (average 17.0 hours). This minor distinc- tion might be quality to the higher likelihood of hospitalization among our partici-pants, potentially affecting their ability to wear the smartwatch consistently. Never- theless, our results affirm that data collection utilizing the smartwatch remains viable during both the pregnancy and postpartum periods.

7.2 Cross-platform mobile application usage

Beyond smartwatch adherence, we delved into participant engagement with our cross- platform mobile app, focusing on daily surveys and blood pressure monitoring. While Figure 7 reveals an intriguing pattern of app usage across pregnancy and postpartum, with an initial dip followed by a rise and then another decline, further investigation is needed to understand the driving factors behind this dynamic use. Throughout the study, participants contributed a total of 5,493 responses to daily questionnaires, comprising 3,879 responses during pregnancy and 1,614 responses during the post- partum period.

Throughout pregnancy, the application was consistently utilized to address daily in- quiries, with a remarkable average of 77.5% usage per day. Similarly, during the postpartum period, the application was utilized on an average of 57.0% of days, demonstrating its reliability and usefulness. Participants actively engaged with the mobile application, providing responses to the daily ques- tionnaires on a regular basis.

In regards to blood pressure measurements Figure 8 exhibits the mean count of meas- urements captured weekly by all subjects in our investigation. It's crucial to note that a participant with a history of preeclampsia, a pregnancy-related condition leading to high blood pressure, consistently recorded their blood pressure almost every day. Since this frequency of measurement was considered an outlier, we excluded this par- ticipant from the averaging process.



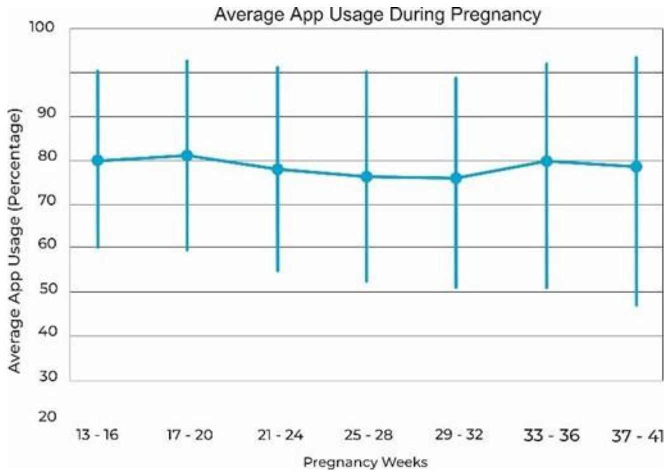


Fig 7. Average app use by 35 high-risk pregnant women.

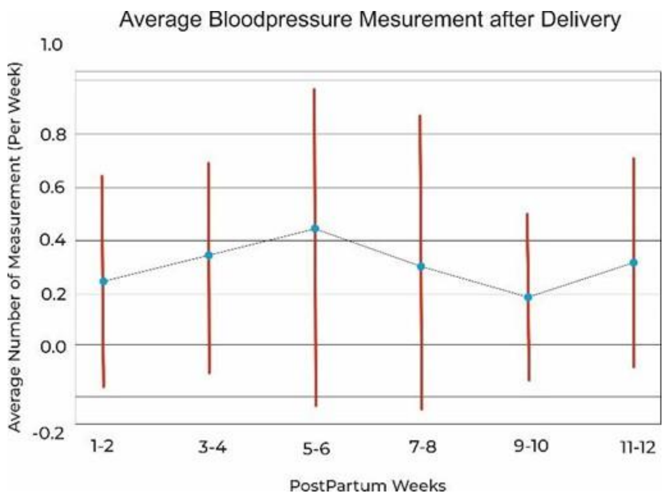


Fig 8. Weekly average blood pressure measurements for 35 pregnant women

Our study indicates that employing a mobile application for daily self-report ques- tionnaires during both pregnancy and the postpartum period is a viable and efficient approach to data collection. Our study found that participants consistently used the app, averaging 5.44 blood pressure measurements per week, aligning with previous research findings. As such, we believe that utilizing a mobile app for daily self-report questionnaires is a promising avenue for future research in this area.

Ensuring strong and dependable measurements is essential for remote monitoring systems to deliver precise and credible risk estimations. In our configuration, the ac- quisition of PPG signals from the wristbands is vulnerable to motion artifacts and environmental influences, which may result in low- quality signals and unreliable risk assessments. Maintaining consistently high signal quality is paramount, especially in the context of long-term monitoring systems.

The precision and dependability of heart rate and HRV measurements are notably influenced by the duration of recording PPG signals. While a 60-second window is adequate for obtaining an accurate heart rate, different standards are in place for HRV parameter measurements, ranging from 24-hour recordings to 5-minute recordings and even recordings less than five minutes. Due to constraints related to battery life in wearable devices, the feasibility of 24- hour recordings is limited. In our investiga- tion, we chose to conduct regular 5-minute recordings every two hours to guarantee a satisfactory number of high-quality signals for a dependable analysis of HRV parame- ters.

Ensuring dependable Heart Rate Variability (HRV) parameters linked to stress re- quires a higher sampling frequency for the Photoplethysmogram (PPG) signal. Accu- rate measurement of heart rate and HRV is highly dependent on sampling frequency. Recognizing this, we opted for a 20 Hz sampling rate for PPG signals in our system. This choice ensures precise HRV parameters, a critical aspect for accurately measur- ing stress levels.

When it comes to remote health monitoring systems, energy consumption plays a critical role, especially for devices that operate on limited battery power. In our case, the PPG method, which involves a light source and sensor, consumes a significant amount of energy. To determine the battery life of the smartwatch, we conducted tests that involved adjusting the duration and intervals of PPG signal col- lection. Our findings showed that a 15-minute interval resulted in a battery life of only 25 hours, while a 240-minute interval increased the battery life to 157 hours. After careful consideration of the results, we have determined that 2-hour intervals are the optimal choice for collecting PPG signals in our study. Our decision ensures that the smartwatch's battery can last for 2-3 days while continuously monitoring. It's im- portant to note that device usage and other functions of the smartwatch, such as Blue- tooth connectivity and physical activity applications, can further impact battery life. Nonetheless, our chosen battery life duration supports feasible long-term monitoring and enables effective data collection in everyday settings.

For obtaining reliable heart rate and HRV parameters, recording the PPG signal for an appropriate duration is essential. Various standards exist for measuring HRV parame- ters, including long-term recordings (24 hours), short- term recordings (5 minutes), and ultra-short-term recordings (less than 5 minutes).

To effectively monitor maternal health, it's essential to conduct 24-hour recordings to track heart rate changes in various conditions. However, wearable devices have lim- ited battery capacity, which makes continuous PPG signal collection challenging. This is because the sensing process, which involves the LED and photodetector, con- sumes a significant amount of energy, which can have a considerable impact on the battery life of the smartwatch. Despite this challenge, finding ways to optimize energy consumption in the sensing process can help improve the battery life of wearable de- vices used in maternal monitoring.

To ensure precise HRV parameters, we programmed the smartwatch to capture PPG signals every two hours for a duration of 14 minutes. This included 2 minutes for sen- sor calibration and two consecutive 5-minute recordings. This method eliminated low- quality signals and minimized the impact of noise and movement artifacts. Our con- sistent sampling frequency also ensured the collection of enough high-quality PPG signals for analysis.

The sampling frequency of the Photoplethysmogram (PPG) signal is crucial in influ- encing the accuracy and reliability of heart rate and heart rate variability (HRV) val- ues. To extract the cardiac frequency within the range of 0.5-3 Hz from the PPG sig- nal, one can confidently employ filter-based techniques.

7.3 ENERGY CONSUMPTION

Efficient energy management is of utmost importance for a remote health monitoring system that relies on devices with limited battery capacity. It is imperative to ensure that the battery-powered sensors in these devices are given meticulous attention to guarantee optimal functionality.

Continuous data collection and transmission in long-term monitoring systems can consume significant amounts of energy, which can impact the feasibility and usability of wearables due to limited battery life. Researchers have explored various energy efficiency methods in IoT-based systems to address this challenge.

The Photoplethysmogram (PPG) technique, utilizing a light source and sensor, is re- nowned for its high energy

consumption. Our system is influenced by three key factors that impact the smart- watch battery life, namely: (1) the duration of PPG signal collection, as discussed in Section 6.2.1; (2) the frequency of PPG signal sampling; and (3) the intervals of time between PPG signal collections.

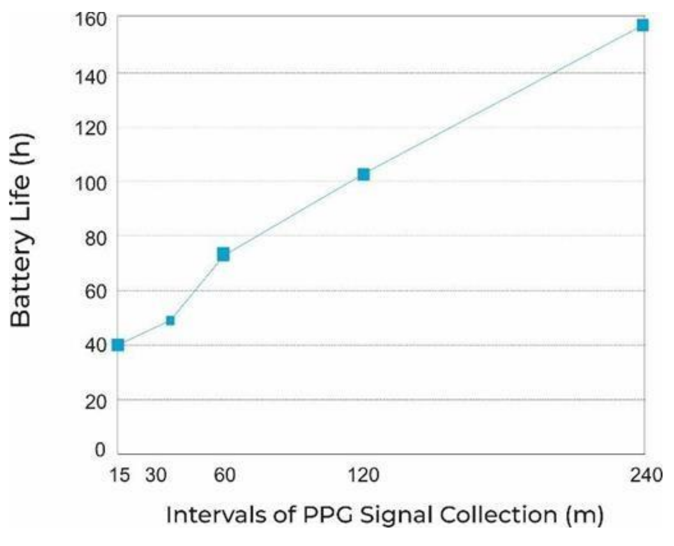


Fig 9. Watch Battery Life vs. PPG Measurement Intervals (14 Minutes Each) [29]

7.4 REAL-WORLD CHALLENGES

Overcoming practical and technical challenges is crucial for the success of long-term remote health monitoring. Implementing various strategies, including improving user experience and integration with emerging technologies, is essential to tackle these obstacles. Sustaining user motivation over an extended period emerges as a key chal- lenge in this context.

Nevertheless, considerable research indicates that factors such as social interaction, personalized monitoring, everyday usability, and thoughtful intervention design can improve user experience and motivate participants to consistently engage in monitor- ing [24, 84, 85].

Wearable devices within these systems must be user-friendly and comfortable for day-to-day use [24]. The system should also feature reliable monitoring functions and interfaces. Our team has carefully selected a wearable device that is highly convenient for both indoor and outdoor use. Through our system's monitoring services, we have seen effective improvements in the well-being of pregnant women (refer to Section 3). Our monitoring applications demand minimal involvement from participants, as the only requisite action is the manual uploading of data.

We provided technical support to the participants in case of any technical problems they encountered during the monitoring period. Additionally, As part of our imple- mentation, we developed a system to send notifications to participants who failed to upload their data for a duration of two weeks.However, in future iterations of the sys- tem, we aim to automate and enable real-time data uploading to enhance the user ex- perience.

An essential factor to consider is the level of effort users must exert in charging the wearable device. This aspect is elaborated on in Section 6.3, with a specific focus on optimizing user effort and data collection. It's worth noting that frequent device charg- ing can lead to increased instances of missing data, which can impact the reliability of the system.

Moreover, with the ongoing evolution of technology, it becomes imperative to inte- grate the system with newer technologies for enhanced adaptability. Built to evolve, our software utilizes cutting-edge technologies like RESTful APIs, Flask, Angular 2, and MongoDB, adhering to industry best practices. This strategic choice grants seam- less integration with future devices and technologies, ensuring our system's enduring relevance. For user convenience, the wearable device runs on Tizen OS, guaranteeing backward compatibility even with major software updates. Additionally, we devel- oped a dedicated app to restart all monitoring applications on the smartwatch, em- powering participants to troubleshoot potential issues with ease. Moreover, in our future initiatives, we plan to integrate the Valid API into our system to streamline the process of collecting data from a diverse array of coverable and accessing devices.

7.5 Integration to the current healthcare system

The current model heavily relies on physical in-person visits and assessments by healthcare providers. However, this innovative system has the potential to bring a new perspective to this traditional approach. By enabling pregnant women to monitor their own measurements, this system could enhance their engagement in self-care Incorpo- rating these novel components into the daily routine of maternity care professionals would necessitate a shift in their practices. It is essential to collaborate closely with them to ensure the successful implementation of this system. Earlier research has demonstrated a notable interest among both maternity care professionals and pregnant women in remote monitoring, particularly within specific cohorts of women.

It is important to assimilate the new remote monitoring system as part of the existing maternity care system to facilitate its implementation. The utilization of digital tech- nology to improve global health services is highly recommended by the World Health Organization (WHO). Developing nations have seen significant progress in maternal and child health services with the help of digital technology. As such, IoT systems are poised to revolutionize healthcare services across multiple countries.

In our implemented IoT-based system, the primary focus was on health monitoring without providing feedback to the mothers. We have ambitious plans to improve our system's capabilities by incorporating risk prediction and identifying potential health issues during both pregnancy and the postpartum period. Bridging the gap between research and clinical care, we actively explore integrating our collected data with ex- isting healthcare systems. By leveraging a RESTful API and presenting data in easily convertible JSON format, our applications pave the way for seamless exchange of critical health information with healthcare providers, potentially informing better clin- ical decision-making. We are optimistic about our ability to deliver data in HL7 for- mat, ensuring seamless integration with the clinical system in the foreseeable future.

8. CONCLUSIONS

Throughout pregnancy, prioritizing the well-being of both the mother and child is essential, as health complications can have enduring effects. Previous studies have largely utilized IoT- based frameworks for monitoring maternal health, but their focus has often been restricted to specific health conditions, abbreviated data collection methods, or reliance on self- reported surveys. Moving beyond existing approaches, our research unveils a game-changing IoT- powered maternal monitoring system. This pioneering system transcends traditional boundaries, offering uninterrupted surveillance of physical activity, sleep patterns, and stress levels throughout pregnancy and the postnatal period.

To assess the efficacy of our system, we conducted a study involving high-risk preg- nant women as real human subjects. The framework utilized a fusion of data acquisi- tion instruments, encompassing a smartphone application and an intelligent wrist- watch, to amass crucial biological indicators and self-reported information. The gath- ered data were securely stored in a cloud server and underwent meticulous analysis.

The effectiveness of the system was assessed by examining the utilization of both the smartwatch and the mobile application. As per our research outcomes, respondents employed the intelligent wristwatch for an average duration of 17.01 ± 4.20 hours per day throughout the gestational period and 13.72 ± 5.71 hours per day in the postnatal phase. Additionally, the smartphone application was used to respond to daily inquiries on 77.5% of the days during pregnancy and 58.0% of the days during the postpartum interval. These findings clearly indicate that the system was easily accessible to users and demonstrated satisfactory user interaction.

Our assessment of the smartwatch system has demonstrated its remarkable energy efficiency and data reliability. The prolonged monitoring system has shown reasona- ble energy consumption, while the photo plethysmography (PPG) based analysis has confirmed its reliability. Our investigation into the combination of the system with the current healthcare infrastructure has revealed several insights that we plan to leverage in our future work. Our aim is to optimize energy utilization and enhance system de- pendability through the implementation of an adaptive data- gathering approach that takes into account the user's physical activity, health status, and stress level. Further- more, we intend to expand the monitoring system to include dietary and preeclampsia monitoring, as well as feedback provision. Breaking down data silos, our next step is crafting powerful APIs. These interfaces will unlock seamless integration with diverse wearable devices and pave the way for open communication with clinical healthcare systems, fostering collaboration and empowering future research and personalized care. Additionally, we recognize the significance of assessing attributes like latency and availability concerning real-time services or interventions, constituting a crucial aspect of our forthcoming endeavors.

Furthermore, we acknowledge the need for future research to assess factors such as response time and accessibility associated with real-time services or interventions.

INFORMED CONSENT STATEMENT: Every participant involved in the study pro- vided informed consent before their participation.

DATA AVAILABILITY STATEMENT: Data Sharing is not relevant or applicable in this context.

CONFLICTS OF INTEREST: No competing interests were disclosed by the authors.

The conduct of this research was independent of any financial influence. The authors maintained complete control over all aspects of the research, including design, data collection and analysis, interpreta- tion, and publication decisions.

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