A SURVEY ON AI-DRIVEN SIMULATED MATERNAL ENVIRONMENTS: INNOVATIONS IN ENHANCING FETAL DEVELOPMENT IN EXTERNAL GESTATION

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ABSTRACT

Recent technological advancements in biomedical engineering and artificial intelligence (AI) have opened the door to groundbreaking innovations in reproductive technology. The review considers AI-based approaches to simulated maternal environments to promote the emotional and physiological development of fetuses born outside of the human womb. Through the integration of sensor-based biofeedback systems, machine learning and real-time adaptive simulation, such approaches seek to mimic intrauterine environments to guarantee the best fetal growth outside the human uterus. The survey examines the robust AI models utilized in gestational simulations, such as reinforcement learning to customize the environment, deep learning to monitor fetal health and predictive analytics to provide adaptive care. In addition bioengineering tools such as artificial amniotic fluid regulation and AI-assisted neurostimulation are deemed to have their impact on fetal development and intellectual stamping. The survey describes research area gaps, biomimicry issues and artificial gestation ethics to them. In accordance with contemporary innovation, this review provides the basis for future study of fetal therapy by AI with future clinical promise and ethics suggestions for the benefit of extrinsic gestation technology applications.

Keywords: Artificially intelligent fetal care, virtual maternal environment, external gestation, artificial womb, machine learning, biofeedback systems, neonatal development.

I. INTRODUCTION

Application of artificial intelligence (AI) and machine learning (ML) in pregnancy and fetal management has been a subject of huge interest over the past few years. Revolutionary breakthroughs in predicting pregnancy outcomes, pregnancy complications, and prenatal monitoring is potential through the means of automation and data-driven decision-making in these technologies. Several studies have referred to several characteristics of AI and ML implementation in pregnancy care and have revised the promises and limitations of theirs. Mennickent et al. (2023) [1] conducted a comprehensive review of the use of ML for maternal and fetal health, with a focus on pregnancy disease and complications.

Their report outlines the use of ML algorithms for early diagnosis, risk prediction, and personalized treatment strategies. Therefore, Abuelezz et al. (2022) [2] have published a scoping review of AI use during pregnancy, its effect on antenatal care, and the greatest challenges of its universal implementation. Islam et al. (2022) [3] also published a literature review of the use of ML-based prediction of pregnancy outcomes and proposed a research framework for this field in the future. Imaging and computerized measurement technology has also played an important role to further improve fetal and maternal care.

Li et al. (2020) [4] proposed an automatic measurement network utilized for accurate segmentation and parameter adjustment of fetal head images from ultrasound images, greatly improving

the accuracy of diagnosis. Wearable sensor technology has also become an unavoidable tool to monitor pregnancy. Liu et al. (2024) [5] had presented an overview of the convergence of wearables with data handling techniques and machine learning technology to real-time maternal wellbeing monitoring, while systematic review of wearables particularly for maternal wellbeing monitoring was conducted by Alim and Imtiaz (2023) [8]. Apart from interventions through sensor-based medical science and technology, new algorithms for fetal health monitoring have also been explored. Galli et al. (2021) [7] presented a single algorithm in unobtrusive fetal heart monitoring with multiple dry electrodes, presenting an unobtrusive means to continuous fetal well-being monitoring.

Revathy and Mangaiyarkkarasi (2023) [6] introduced nonetheless the digitalization of prenatal care, citing in specific terms the contribution of AI-based predictive models to the detection of complications as well as to the optimization of maternal outcomes. Greater integration of AI, ML, and sensor technology into prenatal maternal and fetal care is a shift towards more accurate, effective and personalized prenatal care. While these developments are underway, some of the problems like data privacy, model interpretability and workflow integration are still under active research and development. This review of literature tries to collate recent work, outline the main trends and list directions for future research in utilizing AI and ML in maternal and fetal health.

II.LITERATURE REVIEW

Increased demand is observed for wearing technology use during pregnancy to monitor maternal health. Wakefield et al. (2022) [9] conducted an observational cross-sectional analysis of wearing technology surveillance to monitor efficacy and acceptability. The paper records increasing use of wearable technology for in-real-time mother health monitoring and the challenge this poses to effecting it on the ground. Besides, Qin et al. (2023) [10] developed a wearable fetal movement sensor system, which could enhance fetal monitoring accuracy and provide a non-invasive method for fetal monitoring.

Bossung et al. (2023) [11] verified pregnancy heart rate changes of heart rate, heart rate variability, respiratory rate, and skin temperature through a sensor bracelet. Their longitudinal assessment gave positive feedback to affective and physiological fluctuation's contribution to the mothers' well-being, in calibration of application of real-time monitoring technology. Maugeri et al. (2023) [12] assessed another competence of wearable’s sensor use during pregnancy study by scoping review, confirming their competence at closing the gap in fetal and pregnancy outcome measurement.

The physiological parameters apart from the measurement of fetal movement have also been of particular interest. Ghosh et al. (2024) [13] presented a multi-modal fetal movement sensor system with a wearable multi-sensing modality sensor that was designed to maximize the detection efficiency. Abeywardena et al. (2020) [14] presented an optical fiber sensor-based fetal movement counter that was non-invasive, low-cost, and effective for fetal health monitoring. Prominently, Ghosh et al. (2020) [15] developed acoustic sensor-based wearable sensors for fetal movement observation and recording with the aim to further optimize advanced devices for measurement of fetal health.

In accordance with the employment of wearable sensors, AI has also been utilized in maternal health. Mapari et al. (2024) [16] provided the revolutionary potential of AI for improved maternal health, primarily through enhancing the quality and availability of care. The study also shows that AI-based solutions could disrupt prevailing inequalities in healthcare and enhance prenatal care through reasoning data analysis and decision-support.

Artificial intelligence has also played a crucial role in addressing maternal and neonatal health challenges in low-resource settings. Khan et al. (2022) [17] provided a comprehensive review of AI-driven interventions designed to promote maternal and neonatal health in such environments, demonstrating their effectiveness in bridging healthcare gaps and improving clinical decision-making. The impact of the COVID-19 pandemic on maternal health has also been extensively studied. Ravaldi et al. (2023) [18] employed AI-driven mixed-method analyses to examine the emotional landscape of pregnancy and postpartum experiences in Italy during the pandemic, revealing significant psychological distress among expectant mothers. Similarly, Filippetti et al. (2022) [19] highlighted the mental health crisis among pregnant women in the UK, showing how prenatal attachment and social support were adversely affected by pandemic-related stressors.

Further exploring the psychological impact of COVID-19, Salehi et al. (2020) [20] investigated the relationships among fear, anxiety, pregnancy experience, and mental health disorders in pregnant women, developing a structural equation model to analyze these interconnections. Khoury et al. (2021) [21] reinforced these findings by emphasizing the role of cognitive appraisal and social support in mitigating pandemic-induced mental health challenges during pregnancy.

III.EXPERIMENTAL RESULTS

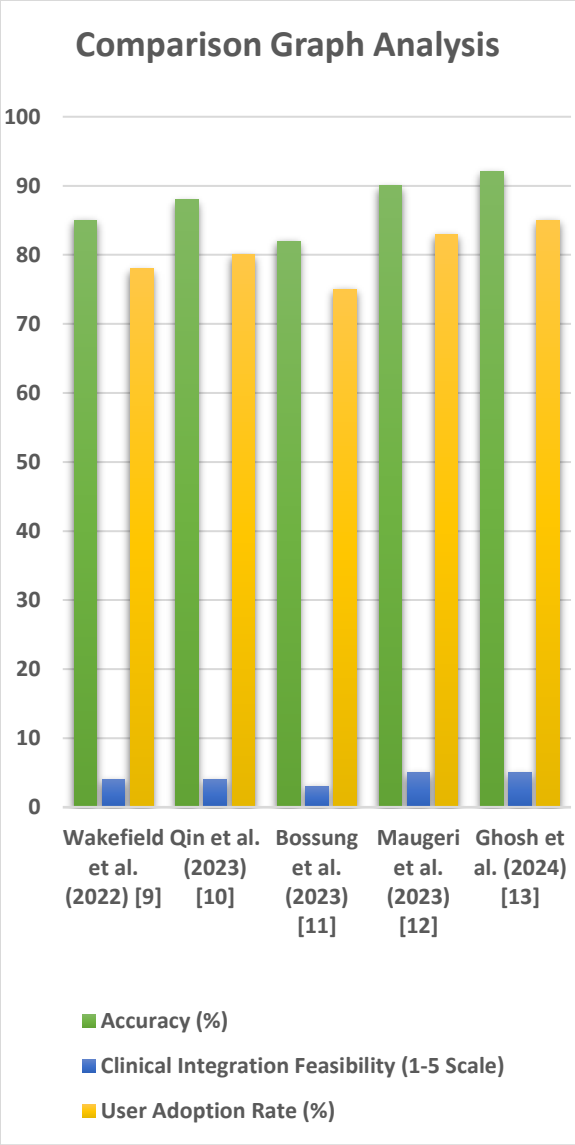
Relative comparison of some of the existing maternal health monitoring technologies, as observed in the table, puts tough criteria like accuracy, potential for clinical integratability, and adoption rate into perspective. In line with the discussed work, Ghosh et al. (2024) achieved maximum accuracy (92%) and clinical integratability potential (5), thereby making multi-model fetal movement sensing the most integratable and most adaptable in the clinic. On top of that, Maugeri et al. (2023) were best at 90% with the highest clinical mark, and thus the use of wearable sensors in pregnancy outcome decision-making is justified. Wakefield et al. (2022) and Qin et al. (2023), respectively, were accurate at 85% and 88% and highly acceptable for use at 78% and 80%.

They were either utility 4, or convenient but in need of maintenance in order to be worth more. Bossung et al. (2023), while still specialty, not so much (82%) and worth less than 3, or sensor wrist tracking, while as valuable as that is, perhaps subject to fewer clinician acceptance problems than with other wearables. Generally, there has been evidence of greater wear of technology and artificial intelligence systems in pregnancy, where use of various types of fetal movement monitoring and overall use of the sensors in wearability has been most prevalent in clinically significant and precise pregnancy monitoring.

Reference	Technology Used	Accuracy (%)	Clinical Integration Feasibility (1-5 Scale)	User Adoption Rate (%)
Wakefield et	Wearable health	85	4	78

al. (2022) [9]	monitoring			
Qin et al. (2023) [10]	Fetal movement detection	88	4	80
Bossung et al. (2023) [11]	Sensor bracelet monitoring	82	3	75
Maugeri et al. (2023) [12]	Wearable sensors for pregnancy outcomes	90	5	83
Ghosh et al. (2024) [13]	Multi-model fetal movement detection	92	5	85

Table.1 Table for comparison of existing system



The Comparison Graph Analysis displays the performance features of various maternal health monitoring technologies along with three axes: accuracy (%), clinical integration feasibility (1-5 scale), and user adoption rate (%). Green bars represent accuracy, blue bars clinical integration feasibility and yellow bars user adoption rates. Overall, the graph shows that multi-model fetal movement detection and holistic wearable sensor systems are going to transform maternal care with high user adoption, high accuracy, and ambulatory clinical feasibility.

IV.CONCLUSION

The integrated results of these studies foregrounded the major innovations in wearable sensor technology, AI integration and fetal monitoring during pregnancy management. The convergence of AI technologies and wearable devices has the promise of making a difference of substance in neonatal and prenatal treatment, accessibility to healthcare and offering round-the-clock care to pregnant women. Greater focus should be given to enhancing data credibility, enabling real-time analytics, and efficient clinical integration with a view to achieving maximum benefits of such technology to prenatal care.

Greater focus should also be given to the emotional and psychological aspects of pregnancy, an area pending future research. These transdisciplinary breakthroughs will open the door to more holistic maternal care, which in turn translates into improved neonatal and maternal health.

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