ϕ-Fetus: A Phantom In-utero Fetus for Fetal Heart Simulation

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***Abstract*—Bench-top performance evaluation of novel continuous fetal heart monitoring sensors that utilizes surface mechanical vibrations is hampered by the absence of a physical phantom that is able to simulate fetal heartbeat realistically in the frequency and amplitude domains. In this work, we present the design of ϕ-Fetus, a phantom in-utero fetus built with a medical gel and interchangeable actuators. The medical gel was molded for a shape and size that match the maternal abdominal dimensions. Under the square wave excitation of the speaker actuator at 2-2.8 Hz, the phantom delivers accurate and consistent surface vibration responses, as recorded by an accelerometer, validating its precision in frequency control. By pumping the balloon with specific initial volume and pumping volume that correlates to respective cardiac volume and stroke volume of the fetus from 20 to 40 weeks of gestation, the phantom delivers peak accelerations that matches actual data points through interpolation, thus validating its realistic simulation of fetal heartbeat. These results demonstrate that the phantom is able to provide a tunable, repeatable, and physiologically relevant platform for testing and benchmarking of novel fetal heart monitoring sensors, and enables quantitative validation of wearable sensors applicable to future prenatal sensing research.**

***Index Terms*—fetal monitoring, phantom, sensor validation**

I. Introduction

Portable, continuous heart rate sensors have advanced considerably over the years, but most systems rely either on bioelectric signals like electrocardiography (ECG) [1, 2, 3, 4] or optical signals like photoplethysmogram (PPG) [5, 6]. Mechanical modalitites such as ballistocardiogram (BCG) and seismocardiogram (SCG) have also demonstrated their efficacy in heart rate detection [7], but their current applications are limited to adult subjects, with their potential for in-utero fetal monitoring unexplored. Therefore, adapting these novel mechanical sensing techniques for continuous fetal heart-rate monitoring would fill this gap and improve prenatal care.

However, access to physiological signals from protected populations, such as pregnant women, poses significant challenges due to ethical and logistical constraints on data collection. Medical phantoms are often employed to simulate these signals, yet dedicated phantoms for pregnancy and fetal monitoring are still rare. Of the few existing solutions, most are numerical models without any physical embodiment [8, 9]. The limited physical phantoms have been designed primarily for MRI or ultrasound applications, so most of them do not reproduce mechanical motions[10, 11], and the remaining ones that generate motion are typically not meant for quantitative analysis of mechanical waves. For example, Yahya et al. developed a dynamic optical phantom with artificial blood pumping to study fetal blood oxygen saturation changes [12], and Laqua et al. created pulsating vessel phantoms for oximetry research [13]. Rathbun and Zweig's low-cost fetal heart phantom, constructed from a balloon and a toy fish, produces mechanical vibrations to be measured by an ultrasound sensor, but is intended solely for ultrasound skill training and therefore does not require precise motion control, resulting in a mechanism that lacks rigorous regulation of the signal output [14].

To address this gap, we developed ϕ-Fetus, a physical phantom in-utero fetus with interchangeable actuators to produce highly controllable, tunable mechanical waves that match fetal heartbeat amplitudes and frequencies at different gestational stages. Because no published data quantify surface vibration levels on the maternal abdomen caused by fetal heartbeat, we validated the phantom's output by interpolating amplitudes from studies on adult heartbeats. This novel platform provides a standardized, adjustable, and fully quantifiable testbed for evaluating the accuracy, sensitivity, and dynamic range of emerging fetal-monitoring sensors.

II. Methods

The ϕ-Fetus system setup is shown in Figure 1. The phantom consists of an enclosure that simulates a pregnant womb and interchangeable mechanisms that generate mechanical waves to mimic the fetal heartbeat. To simulate the abdominal conditions during pregnancy, the enclosure was molded using Humimic Gel as shown in Fig. 2 A, which is designed to simulate human tissue for medical device testing and design. The material and acoustic properties of gel #0, the model used in our experiments, can be found in table II. The enclosure is molded in a bowl shape, with the thickness at the center being 9.1 mm and the thickness at the edge being 21.2 mm, which conforms to the maternal abdominal dimensions across stages of pregnancy [15, 16]. The gel-filled phantom was sealed with water inside to mimic the amniotic fluid and provide realistic internal damping, and the actuator was embedded within the abdominal region to generate low-frequency pulsations representative of fetal heartbeat activity. The phantom uses two actuator choices to simulate fetal heartbeat: 1) a speaker

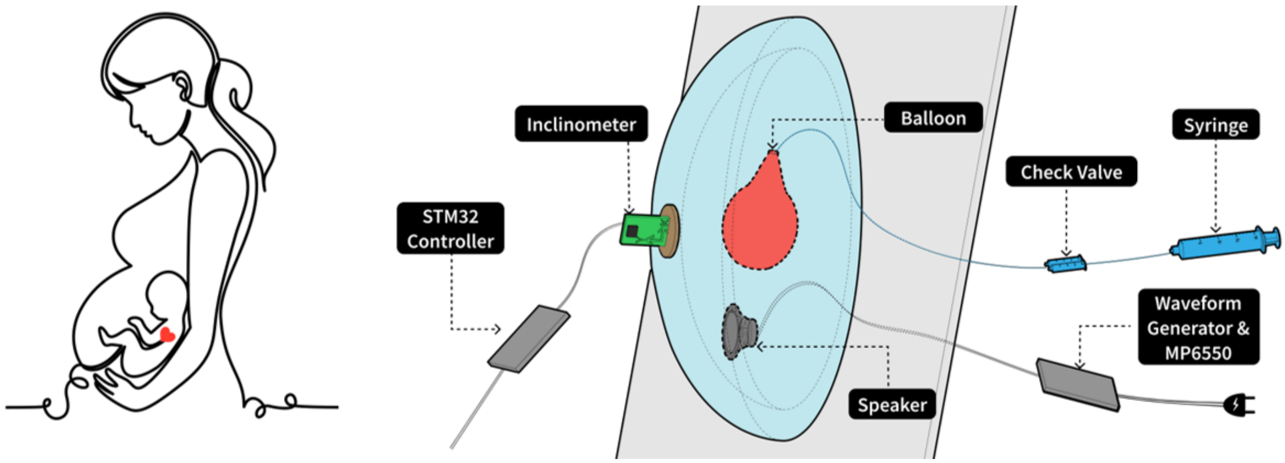

Fig. 1. Overview of the proposed ϕ-Fetus

driven by a waveform generator for precise and programmable frequency control of the vibration, and 2) a syringe-driven balloon that generates realistic vibration amplitude across 20 to 40 weeks of gestation.

The speaker (Visaton GmbH & Co. KG model: BF 32 S WP - 8 Ohm), as shwon in Fig. 2 B, was driven by an H-Bridge motor driver with voltage-controlled power (Pololu model: MP6550)[17], powered by a desktop power supply, and controlled by a signal generator. Square waves of 2Hz with a 67% onset ratio were triggered to simulate heartbeat patterns. The purpose of using a speaker is to generate a repeatable signal for sensor frequency characterization.

On the other hand, the balloon was fixed on the tip of a tube, which is split into two parallel paths with two one-way check valves in opposite directions, as shown in Fig. 2 C. The tubes are coupled back together on the other side of the check valve and connected to a syringe. The check-valve system enables two-way flow control similar to a human heart. The balloon is filled with a pre-determined volume of water to simulate the fetal heart inside the womb, and heartbeats were simulated by manually pumping a set amount of water in and out with a specific frequency. Syringes were modified with stops to facilitate accurate control of the pumping volume. The initial volume filled inside the balloon corresponds to the cardiac volume and the volume of water being pumped inside the balloon each time corresponds to the stroke volume of the heart for a specific gestation week. Specific initial balloon volumes and corresponding pumping volumes are calculated and estimated from [18, 19, 20] and listed in Table I. The purpose of using a balloon is to simulate different vibration magnitude of fetal heart sizes across the stages of pregnancy.

The generated signal can be collected using multiple sensors simultaneously or independently. We characterized the phantom to ensure the efficacy of the phantom, specifically that our fetal heart actuators' mechanical properties were within the range of a human fetus in the womb. Phantom validation data for both actuators was collected by placing a high-sensitivity 2D inclinometer, STMicroelectronics IIS2ICLX (0.122 mG/LSB,$\pm 500 mG$ range,$15\mu G/\sqrt{Hz}$ noise) [21], onto the surface of the phantom and recording the acceleration in the direction normal to the phantom surface, as shown in Fig. 1 and Fig. 2 D. Two experiments were conducted to validate the actuators. To test the frequency consistency of the heartbeat-like signal produced by the phantom, we used the speaker actuator powered in constant voltage mode at 5V and controlled with a square wave with 33% onset to simulate the heartbeat contraction cycles. We also tested the balloon

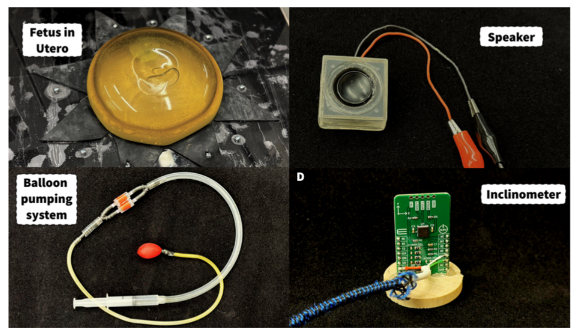

Fig. 2. Individual components used to build the ϕ-Fetus

TABLE I
BALLOON SIZE CORRESPONDENCE TO PREGNANCY STAGES (VOLUMES GREATER THAN 1ML ARE ROUNDED TO THE NEAREST ML DUE TO SYRINGE CONSTRAINTS)

pregnancy stage (weeks)	initial balloon volume (mL)	pump volume (mL)
20	4	0.5
26	10	2
30	15	3
34	26	4
40	38	10

TABLE II
MATERIAL AND ACOUSTIC PROPERTIES OF THE PHANTOM

Young's Modulus	Firmness	Density	Needle Resistance
0.57 MPa	686 g	945.284 Kg/m^3	0.92 N
Speed of Sound	Acoustic Impedance	Acoustic Attenuation	Efficiency
1449.30 $\pm$ 3.37 m/s	1.37 $\pm$ 0.002	α: 0.223 $\pm$ 0.002	η: 1.7 $\pm$ 0.04

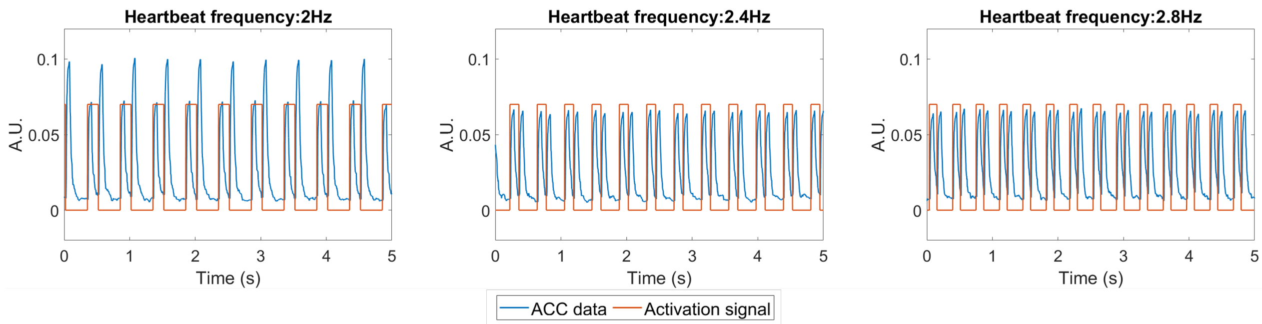

Fig. 3. Change of accelerometer data obtained from the phantom generated by the speaker playing square waves from 2Hz to 2.8Hz

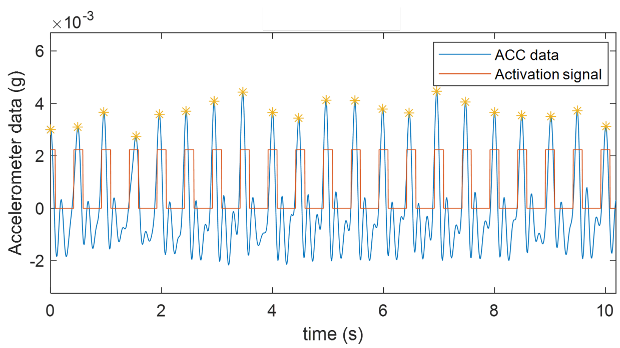

Fig. 4. Acceleration obtained from the phantom generated by the balloon with volumes corresponds to 40 week of pregnancy pumping at 2 Hz

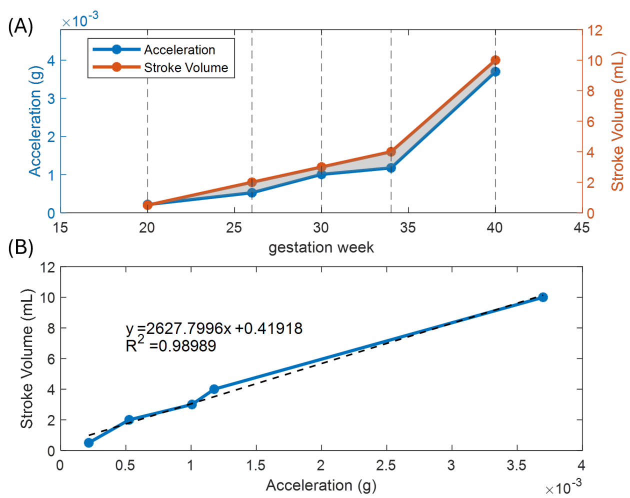

Fig. 5. Acceleration obtained from the phantom generated by the balloon pumping at 2 Hz

actuator's conformation of vibration magnitude with actual fetal heartbeats, during which the balloon and the syringe are filled with water of specific volumes according to Table I and pumped manually at 2Hz. All data were processed in MATLAB (R2024b, MathWorks, Natick, MA).

III. Results and Discussion

The speaker actuation experiment results, presented in Fig. 3, show that the accelerometer was able to detect synchronized surface accelerations caused by each speaker-simulated heartbeat in the range of 2-2.8 Hz, which corresponds to 120-168 beats per minute, covering the nominal fetal heart rate range. It can be seen that for each heartbeat cycle of the speaker, two acceleration extrema were produced, one at the rising edge and the other at the falling edge, and data for each simulated heartbeat resembled a ”W” shape. The consistent match between the speaker output and the sensor response confirms the phantom's ability to reliably generate and transmit specific vibration frequencies, validating the use of this phantom to quantify the frequency-related response of the sensors for fetal heart monitoring.

A sample acceleration curve obtained from the phantom using the balloon actuator is shown in Fig. 4. The peaks have an average maximum acceleration of 3.7 mg and a standard deviation of 0.4 mg, indicating that the balloon actuator can produce consistent responses in amplitude. The ”W” shape of the signal is also more prominent because the pumping displacement is not instantaneous and has a smoother curve.

Acceleration response across balloon actuators that represent different gestation weeks is shown in Fig. 5 (A). It shows that across the gestation weeks, the increase of maximum surface acceleration from heartbeats is consistent with the increase of stroke volume. Fig. 5 (B) plots the direct relationship between the maximum acceleration and the stroke volume, and shows that the relationship is proportional ($R^2 = 0.99$). We were not able to find any dataset that measures absolute surface acceleration from fetal heartbeats, so a direct validation is not possible. The closest data available was from an adult who has an 88mL stroke volume and measured surface acceleration of 0.045 g [22]. The predicted acceleration would be 0.033 g based on our fitted model, which is reasonably close given the difference between adult and fetal anatomies as well as the simulation nature of the phantom. Thus, we argue that it is appropriate to use our phantom signal to quantify the magnitude-related response of the fetal heart monitoring sensors and systems.

Together, these experiments show that our phantom can provide precise frequency control and realistic amplitude ranges, thereby providing a robust and reproducible platform for subsequent sensor validation.

Although the phantom meets our basic validation goals, several limitations remain. For example, we accepted coarse tolerances for ease of fabrication. Specifically, the cardiac volume and stroke volume were rounded to the nearest milliliter due to the constraints of the syringes. Additionally, while the speaker actuator provided an accurate frequency signal, the high-frequency components of the rectangular wave output also introduced noise to the recorded data. Furthermore, the abdomen anatomy was also simplified with one single Humimic Gel layer, whereas a multilayer construction that separately models skin, fat tissue, abdominal muscle, and uterine wall would better model the inference of signal from fetal heart to abdominal surface. In addition, the balloon actuator needs to be pumped manually because the syringe pumps we tested cannot start and stop fluid flow fast enough to generate a waveform around 2 Hz, but there may still exist alternative automatic apparatuses to fulfill this requirement.

Beyond addressing the current limitations, there are also additional directions for future exploration. One would be to explore a simple and accurate controlling mechanism of the actuator location to represent different fetal positions. Additional choices of actuators could also be developed to simulate episodic fetal motions like kicks and stretches. Different enclosure materials could also be explored for a variety of sensor mechanisms.

IV. Conclusion

In this work, we presented ϕ-Fetus, a phantom in-utero fetus to simulate the fetal heartbeat across different stages of pregnancy. Through measuring surface acceleration from two different actuators, we were able to show that the phantom is able to produce precise and realistic surface vibration data for preliminary testing of appropriate sensors.

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