International Journal of Internet, Broadcasting and Communication Vol.16 No.4 273-281 (2024)
http://dx.doi.org/10.7236/IJIBC.2024.16.4.273

IJIBC 24-4-31

Development of Cam Pulsation Simulator for Generating Radial Pulse Waveforms across All Age Groups

Yong-Jun Lee[1], Jun-Hyeok Lee[2], Jin-Ho Choi[1], Min-Seo Jung[2], Young-Min Kim[3], Tae-Heon Yang[4], Dongbum Pyo[5,*]

[1]Master's Course, Department of Mechanical Engineering, Konkuk University, Korea
[2]Bachelor's Course, Department of Mechanical Engineering, Konkuk University, Korea
[3]Principle Researcher, Digital Health Research Division, Korea Institute of Oriental Medicine, Korea
[4] Associate Professor, Department of Mechanical Engineering, Konkuk University, Korea
[5,]Senior Researcher, Human-Centric Robotics R&D Department, Korea Institute of Industrial Technology, Korea*

bark2031@konkuk.ac.kr, wnsgur5310@konkuk.ac.kr, cjin4872@konkuk.ac.kr, marcuss@konkuk.ac.kr, irobo77@kiom.re.kr, thyang@konkuk.ac.kr, pyodb@kitech.re.kr

Abstract

The development of a radial pulse simulator is pivotal for advancing wearable medical devices and enhancing pulse diagnosis methods prevalent in Oriental medicine. Such a simulator can be utilized for the calibration of wrist-worn wearable device sensors, as well as for training medical professionals in pulse diagnosis. This study introduces a novel, simple, and cost-effective pulse simulator that can generate a wide range of blood pressure waveforms. This simulator was designed and constructed as a prototype pulse simulator using two precision solenoid valves, an air chamber, a Half-CAM, a pneumatic sensor, and electronic control systems. By regulating air pressure through controlled opening and closing of the solenoid valve, the simulator can produce the desired pulse waveform. The performance of the proposed simulator was evaluated by replicating age-related radial pulses. Pulse waveforms generated by the simulator for four representative age groups (10, 50, 60, and 90 years) were compared with corresponding in vivo data. The experimental results demonstrated that the RMSE (Root Mean Square Error) estimate between the simulated in vivo pulse data and the actual in vivo pulse data was within 10% in all age groups. These findings demonstrate that fine pneumatic control by a solenoid valve allows the generation of sophisticated waveforms and validate that the proposed pulse simulator is capable of generating a diverse range of pulse waveforms.

Keywords: *radial pulses, pulse generation, pulse simulation, pulse waveform, solenoid valve.*

Manuscript Received: October. 4, 2024 / Revised: October. 10, 2024 / Accepted: October. 15, 2024
Corresponding Author: pyodb@kitech.re.kr
Tel: +82-31-8040-6725, Fax: +82-31-8040-6380
Senior Researcher, Human-Centric Robotics R&D Department, Korea Institute of Industrial Technology, Korea

1. Introduction

The radial pulse, measured at the distal part of the wrist, provides crucial health information. The radial pulse is represented as the sum of one forward wave (P_f) and two reflected waves ($P_{r1,2}$), and it has been widely utilized in Oriental medicine to monitor biological signals and diagnose internal health conditions [1,2]. For thousands of years, the primary method for diagnosing diseases was the palpation of the radial pulse measured with three fingers [3-5]. In Western medicine, radial pulse pressure is also used as a surrogate marker for arterial compliance and cardiovascular diseases [6]. Additionally, the quality of radial pulses is used as a rapid assessment method in tactical combat casualty care to determine the priority of casualty treatment on the battlefield [7]. These varied applications underscore the importance of accurate radial pulse measurement. Unfortunately, the techniques for palpating and diagnosing the radial pulse in the wrist are subjective, and consistent measurement requires extensive practice and training over a long period of time.

In parallel, wearable technology has seen considerable growth in recent years. These non-invasive devices can be worn without burdening the patient's body while providing feedback on biophysical and biochemical characteristics [1]. The device worn on the wrist can detect radial pulse information to track the wearer's physical activity and vital signs. Nevertheless, the accuracy of these devices is often insufficient for clinical use [8, 9]. To examine these differences, we must verify the accuracy and reliability of wearable health devices, which often require clinical trials. To effectively calibrate wearable devices worn on the wrist, developing a pulse generator that can consistently and repeatedly produce various radial pulses is crucial. Without these simulators, sensor validation generally relies on clinical trials. However, this approach, relying on human subject testing, is a resource-intensive process. Use of a pulse generator allows conducting sensor validation without the need for human subjects, thereby eliminating the high costs and error issues inherent in human testing due to differences in characteristics among subjects. Similarly, the pulse simulator can play a crucial role in converting the doctor's subjective assessment of the pulses felt at the fingertip into an objective physical quantity. Establishing a standardized method for learning pulse diagnosis techniques using a pulse simulator is essential for educating students and professionals in the field of traditional medicine, promoting continuous expansion.

Currently, various commercial blood pressure waveform generators are available for use in medical education and laboratories. However, these devices often suffer from drawbacks such as large size and high production and maintenance costs. Additionally, they typically offer limited functionality by providing only a narrow selection of pre-installed pulse models. In response to these limitations, research is being conducted on a cam mechanism-based pulse simulator that can reduce the size and cost of the pulse generator and increase efficiency [10,11]. These simulators use a cam disk to accurately and consistently reproduce the specified pulse waveforms. However, their ability to generate pulse waveforms is restricted to discrete outputs, meaning that a unique cam disk must be manufactured for each desired pulse waveform. In addition to cam-based simulators, research has explored pulse simulators utilizing smart materials. Wang and Chung examined pulse waveforms using pulse transducers and identified methods for analyzing pulse waves generated from various pulse parameters [12]. Eaton et al. used magnetorheological (MR) fluid to generate pulses. They integrated the MR fluid chamber into a cam-based pulse simulator to form the fundamental pulse generated from a single cam disk, thereby generating a wide range of pulse waveforms [13]. This system is more complex to implement than a cam-based system and may introduce noise into the generated waveform.

To address these limitations, this study proposes a pulse generator that simulates arbitrary pulse waveforms using pneumatic pressure. The proposed system controls the opening and closing of two high-speed precision solenoid valves to generate the desired pressure waveform. A prototype was constructed, and the system's performance was validated by comparing the experimentally generated pulse waveforms with in vivo pulses using the RMSE.

2. Design and fabrication of radial pulse simulator

This section details design of the radial pulse simulator developed to generate pulse pressure waveforms corresponding to different age groups. Our study introduces a novel method to reduce baseline pressure through valve control utilizing a single cam, enabling the generation of age-specific pulse waveforms using a single simulator, eliminating the need for device replacement.

2.1 Design and working principle

Figure 1 illustrates the simple configuration and operation of the simulator. The pressure generated in the base pulse-generating part, shown in Figure 1(a), exceeds the pressure level of the waveform for all ages, and the pressure inside the air chamber increases accordingly. The pulse waveform monitoring part Figure 1(b) monitors the pressure inside the tube through a small pressure sensor. In the pulse shaping part Figure 1(c), the basic pulse waveform generated in Figure 1(a) is formed by releasing air from the solenoid valve connected to the air chamber while the half cam is in the high position. When the half cam returns to the low position, the exhaust valve opens, and the internal pressure of the system becomes equal to the atmospheric pressure. As a result, the solenoid valve can be controlled to adjust the internal pressure of the system, thereby generating an arbitrary waveform.

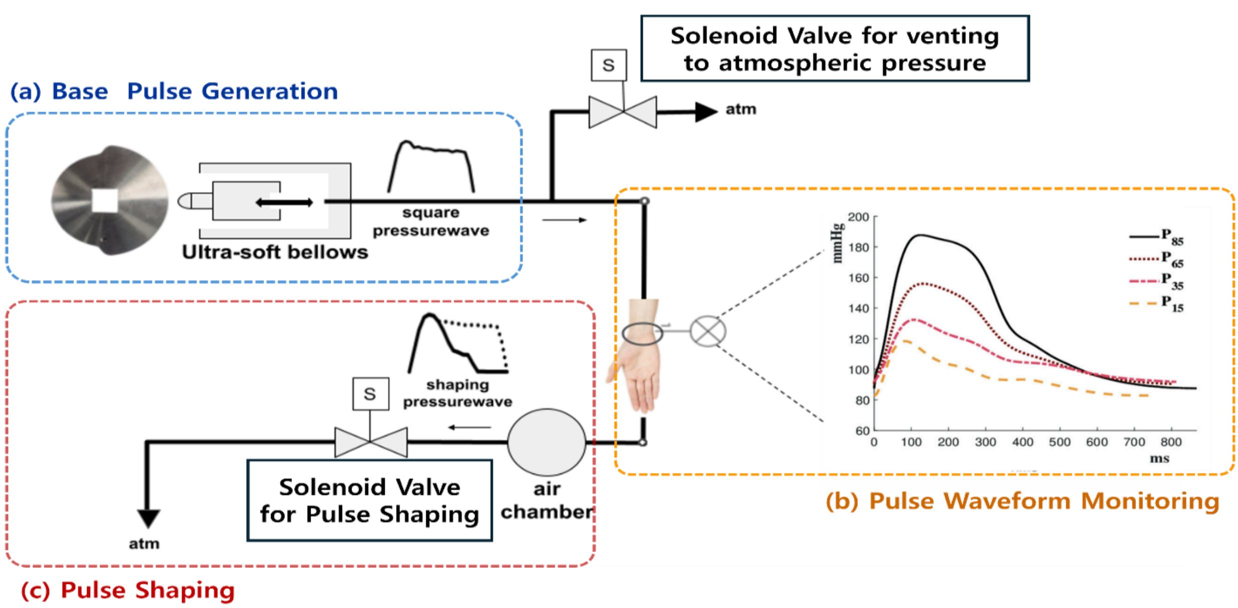


Figure 1. Conceptual diagram of the Cam Pulsation Simulator that generates age-specific pulse pressure waveforms: (a) Base pulse generation part including a half cam with DC motor that generates a base pressure waveform and bellows to transmit pressure, (b) Pulse waveform monitoring part including artificial hand and miniature pressure sensor, (c) Pulse shaping part composed of an air chamber and a solenoid valve for atmospheric ventilation.

2.2 System fabrication

Figure 2 illustrates the detailed configuration of the developed pressure waveform simulator. The half-cam is driven by a DC motor, converting the rotational motion of the cam into the linear motion of the ultra-soft bellows via a piston, which compresses the air. At the end of the bellows is a node where tubes are connected. Each tube is connected to a venting valve, an air chamber, and a pressure sensor, with the air chamber's internal volume being manually adjustable. The microcontroller serves two primary functions: data collection and signal generation. There are two types of data being collected. The first is to monitor changes in the internal pressure of the system through pressure sensors. The second is to check the pumping start point of the base pulse pressure and rotation period of Half-CAM through the magnetic sensors and magnets attached to the DC motor and half-cam. The generated PWM signals are amplified by signal Amplifier and sent to the valve to regulate current flow in the solenoid. The solenoid valve repeatedly turns on and off, releasing an extremely small amount of air, and controls the opening rate of the valve when the on signal is input through the duty of the PWM signal.

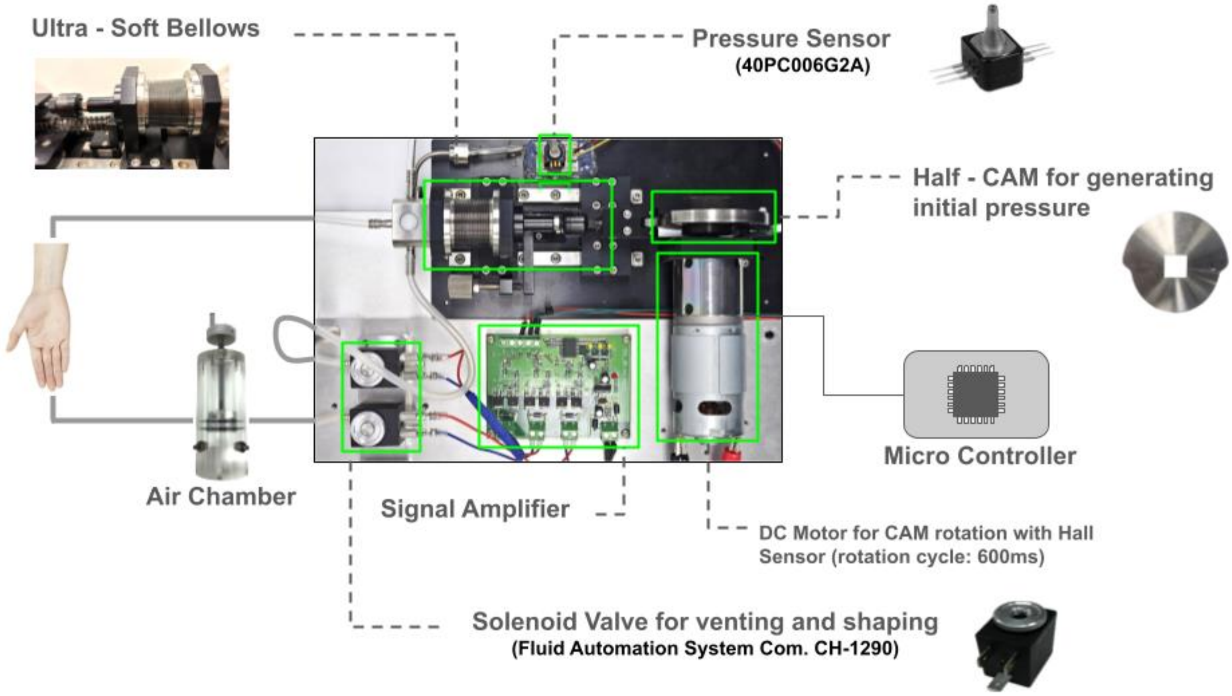


Figure 2. Configuration of the fabricated Cam Pulsation Simulator: Each component is controlled and monitored by the Micro Controller.

3. Evaluation of radial pulse simulator

3.1 Study of waveform slope depending on factors

Our system controls the solenoid valve in milliseconds; however, if the signal is too small, the valve encounters physical difficulties in operating. The experimentally determined effective range of the PWM duty cycle is between 45% and 100%. Within this range, we have set the target slope range to represent the human pulse pressure waveform. According to normalized in vivo data, the decline phase of human pulse pressure in individuals aged 10 to 90 falls within a slope range of -0.0008 to -0.008. In addition to the half cam, the air chamber—another factor affecting the internal system pressure—also influences the rate of pressure change during air release. Therefore, we identified the appropriate slope range by adjusting the two control parameters: the volume of the air chamber and the PWM duty cycle.

Figure 3 presents a slope study conducted under experimental conditions with three different air chamber volumes and six different PWM duty cycles. To ensure experimental accuracy and improve the visibility of the plot, a delay of a few seconds was introduced after the half-cam rise. According to the results, the slope ranged from -0.0027 to -0.0044 in Figure 3(a), -0.0018 to -0.0033 in Figure 3(b), and -0.0011 to -0.0022 in Figure 3(c), showing a tendency for the slope to increase as the volume of the air chamber increased. All three plots fell within the target slope range, but we considered the 60 ml air chamber with a slope range of -0.0011 to -0.0022 to be the suitable condition. Owing to the nature of the system, reproducing the rapid release of air is easy; however, the slow release of air requires more precise control. Thus, compensating for this limitation by adjusting the air chamber volume, which serves as a constant parameter in the system, was determined to be more efficient. The calculated slope range of -0.0011 to -0.0022 yielded the most significant results. To ensure a stable gradient range, a 65 ml air chamber was applied as a constant factor in the system, following the observed trend.

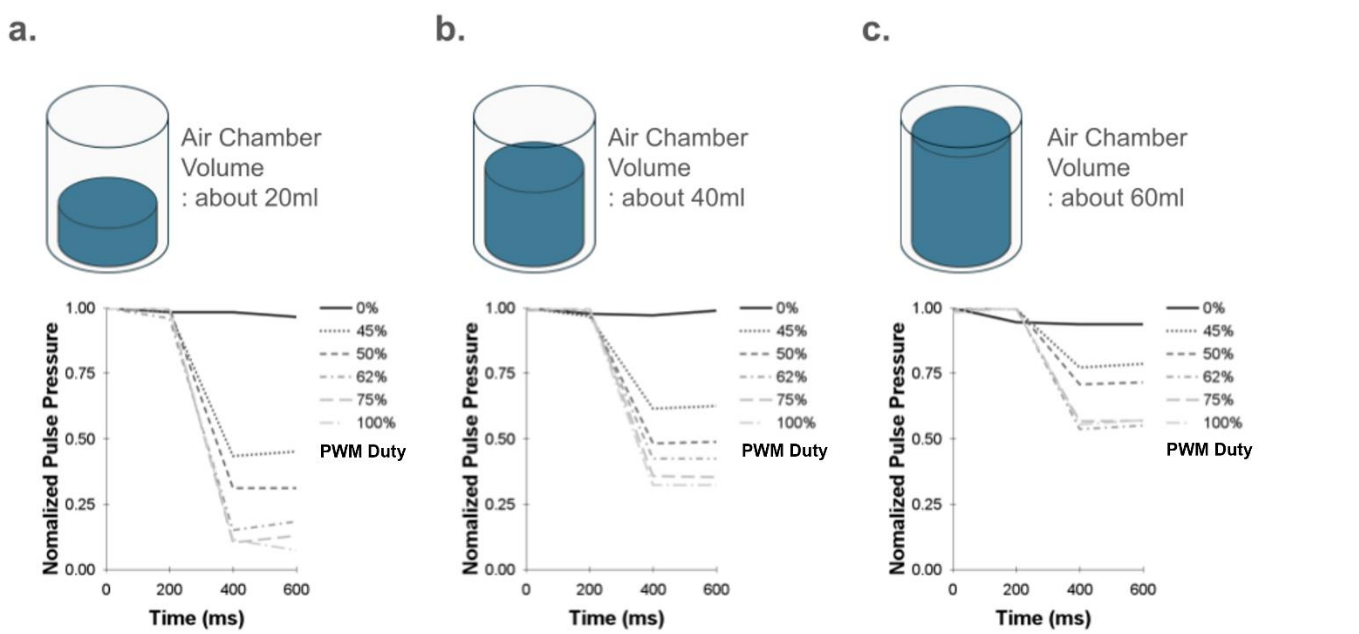
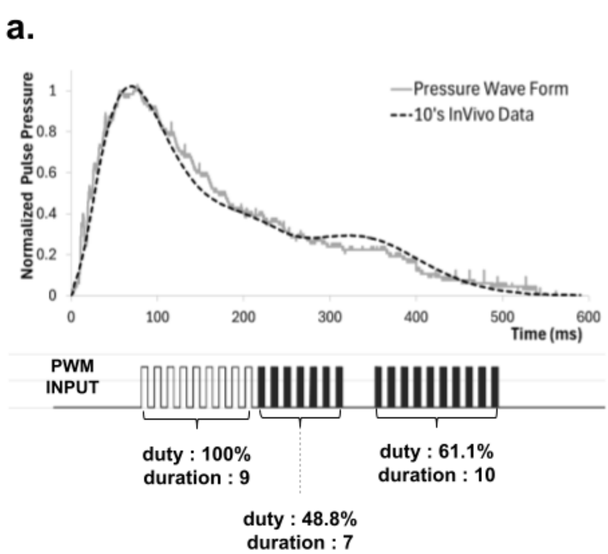


Figure 3. Study on waveform slope based on air chamber volume and PWM signal duty: (a) Slope change according to PWM change in 20ml air chamber, (b) Slope change according to PWM change in 40ml air chamber, (c) Slope change according to PWM change in 60ml air chamber

3.2 Generating waveform with simulator

To simplify the experiment and analysis, we selected and simulated four in vivo waveforms representing age-related pulses: 10, 30, 60, and 90 years. These waveforms were chosen to reflect pulse pressure characteristics at key stages of the human life cycle, including adolescence, young adulthood, middle age, and old age, thereby capturing significant variability in pulse behavior. These in vivo waveforms were obtained from published in vivo data. For each waveform, a unique control input was sent to the solenoid valve, and the system control parameters were adjusted to achieve an error rate within 10% of the in vivo data.

Figure 4 presents the waveforms for the four different age groups. The figure shows graphical comparisons of In Vivo vs. simulated waveforms for each age group. The primary control parameters generating these waveforms are duty and duration. Duty refers to the duty value of the PWM signal, which determines the valve's opening rate based on slop study shown in Section 3.1. As previously confirmed in Section 3.1, duty values in the range of 45% to 100% were used. The microcontroller's PWM signal frequency was set at 1 kHz. Duration refers to the length of the slope interval and is determined by the number of valve openings. A PWM signal is applied for 10 ms per input, followed by a 10 ms delay. The reason for using this method of repeatedly turning the valve on and off is simple: at the system's baseline pressure level, continuously opening the valve, even for just tens of milliseconds, will cause the internal pressure to rapidly drop to atmospheric pressure.



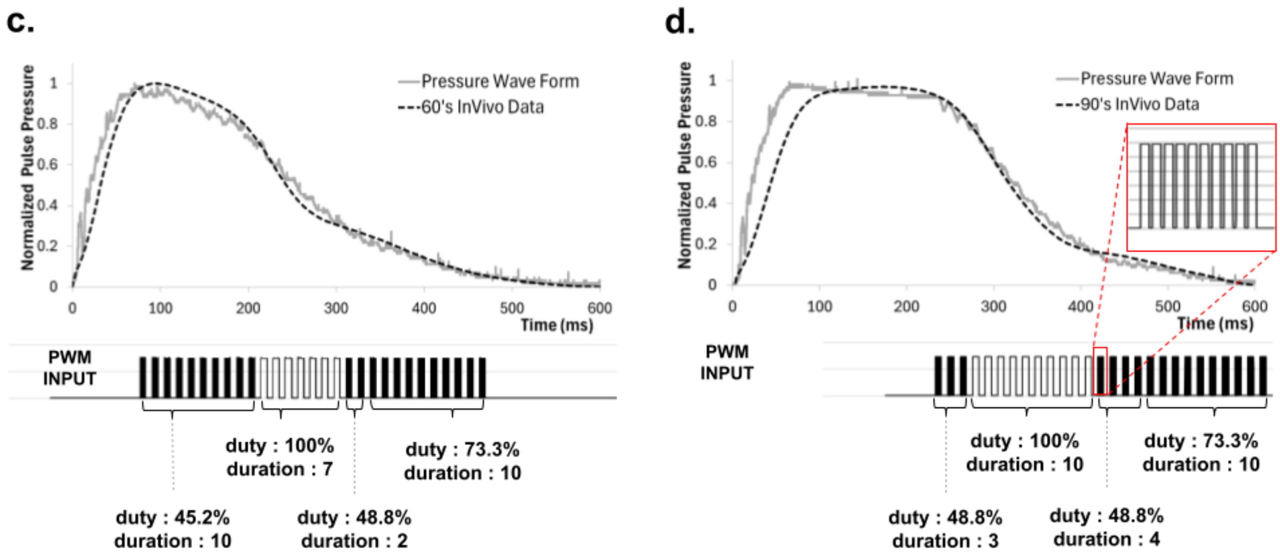


Figure 4. Radial waveform generation: Comparison of average in vivo data and simulator-generated waveforms for (a) 10 years, (b) 30 years, (c) 60 years, and (d) 90 years. PWM INPUT is the signal input to the solenoid valve for shaping.

The plot duty and duration settings were determined experimentally by referring to slope study data. The generated plots exhibit unique characteristics. Between Pr1 and Pr2 in Figure 4(a) and 4(b) and between Pf and Pr1 in Figure 4(d), there exists a flat region, which corresponds to the input delay of the PWM signal. Additionally, as the system's internal pressure continuously decreases, maintaining a constant duty results in changes to the plot's slope. Consequently, the intervals corresponding to Pr2 in Figure 4(c) and 4(d) show a nearly constant slope, but this was achieved by varying the duty. The accuracy of the simulator verified using RMSE is listed in Table 1. The 90 years waveform shows the highest error. As one gets older, the slope of the rise in blood pressure tends to become gentler, but since the rise slope of the half cam is constant, it is thought that an error occurred in this area.

Table 1. RSM Error between waveforms

Age	**RMSE(%)**
10 years	**4.5%**
30 years	**5.2%**
60 years	**5.9%**
90 years	**8.7%**

4. Conclusion

This study developed a simulator capable of representing radial pulse waveforms of humans across all age groups. This simulator was designed as a system utilizing a half cam and a solenoid valve to perform pressurization and depressurization. The constant parameter for waveform generation was the volume of the air chamber, while the control parameters were the duty and duration of the PWM input signal to the solenoid valve. We selected ages 10, 30, 60, and 90 to represent the human life cycle and generated corresponding waveforms using the simulator. The system achieved a minimum RMSE of 4.5% for the 10-year waveform and a maximum RMSE of 8.7% for the 90-year waveform, successfully meeting the target of an RMSE below 10%. These results demonstrate that the proposed simulator can accurately reproduce pulse waveforms across all ages through proper control of the system's parameters. However, depending on the length and curvature of the air tube used in the system, slight errors may occur even if the same adjustment factor is entered due to friction or reflection inside the tube. Additionally, since this study aimed to generate blood pressure waveforms, normalizing the time axis of the generated waveform is necessary. Because the waveform of this simulator was created based on normalized in vivo data, the absolute magnitude of blood pressure cannot be confirmed. If we utilize a sample that includes the magnitude of blood pressure, we may be able to devise an advanced waveform shaping system. In addition, current simulators have the limitation that they only control rising waveforms and falling waveforms, so a system that can generate rising waveforms and adjust the slope is needed to create a system that can express even abnormal waveforms with multiple rising waveforms. Through this study, human subject testing can be replaced in research on blood pressure measurement, and through follow-up research, we can look forward to the development of a system that tests the physical properties of materials and structures in the development of artificial skin, organs, and tissues.

5. Acknowledgement

This work was supported by Institute of Information & communications Technology Planning & Evaluation (IITP) grant funded by the Korea government(MSIT) (No.2022-0-01049, Development of teaching-less product assembly system for smart factory based on autonomous robot task planning and manipulation) and National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT)(RS-2024-00342395).

References

[1] G. Jo, T.H. Yang, J.U. Kim, J.H. Koo, and Y.M. Kim, “Development of a mathematical model for age-dependent radial artery pulse wave analysis based on pulse waveform decomposition,” IEEE Access. 2020.

[2] G. Jo, T.H. Yang, J.U. Kim, J.H. Koo, and Y.M. Kim, “Development of a mathematical model for age-dependent radial artery pulse wave analysis based on pulse waveform decomposition,” IEEE Access. 2020.

[3] R. Velik, “An objective review of the technological developments for radial pulse diagnosis in Traditional Chinese Medicine,” Eur J Integr Med. 2015 Aug 1.

[4] J. Yang, L. Yang, W. Liu, S. Du, L. Xu, G. He, et al., “Analysis of the radial pulse wave and its clinical applications: A survey,” IEEE Access. 2021.

[5] K.A. O’Brien, S. Birch, E. Abbas, P. Movsessian, M. Hook, and P.A. Komesaroff, “Traditional East Asian medical pulse diagnosis: A preliminary physiologic investigation,” https://home.liebertpub.com/acm. 2013 Oct 15.

[6] K. Kyung-Won, “Comparison of pulse diagnosis in Oriental and Western medicine,” Indian J Sci Technol. 2016 Jan 20.

[7] J.M. Wightman, “Radial pulse quality as a diagnostic test in tactical combat casualty care,” Mil Med. 2020 Nov 1.

[8] N.B. Lee, C.G. Park, “Reproducibility of regional pulse wave velocity in healthy subjects,” Korean J Intern Med. 2009

[9] R. Kelly, C. Hayward, A. Avolio, M. O’Rourke, “Noninvasive determination of age-related changes in the human arterial pulse,” Circulation. 1989.

[10] E. Ottaviano, D. Mundo, G.A. Danieli, and M. Ceccarelli, “Numerical and experimental analysis of non-circular gears and cam-follower systems as function generators,” Mech Mach Theory. 2008 Aug 1.

[11] H. Wang, Y. Cheng, “A quantitative system for pulse diagnosis in traditional Chinese medicine,” Annual International Conference of the IEEE Engineering in Medicine and Biology - Proceedings. 2005.

[12] M. Eaton, J.H. Koo, T.H. Yang, and Y.M. Kim, “Simulating age related radial pulses using magneto-rheological fluids,” Proceedings of ASME 2022 Conference on Smart Materials, Adaptive Structures and Intelligent Systems, SMASIS 2022. 2022 Nov 14

[13] N.A. Shirwany, and M.H. Zou, “Arterial stiffness: A brief review,” Acta Pharmacologica Sinica 2010 31:10. 2010 Aug 30.

[14] M. Tan, Y. Xu, Z. Gao, T. Yuan, Q. Liu, R. Yang, et al., “Recent advances in intelligent wearable medical devices integrating biosensing and drug delivery,” Advanced Materials. 2022 July 1

[15] T.H. Yang, G. Jo, J.H. Koo, S.Y. Woo, J.U. Kim, and Y.M. Kim, “A compact pulsatile simulator based on cam - follower mechanism for generating radial pulse waveforms,” Biomed Eng Online. 2019 Jan 3.

[16] T.H. Yang, J.U. Kim, Y.M. Kim, J.H. Koo, and S.Y. Woo, “A new blood pulsation simulator platform incorporating cardiovascular physiology for evaluating radial pulse waveform,” J Healthc Eng. 2019.

[17] K. Kohara, Y. Tabara, A. Oshiumi, Y. Miyawaki, T. Kobayashi, and T. Miki, “Radial augmentation index: A useful and easily obtainable parameter for vascular aging,” Am J Hypertens. 2005 Jan 1.

[18] J.H. Jeong, Y.M. Kim, and B. Lee, “Design and Evaluation of Enhanced Mock Circulatory Platform Simulating Cardiovascular Physiology for Medical Palpation Training,” Applied Science. 2020 August 6

[19] D.J. Kim, G. Jo, J.H. Koo, T.H. Yang, and Y.M. Kim, “Development of a Simulator Capable of Generating Age-Specific Pulse Pressure Waveforms for Medical Palpation Training,” Applied Science. 2022 November 14.

[20] M. Eaton, J.H. Koo, T.H. Yang, and Y.M. Kim, “Replication of Radial Pulses using Magneto-Rheological Fluids,” MDPI. 2024 August 6

[21] T.H. Yang, J.I. Kim, J.H. Koo, G. Jo, and Y.M. Kim, “Advancing Radial Arterial Pulsation Simulation: Wave Decomposition Modeling With Hardware Implementation,” 2024 July 1