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EXPERIMENTAL EVALUATION OF A MAGNETORHEOLOGICAL FLUID-BASED PULSE SIMULATOR FOR GENERATING RADIAL PULSE WAVEFORMS

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Abstract. Many health diagnostics rely on the use of the radial pulse, which is taken at the radial artery in the terminal region of the wrist. Two specific applications of the radial pulse include Oriental Medicine (OM) and wearable technology. OM has utilized palpations of radial pulses using three fingers as their primary diagnosis method. In addition, wearable technology, such as smart watches, strive to measure blood pressure (BP) non-invasively using radial pulses. A pulse generator capable of recreating a range of radial pulses could be of great use to help train medical professionals in OM or calibrate sensors in wearable technology. The goal of this study is to design and test a new pulse simulator that incorporates a Magneto-Rheological (MR) fluid device to reproduce a wide range of radial pulses. A base pulse waveform is produced by a cam generator and sent to an MR device which consists of a silicone tube submerged in MR fluid. The MR fluid is used to reshape the base pulse waveform to the desired pulse waveform. This study examined the pulse shaping performance of the MR device by comparing the reproduced radial pulses with those of *in vivo* radial pulses. The study evaluated the results of shaping a base pulse to two representative pulse waveforms, and found the method was effective in shaping to a range of age-related pulses.

Key words: Magneto-rheological fluids, radial pulse waveform, pulse generator

1 INTRODUCTION

Radial pulses are a crucial part of healthcare and have been used for generations to evaluate a

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person's health [1-3]. Nowadays in western medicine, the augmentation index and augmentation pressure derived from radial pulse pressure waveforms have been proven to be trustworthy markers for determining arterial compliance and cardiovascular disease risk, in addition to providing information about a person's general health state [1], [2]. Palpating radial pulse pressures with three fingers has been a crucial diagnostic method in Oriental Medicine (OM) and Tactical Combat Casualty Care (TCCC), both of which utilize radial pulse quality as a diagnostic tool [6-8]. In recent years, wearable technology has significantly transformed the healthcare sector and individual healthcare practices. Wearable healthcare devices make it possible to continuously monitor vital signs in real-time, providing users a better understanding of their health status. Particularly, wrist-worn systems strive to offer non-invasive, real-time blood pressure (BP) monitoring features based on sensor readings from radial pulses. By using this technology, people may check their blood pressure more conveniently and easily, potentially leading to improved overall health outcomes.

Advancing radial pulse-based technology and its medical applications requires the development of pulse simulators capable of generating a wide range of real human radial pulses. Pulse simulators that can generate radial pulses consistently and repeatedly can be utilized to calibrate wearable sensors and train medical professionals in pulse palpation. The three-finger technique used in OM can be subjective, therefore, creating a pulse generator which “standardizes” pulses may help train physicians and trainees in the field. Moreover, for wearable healthcare devices, the embedded sensors in wearable technology need to be certified and calibrated to guarantee the quality and dependability of the data they collect [3]. While clinical trials are the most direct and essential method for advancing the fields, they can be resource-intensive due to the involvement of human subjects, which is costly and time-consuming [4]. Thus, pulse simulators can be used to validate and calibrate wearable technology as a low-cost and dependable alternative to human subject testing.

Currently, there are a few pulse generators available in the market, and ongoing research is aimed at developing more advanced and versatile pulse simulators. Pulsatile blood pumps that mimic animal pulses are one sort of commercially accessible pulse generators, while other types are employed in medical professional training [5], [6]. Unfortunately, the user-defined pulse waveforms that can be generated by these pulse generators are constrained, and they are often bulky. In an effort to develop a wide range of pulse waveforms, a study was conducted on a magnetorheological (MR) fluid-based pulse system in an effort to provide a greater variety of radial pulses [7]. The system employed a peristaltic pump to circulate the MR fluid and a magnetic valve to regulate the motion of the MR fluids in order to generate pulse pressure waveforms. This study presented the creation of different "two-peak" pulse waveform patterns and demonstrated the controllability of the augmentation index by varying the peak amplitude ratio and the separation or time delay between the two peaks. In another investigation, Yang et al. created a small pulsatile simulator using a cam-follower system [8]. A specially formed disk cam rotates to create the desired pulse waveform. The cam's profile is produced using *in vivo* data, or actual radial pulses collected from human individuals. They showed that an *in vivo* pulse waveform can be reliably generated by the cam-based pulse simulator. However, the cam-based simulator requires the fabrication of a new cam disk for a target or desired pulse waveform. For example, to generate a pulse for a 30-year-old and an

80-year-old, two distinct disks would be required. Therefore, the cam-based pulse simulator is not able to continuously generate a range of radial pulses. Eaton et al performed a feasibility study which generated a range of pulse waveforms using a MR pulse shaping method [9]. MR fluid was used to shape a cam-generated base pulse to a desired waveform. The study demonstrated that the MR system could replicate a range of pulses using multiple age-specific cam disks. The study used a 20, 35, and 80 year-old cam to shape to a 20, 35, and 80 year-old pulse waveform. Although the results indicate that the MR fluid system is feasible to shape a waveform to a specific age-related pulse, further improvements are necessary in order to produce a wide range of target pulse waveforms using a single cam.

The goal of the present study is to build upon the feasibility study in order to replicate a range of age-related pulses using only a single cam. The "MR pulse shaping" technique with a single base cam eliminates the need for multiple cam disks for people of different ages. The pulse shaping technique also allows pulses to be generated continuously and repeatability. For this experimental study, an MR fluid chamber was constructed and is connected to the cam pulse generator which sends a baseline pulse pressure wave. A magnetic field will change the properties of the MR fluid, resulting in the desired age specific pulse waveform. The practicality of producing a variety of radial pulses will be assessed by comparing the findings to *in vivo* data. The subsequent sections will discuss the experimental setup and the pulse shaping method in detail. The experimental results section will compare the MR shaping method's pulses with two samples of *in vivo* pulses.

2 EXPERIMENTAL SET UP

Figure 1 shows the experimental setup used in this study to shape the base pulse. The most important components of the set-up include the cam pulse generator, an electromagnet, MR chamber, and plunger assembly. Using the cam system, a base pulse is generated. The silicone tube containing the base pulse connects the cam to the MR chamber, which is placed on top of the electromagnet. Above the MR chamber sits the plunger assembly, and a laser sensor is placed above the plunger assembly to measure the displacement, which represents the pulse waveform. The electromagnet is controlled via an Arduino and driver board. Duty values are the input into the Arduino to create pulse width modulation (PWM) signals. These signals are used to control the electromagnet, which affects the magnetic field input to the MR chamber. Additionally, a Gauss meter is inserted between the electromagnet and MR chamber to measure the magnetic field in real time. Data from the laser sensor and Gauss meter is collected using a data acquisition system. A detailed analysis of each component is presented below.

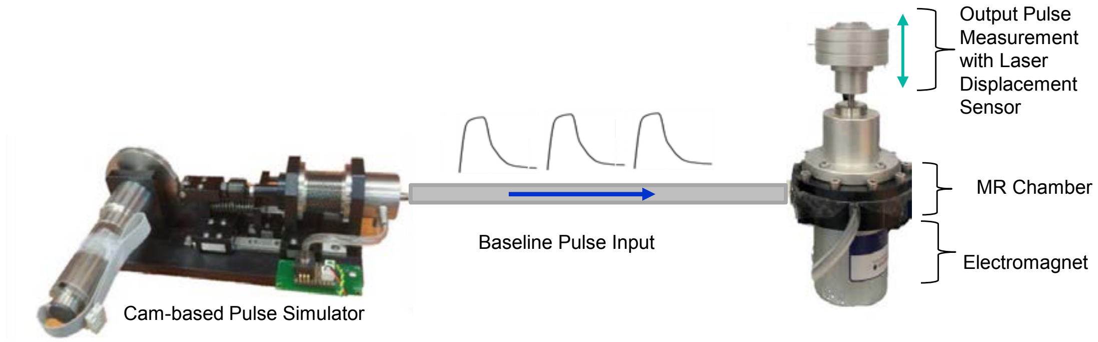

Figure 1. Experimental set-up including cam generator, electromagnet, MR fluid chamber, and laser sensor

Although reference [10] contains a comprehensive discussion of the design and construction of the cam system discussed in this section, a basic summary is given here. This system creates a base pulse. A DC voltage is delivered to the profile cam disk to power the motor and rotate it. The type of base pulse generated depends on the disk's geometry. The cam system incorporates two sensors to measure different characteristics of the pulse. A probe (Hall effect sensor) fixed to the cam is utilized to monitor the rotation of the cam disk, while a pressure sensor is placed on the cam to measure the internal pressure of the baseline pulse. The Hall probe reading allows the MR fluid to be actuated at the start of the pulse.

The MR fluid chamber is a critical part of this study as it allows for adjustable stiffness. The chamber has a diameter of 64 mm and an overall height of 28 mm with its cover. Within the chamber is a silicone tubing (representing the radial artery) which receives the base pulse from the cam generator. The chamber is filled with MR fluid to surround the tubing, and a flexible membrane is stretched over the fluid to prevent leakage. After constructing the apparatus, a frictionless plunger assembly was created to sit directly on top of the MR fluid chamber. The assembly is composed of a piston and cylinder with a head that can generate an adjustable "hold-down pressure" by varying the weights placed on the head of the plunger. Details on the construction and function of the plunger can be found in the authors' earlier study [14]. When the tube in the chamber expands, the plunger will correspond directly with that movement. Thus, controlling the MR fluid surrounding the tube in the chamber would allow shaping of the base pulse waveform. To measure the displacement of the plunger head, a sensor was set up directly above. This displacement is then recorded and matched to the *in vivo* pulses. In order to shape the baseline pulse into the desired pulse waveforms, the MR fluid chamber is placed directly on top of the electromagnet. By varying the magnitude of the electromagnet, the MR fluid inside the chamber is altered, which in turn affects the expansion of the silicone tube. As a result, the displacement of the plunger head changes, leading to the desired pulse waveform. The effectiveness of the MR pulse shaping method will be evaluated by comparing the generated pulses with *in vivo* data.

3 SINGLE CAM PULSE SHAPING

The primary goal of this study isto use a single cam to create a range of radial pulse waveforms. In other words, the cam pulse generator will only require a single cam to replicate a range of radial pulses rather than multiple disks. The base pulse waveform, created by a single cam, for the current study is representative of an elderly pulse waveform which will be shaped to the two ages. The baseline pulse shown in Figure 2 will then be shaped into two ages, 20 and 80 year-old. The *in vivo* pulse waveforms of the two ages represent distinct variations of age-related pulses. These two pulses are illustrative of the lifespan of an average human. A younger pulse has a sharp initial peak while older pulses tend to plateau and then descend. The profile of this cam is similar to the pulse waveform of a 80 year-old because it is much easier to constrict the pulse rather than expand a pulse. In other words, it is much easier to create the various peaks of a 20 year-old from a 80 year-old pulse. Thus, the experimental data collected will be compared to the *in vivo* pulses below to determine the effectiveness of using MR fluid to shape a single cam to multiple pulses.

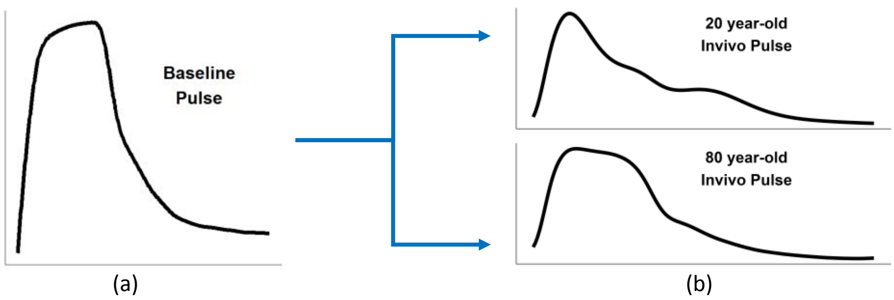

Figure 2. (a) Baseline pulse generated from the CAM to be shaped into various pulses (b) 20-year-old and 80-year-old *in vivo* pulses representative of a lifespan of pulses

A brief explanation of the pulse shaping technique used to achieve the results is explained as follows. The main components of the technique included the Arduino, driver board, and electromagnet. PWM signals are generated by input duty values using an Arduino. These duty values are percentages (which range from 0-100%), and they represent the percentage of time the signal is on. The PWM signals were used in an open loop control system to change the magnetic field output from the electromagnet. The Arduino communicates with the electromagnet to generate the magnetic field based on the duty values. Not only could the magnitude of the duty value be changed but the time duration of each duty value could be altered. By changing the duration and value of the duty cycle, the MR fluid would react accordingly. The MR fluid would control the expansion of the silicone tubing within the MR fluid chamber. Therefore, the goal of this research was to use MR fluid to shape a baseline pulse into a variety of pulse waveforms.

The study initially investigated the relationship between duty values and the resulting magnetic field. It was noted that the generated magnetic field closely matched the input duty values in terms of form. The electromagnet's output magnetic field increased when the duty values were increased, whereas it decreased when the duty values were decreased. As a result, the magnetic field had the same effect and lasted for the same amount of time as the input duty values. Once the relationship between duty values and magnetic field was established, then the connection between magnetic field and plunger displacement was established. It was discovered that a magnetic field's presence restricted the silicone tube's ability to expand. Results suggested that the MR fluid hardens and constricts the expansion of the silicone tube inside the chamber, resulting in a smaller displacement of the plunger head. Therefore, it was determined that increasing the magnetic field decreased the displacement.

4 RESULTS AND DISCUSSION

This section discusses the results using the MR fluid to shape the base pulse to a variety of ages. The study investigated shaping the baseline pulse into pulse waveforms of two ages (20 and 80-year-old). This range of ages can be representative of the lifespan of an average human. Therefore, if the method can shape to these two ages, it can be considered successful to shape to a variety of ages within 20-80yrs-old. The results of shaping the baseline pulse to a 20-year-old *in vivo* waveform are shown in Figure 3. The solid blue line is the *in vivo* pulse while the dotted red line is the experimental data. The plunger was able to quickly descend to create the initial sharp peak. Additionally, it was able to match the complex diastolic phase of the 20-year-old pulse with its multiple peaks and plateaus. Due to the nature of pulse shaping, the experimental data is not considered after 0.4 seconds. The most important part of the waveform is the first 0.4 seconds. The initial peak and subsequent second peak are the crucial part. The pulse after 0.4 seconds is very low, and any differences at that point would be nearly unnoticeable by a human measuring the pulse.

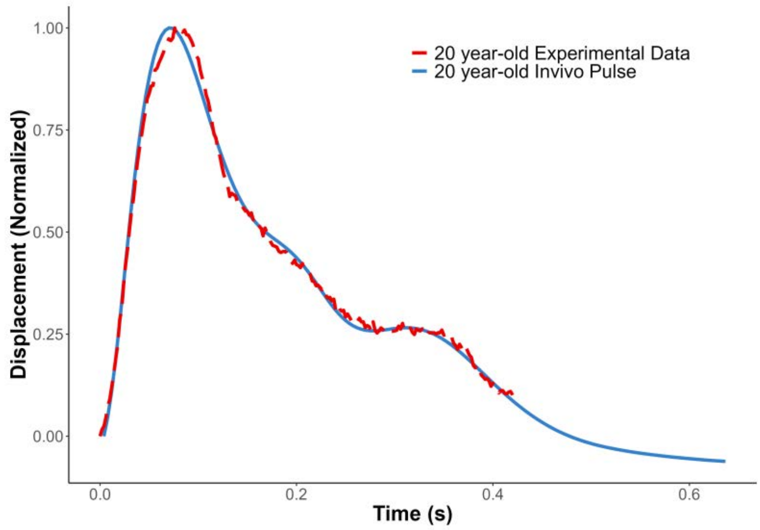

Figure 3. Shaping baseline pulse (red dotted line) to 20-year-old in vivo pulse (blue solid line)

Figure 4(a) below illustrates the input duty values while Figure 4(b) shows the resulting magnetic field generated from those duty values used to shaped the base pulse to a 20-year-old *in vivo* pulse. The quick descent in the displacement can be noted by the 100% duty value directly after 0% in Figure 4. The complex shape of the rest of the pulse waveform can be noted by the sporadic duty values, which range from 60%-100%. As noted in an earlier section, the magnetic field generated is very similar to the input duty values. Duty values ranged from 0-100%. At the maximum duty value of 100%, the maximum magnetic field is around 17mT. Near the end of the cycle about 3 peaks can be observed. These 3 peaks are representative of the 20-year-old *in vivo* pulse, which has three concavities during diastole. Therefore, the shape of the duty values are very similar to the desired *in vivo* pulse.

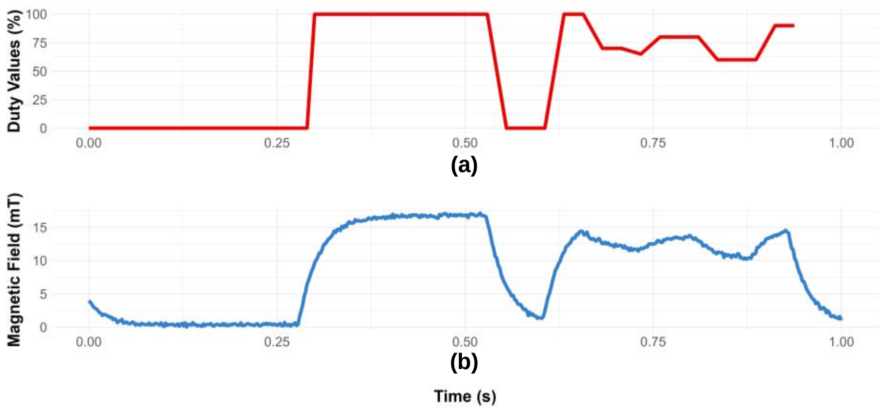

Figure 4. Duty values (red) and magnetic field (blue) used to shape baseline pulse to 20 year-old in vivo pulse

The other age the base pulse was shaped into was an 80 year-old, as shown in Figure *5*. An 80 year-old *in vivo* pulse is very similar to the base pulse, therefore, very little control was required to match the base pulse to the *in vivo* pulse. Not to mention, an 80 year-old pulse has no additional peaks after the main peak. The first peak was replicated well as it did not need to quickly descend from before. Furthermore, the base pulse can also be shaped to create a smooth diastolic phase, which is drastically different than the younger pulses.

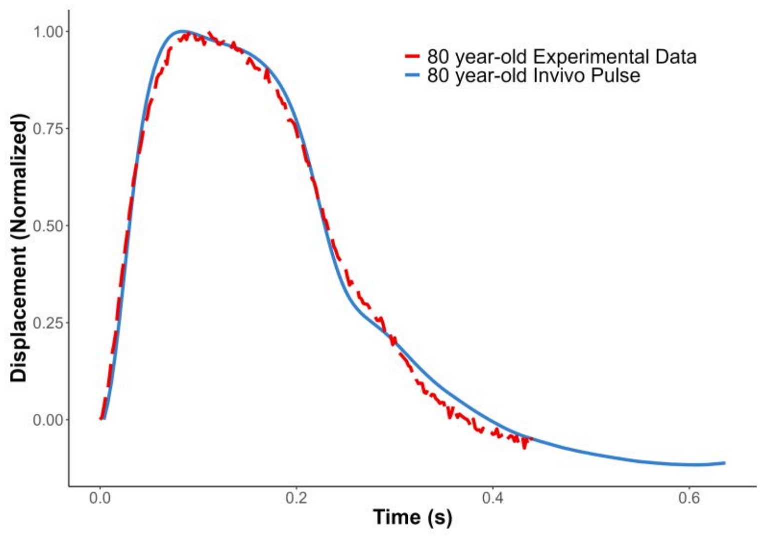

Figure 5. Shaping baseline pulse (red dotted line) to 80 year-old in vivo pulse (blue solid line)

The duty values used to generate the 80 year-old results are in Figure 6(a). It steadily rose from 0% to 100% after the initial 100%. This rise in duty values is also noted in the magnetic field in Figure 6(b). This steady rise back to 100% duty is expected because of the shape of the desired waveform. The smooth diastolic phase contrasts that of the 20 year-old, which has varied peaks. While the required peaks are present in the input duty values for the 20 year-old, there are no peaks in the duty values for the 80 year-old. Furthermore, an 80 year-old pulse has a much lower diastolic phase than a 20 year-old, therefore, the 100% duty value is required at the end to fully constrict the expansion of the tube. Because the initial peak and diastolic phase were matched well, the base pulse was successful in shaping an 80 year-old pulse waveform.

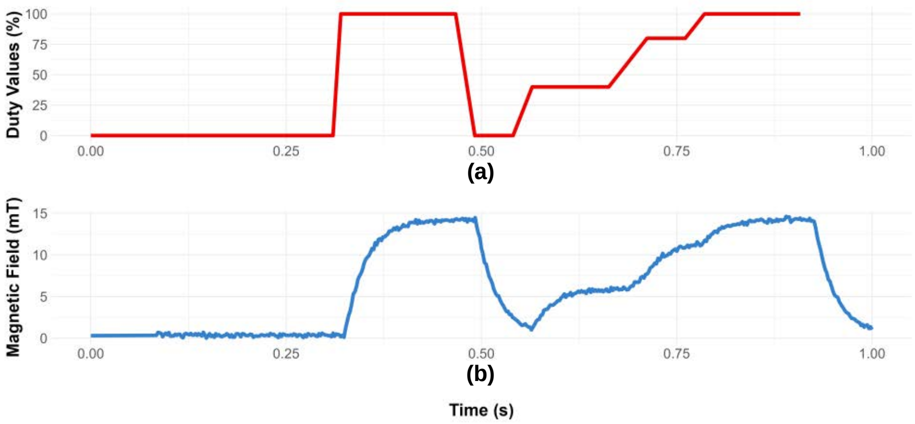

Figure 6. Duty values (red) and magnetic field (blue) used to shape baseline pulse to 80 year-old in vivo pulse

To understand the performance of pulse shaping better quantitatively, the root mean square error was calculated between the *in vivo* pulse and the experimental data. The equation for the root mean square error (RMSE) is given below.

$$RMSE = \sqrt{\frac{(exp - invivo)^2}{N}} \tag{1}$$

The difference between the experimental data and the *in vivo* data was calculated and then squared. It was divided by the total number of data points (N), and then the square root was taken. This equation required the same number of data points between the experimental and *in vivo* data. Therefore, the number of experimental data points was reduced to match the *in vivo* data points, and the error was calculated. The RMSE was found for both ages. The 20 year-old shaping experienced the highest error of 3.7%, while the 80 year-old had a similar error of 3.4%. Because these errors are very low across both ages, the pulse shaping method was considered successful, and a single cam disk can be used to replicate a range age-related radial pulses.

5 CONCLUSION

In this study, a baseline pulse generated by a cam pulsatile system was modified to determine if it could reproduce age-related pulses by using MR fluids. An MR chamber was used for the pulse shaping, and depending on the magnetic field input, the MR fluid would restrict the expansion of a silicone tube (which mimicked the radial artery). Using the experimental setup and procedure, the study was able to shape the pulses of varied ages (20 and 80) using a single cam disk. The results showed that it is possible to generate a variety of pulses constantly and repeatedly using the cam pulsatile system without the use of several distinct cam disks. The study's implications include the creation of a platform for sensor evaluation that can help progress sensor technologies for wearable devices and aid in development of a system of "standard" pulses that could be used to teach healthcare professionals in eastern medicine about pulse diagnosis.

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