University of Wisconsin - Madison
Department of Biomedical Engineering

Arterial Actuator

Mid-semester Report

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I. Abstract

In an effort to diagnose and prevent cardiovascular disease, the ultimate goal of this project is to design a system that can measure blood pressure and arterial stiffness on a single artery. The system will include a piezoresistive sensor, an ultrasound probe, and an actuator. This semester, the actuating mechanism and overall system assembly need to be designed and fabricated. Through preliminary pressure sensor research, it was determined that the artery used does not significantly affect output. Therefore, the radial artery was chosen due to its ease of access. Four preliminary design ideas were developed for the actuating mechanism: a spring-loaded method, an air-loaded approach, an air jet, and a protrusion in an inflatable cuff. Similarly, three preliminary options were considered for the method of overall system stability and assembly. These were a portable brace, a mounted sleeve, and a surface strap. Through the use of design matrices, the pros and cons of each design were considered. It was determined that the air-loaded actuating mechanism and mounted sleeve system for stability and assembly would be the best designs to pursue. Some of the work that still needs to be done includes ordering materials for the various components, assembling the entire system, and testing its functionality.

II. Problem Statement

Cardiovascular disease is one of the top killers in today's society. Blood pressure and arterial stiffness are indicators of cardiovascular health. Currently, blood pressure is measured via sphygmomanometry and arterial stiffness via arterial tonometry. Although effective, the speed and accuracy of these methods can be improved. The long-term goal is to design a system that quantitatively measures blood pressure and arterial stiffness on a single artery. The semester goal is to design and fabricate an actuating mechanism and assemble the system comprised of an ultrasound probe, a piezoresistive pressure sensor, and an actuator.

III. Background

Arterial blood pressure is the key driving force for propelling blood to the body's tissues (Sherwood et al., 2005). Blood pressure is highly regulated in order to ensure sufficient nutrient and oxygen supply to the body. The maximum pressure exerted in the arteries, known as systolic pressure, occurs when the heart contracts. In contrast, the minimum pressure, known as the diastolic pressure, occurs with the relaxation of the heart between contractions (Sherwood et al, 2005). Blood pressure is usually reported as systolic pressure over diastolic pressure, which is around 120/80 mm Hg in a healthy patient.

Arterial stiffness is the elasticity of the arterial walls. The arteries stiffen as a result of age, atherosclerosis, and fraying of the elastic fibers in the arterial walls. Atherosclerosis is caused by plaque buildup, which can lead to myocardial infarction (heart attack), stroke and other cardiovascular diseases.

Current methods

The two main methods to measure arterial blood pressure are the auscultatory and oscillometric methods. The auscultatory method uses a mercury sphygmomanometer (blood pressure cuff) and the Korotkoff sound technique (stethoscope) to measure blood pressure. The auscultatory method is performed by first placing the stethoscope under the blood pressure cuff, and then inflating the sphygmomanometer to above 180 mm Hg. After inflation, air pressure within the cuff is slowly lowered. **Figure 1** shows the setup of measuring the arterial blood pressure using the sphygmomanometer and stethoscope. The pressure displayed on the sphygmomanometer when the first sound occurs is the systolic blood pressure. The

Figure 1: Measuring arterial blood pressure via the auscultatory method

Image courtesy of Acupuncture and Herb: http://www.acupuncturebrooklyn.com/uncategorized/hypertension-epidemic-causedd-by-wrong-bp-cuff- size-karen-vaughan diastolic blood pressure occurs at the time when individual heart beats are no longer heard. These sounds are caused by the turbulent flow that exists due to occlusion in the arteries as they are constricted to some point between systolic and diastolic pressure (Widmaier et al., 2008).

Figure 2: Blood pressure monitor that uses the oscillometric method

Image courtesy of Blood Pressure Monitors: http://blood-pressure-monitors.thebighealth.com

On the other hand, the oscillometric method uses an array of electronic transducers to detect the degree of oscillations caused by the blood. This method uses the same technique as the auscultatory method except the pressures are recorded based on oscillations that occur during turbulent flow rather than sounds. While the oscillometric method is easier and faster, some studies indicate that it is less precise when compared to the auscultatory method (Park et al., 2001). **Figure 2** shows a blood pressure monitor that uses the oscillometric method.

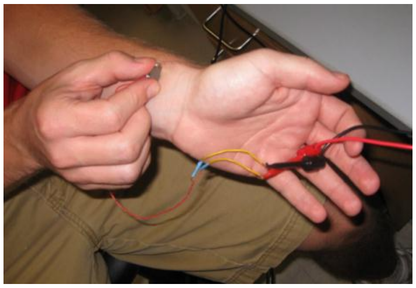
Pulse wave velocity (PWV) has been considered to be the most effective way to measure arterial stiffness. PWV is calculated based on the transition time of the pulse and distance traveled by the pulse between the carotid artery and femoral artery (O'Rourke et al., 2002). PWV has been proven to be directly correlated to central arterial stiffness. There are several ways to measure PWV: pressure-sensitive transducers, Doppler ultrasound, and applanation tonometry. After collecting data via PWV, the Moens-Korteweg equation, PWV=$\sqrt{(Eh/2\rho R)}$, is used to calculate arterial stiffness (Oliver and Webb, 2003). In the equation, E is Young's modulus (elasticity/stiffness) of the arterial wall, h is wall thickness, R is arterial radius at the end of diastole, and ρ is blood density.

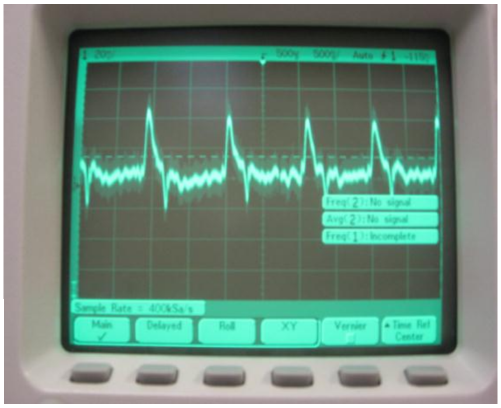
IV. Design Components

The proposed system is comprised of three primary parts: the ultrasound probe, the pressure sensor, and the actuator. Ultrasound is used to locate the exact position of the artery and to determine when the artery is compressed halfway. When this occurs, the pressure applied to the artery by the compression force is equal to the pressure applied by the blood inside the artery (i.e. blood pressure). The second component is the pressure sensor, which is used to determine the amount of pressure applied to the artery. This sensor outputs a pressure waveform, which displays the patient's pulse on an oscilloscope. The third component of the system is the actuator, which is used to induce a step input force on the artery. Ideally, this is an instantaneous, on-off hit on the artery. Once this force is applied, the response of the artery can be observed on the pressure waveform and the arterial stiffness can be determined. The longer it takes the artery to return to its normal state, the stiffer the artery.

V. Preliminary Data

At the beginning of the semester, a piezoelectric sensor was connected to an oscilloscope to output the pressure waveform. The sensor was placed at three artery locations: the radial, brachial, and carotid arteries. At each location, a pressure waveform was displayed and the pulse of the subject was seen on the oscilloscope (**Figures 3 & 4**). On this waveform, the systolic and diastolic blood pressures could easily be seen. A similar waveform could be displayed from all three locations, so it was decided to focus on using the radial artery for this project because it is the most accessible.





Figures 3 & 4: Obtaining the output waveform of the piezoelectric sensor on the radial artery via oscilloscope

VI. Preliminary Designs

Actuator for measuring arterial stiffness

The first goal of the project is to design and fabricate an actuator that is able to produce a step input on the radial artery. This will allow for the measurement of arterial stiffness. The four proposed mechanisms for the actuator were spring-loaded, air-loaded, air jet, and protrusion in a cuff designs.

The spring-loaded design, similar to the release of a pen or a solder remover, uses a spring force to actuate an object onto the artery. This provides the necessary compression force. The design incorporates variable spring compressions to yield a number of lengths of release. This provides adjustability and accounts for differences in patient body composition and artery location.

The air-loaded design (**Figure 5**) uses a similar actuating mechanism as the spring-loaded design: it drives an object to provide artery compression. However, the air-loaded design uses the pressure of compressed air to release the actuator and thus, is more sensitive to adjustments for individual users. The pressure required to compress the artery halfway can be measured, recorded, and repeated for the step input.

The air jet design incorporates a needle, attached to a source of compressed air, which can concentrate air in a small area. The force of the air stream itself is then used to put the necessary pressure on the artery without the use of an actuating object.

Lastly, the protrusion in a cuff design is comprised of an object permanently secured to the interior of an inflatable cuff. The object will move with the cuff and thereby compresses the artery with cuff inflation.

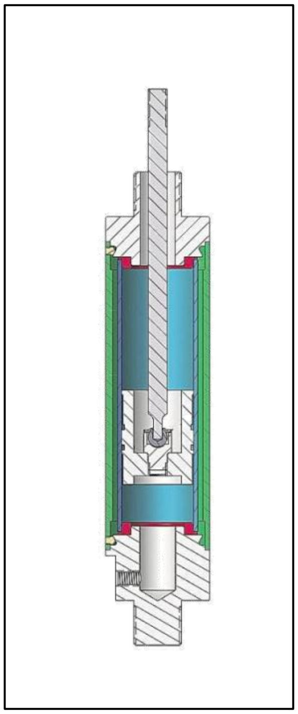


Figure 5: An air-loaded actuator

Image courtesy of Direct Industry: http://www.directindustry.com

Overall system stability and assembly

In order to assemble the components of the system, a stabilizing system is needed to steady the wrist and eliminate motion artifacts from measurements on the radial artery. Furthermore, the stabilizing system needs to incorporate the actuator, ultrasound probe, and pressure sensor to be positioned directly above the artery. Three preliminary designs were proposed for the stabilizing system: a portable brace, a mounted sleeve, and a surface strap.

In the portable brace design, an adjustable Velcro strap holds the stabilizing system together. This design allows the user to move their arm freely but keep their wrist stable, similar to a wrist brace used after injury. The brace contains openings for insertion of the system components. Once the artery is found with the ultrasound probe, the probe can be locked and secured in the same location throughout testing. Similarly, the actuator and pressure sensor are locked once their parameters are set.

The mounted sleeve involves an adjustable cuff on a surface that disallows patient movement. The wrist is inserted into the cuff, which is then adjusted to proper tightness. The ultrasound, sensor, and actuator are placed next to the cuff and can either be secured to the mounted sleeve itself, or to the same surface.

The final design, the surface strap, is similar to the mounted sleeve because the patient's wrist is secured and does not allow movement. Straps (such as Velcro) are attached to a surface and tightened around the wrist and forearm, while the components of the system are attached to the surface next to the wrist.

As shown in **Figure 6**, the position of the ultrasound probe, pressure sensor, and actuator are in the same relative location for every stabilizing design. The only

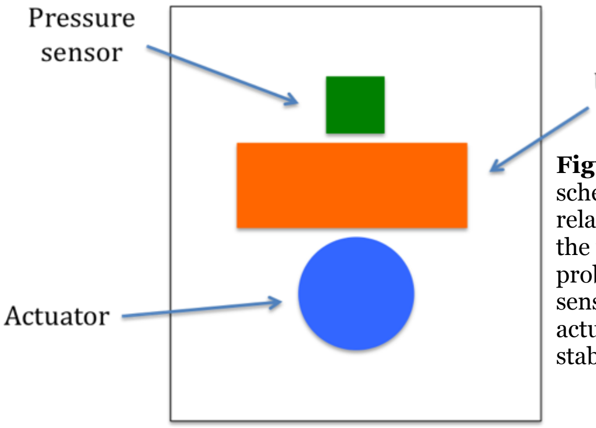


Figure 6: Top view schematic of the relative locations of the ultrasound probe, pressure sensor, and the actuator on the stabilizing system

variation is whether this complex is secured to the stabilizer itself or to a nearby surface. Ideally, the pressure sensor would be directly below the ultrasound but interferences between the ultrasound and pressure sensor may prohibit that conformation.

VII. Design Evaluation

Each preliminary design had its own strengths and weaknesses in comparison to the others, and as a result, was ultimately evaluated with a design matrix. One design matrix was made to evaluate the different actuating mechanisms, while another looked at the overall system stability and assembly methods.

Actuator for measuring arterial stiffness

The four actuating mechanisms were rated on a variety of design criteria. These aspects were selected because of their importance in an effective design. It was determined that certain criteria, such as performance, adjustability, and patient comfort, were more significant, and therefore were weighed more heavily. The scores for each design in each category were added up to give a total score out of 100, which is shown in **Table 1**.

Table 1 – This design matrix displays the design evaluation of the four actuating designs based on a variety of criteria

Weight	Criteria	Spring-Loaded	Air-Loaded	Air Jet	Protrusion in Cuff
30	Performance	24	28	14	14
20	Adjustability	12	17	17	15
20	Patient Comfort	13	13	17	14
12	Ease of Fabrication	9	8	11	11
10	Durability	7	6	9	8
8	Size	6	5	5	7
100	**Total**	**71**	**77**	**73**	**69**

Performance is defined as the ability of the actuator to give an exact step input to the artery. It was given a weight of 30 points in the matrix, designating it as the most important category, because it determines the ultimate effectiveness of the actuating mechanism. The spring-loaded and air-loaded designs scored highest, as it would be rather difficult to make the air jet and protrusion ideas work in an almost instantaneous on-off fashion.

Adjustability is another concern for the actuator. As a result of differing patient body compositions and artery locations, the design must be customizable to perform precisely on a wide variety of patients. The two air-based (air-loaded and air jet) designs are most effective in this area because air pressure can be varied much more easily and precisely than the other approaches. In addition to performance and adjustability, patient comfort was also weighted heavily.

After creating the design matrix, the air-loaded design appears to be the most effective option for the arterial actuator. One flaw of this design matrix, however, is its subjectivity. Most of the ratings given were based on team speculation of how the design would fare in that area. Therefore, though it is likely the air-loaded design will be implemented, experimental testing will be performed on all of the actuating mechanisms to ensure the most effective design is selected.

Overall system stability and assembly

Much like the actuating mechanism, the portable brace, mounted sleeve, and surface strap designs were evaluated using a design matrix (**Table 2**) to determine the best selection for an overall system stability and assembly method.

Table 2 – A design matrix evaluation of the three different overall system stability and assembly methods

Weight	Criteria	Portable Brace	Mounted Sleeve	Surface Strap
30	Patient Comfort	24	21	15
20	Stability	10	18	16
20	Ease of Fabrication	17	16	19
20	Ease of Clinical Use	18	16	16
10	Aesthetics	6	7	5
100	**Total**	**75**	**78**	**71**

Patient comfort stood paramount in deciding the overall system design. If the procedure for measuring blood pressure and arterial stiffness using this mechanism is uncomfortable or painful, the patient will simply opt for the current methods of measurement (which are relatively comfortable procedures). In addition, stress can cause variation in the reading of blood pressure, which makes the device inaccurate. It was determined that the portable brace is the most comfortable method for the patient, followed by the mounted sleeve. The surface strap is significantly more uncomfortable than the others.

Stability is another substantial concern in this design selection; this system must be able to hold the patient's arm relatively still. This is due to the fact that, if the sensor is moved around during reading, motion artifacts will disrupt the output. The portable brace falls short in this category despite standing out in patient comfort. In addition to stability and patient comfort, the ease of clinical use and fabrication were also given significant weight. After careful consideration of each design's strengths and weaknesses, the mounted sleeve design scored the highest in the design matrix. As a result, it will be pursued as the overall system stability and assembly mechanism of the design.

VIII. Future Work

Perhaps the first task that needs to be done is to order materials and components. Specifically, a sensor that can effectively measure blood pressure needs to be ordered. One particular sensor currently under consideration is a piezoresistive pressure sensor. A sample request was sent to All Sensors for their non-invasive blood pressure millivolt output pressure sensor (BP01-G-4V-MINI) seen in **Figure 7** and the surface mount basic pressure sensor. These sensors are approximately 8 mm x 8 mm in area. Furthermore, advice on

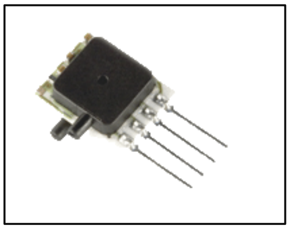


Figure 7: Non-invasive blood pressure sensor model BP01-G-4V-MINI

Image courtesy of All Sensors: http://www.allsensors.com micro-electro-mechanical sensors (MEMS) was received from Ph. D. Candidate Jason Parker from Stanford University. Other companies to research include: Millar, Nova Sensors, SMI, Cardio MEMS, and Digikey.

In addition to sensors, the specific components for the actuator need to be researched and selected. While the air-loaded device will be the focus, the other designs will also be pursued for testing to ensure that the subjective ratings were correct. Finally, raw materials for the assembly of the entire system need to be ordered as needed. This includes the mounted sleeve, as well as options for connecting the sensor, ultrasound probe, and actuator to the overall system.

Professor James A. Will and Mr. Chris Krueger have helped the project by providing ultrasound equipment for experimentation. However, the particular machine is not currently functioning, so it must be fixed in order to give proper output. In addition, once a sensor is selected, it must be tested to ensure it can output a correct blood pressure waveform. This eventually will be converted to useful arterial blood pressure and stiffness data. Once all of the components are tested and functional, the whole system will be assembled. The components and procedure of measuring blood pressure and stiffness will then be tested using the entire device.

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