Edemeter: Wearable and Continuous Fluid Retention Monitoring

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***Abstract*— Fluid retention, known medically as edema, is caused by the retention of fluid in the soft tissue of the lower extremities. This is most commonly found in the ankles and feet due to the effects of gravity. In this paper, we present a wearable device worn around the ankle that monitors edema in the legs and alerts the user of changes. We discuss the Edemeter system's physical and functional design. We also present results from several experiments characterizing the use of flex sensors for measuring ankle swelling, as well as system component power consumption and its impact on battery life.**

I. Introduction

Congestive heart failure is the most common cause of hospitalization and readmission in the United States, costing $39.2 billion dollars annually [1]. Monitoring fluid volume status in patients with chronic heart failure outside of the clinical setting is widespread. The current method for monitoring the condition involves weighing the person several times a day. This can be unreliable since weight gain and loss is affected by a range of factors, in addition to fluid retention. Also, patients can often forget to measure or misremember their weight.

We present a wearable system to monitor lower extremity edema, a common sign of an impending heart failure exacerbation [2], as a way to prevent hospital admissions. Edema can be exacerbated by salt intake and prolonged standing; and it is associated with a number of conditions aside from heart failure, including venous insufficiency and deep vein thrombosis.

We have developed the Edemeter prototype, composed of a Bluetooth-enabled sensored ankle cuff, leveraging data from a flex sensor. With the flex sensor, as the swelling progresses or regresses, the sensor will conform to the shape of the ankle. Following some local processing with a mini-microcontroller, the data from the ankle cuff is wirelessly transmitted to the user's smart phone for storage and for interfacing with the user. Figure 1 provides an overview of the system hardware architecture.

In our experimental results, we examine the feasibility and accuracy of a wearable and continuous approach for detecting edema. Specifically, we examine the sensitivity and accuracy of a variety of flex sensors in estimating small, on the order of a few millimeters, changes in the ankle size. We look at the consistency of the data over extended periods of time, up to an hour. We also examine the power consumption of various protocols for processing and transmitting the data from the ankle to a paired mobile device.

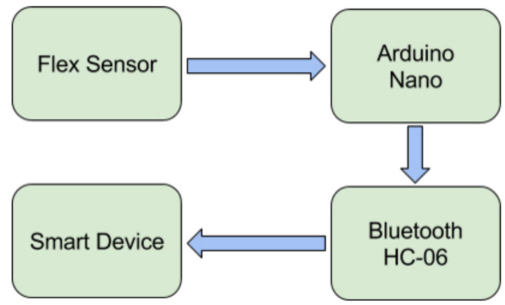

Figure 1. Edemeter hardware architecture composed of a flex sensor affixed to a wearable cuff, an Arduino Mini Pro microcontroller, and a Bluetooth HC-06 module to transfer data to the user's smart phone.

The remainder of this paper provides an overview of the related work in lower extremity monitoring using wearable computing, along with heart failure-induced fluid build-up monitoring approaches. Our Edemeter prototype is described with elaboration regarding its hardware architecture. In depth experimental results and analysis of the Edemeter components in terms of accuracy, consistency, and power consumption are also provided.

II. Related Work

Wearable computing and sensors placed on users' shoes have been leveraged in gait and lower extremity monitoring in the research literature. For example, Hwang et al used the sound generated by the user's footsteps to recognize the terrain on which the user is walking on [3]. Donkrajang et al [4] monitored footsteps using force sensors, leveraging a microcontroller and a ZigBee module to transmit gathered information. Sensored shoes, called smart shoes, have been developed for a variety of applications including detecting diabetic foot ulcers [5] and imbalance [6]. Customizable frameworks for monitoring systems using a variety of sensors have also been developed and explored [7][8].

Due to the significant risks and limited timeframe associated with heart failure exacerbation, research and commercial systems have been developed to create a self-monitoring environment for patient's symptoms. Examples include continuous blood pressure [9], ECG [10], weight [11], and vital signs monitoring for heart failure patients [12][13].

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There is also the monitoring device AVIVO that measures heart rate and fluid level with a monitor strapped to the patient's chest [14], and the commercially available CARDIOMEMS implantable device that monitors systemic fluid levels via direct measurement of the pulmonary artery pressure [15].

Flex sensors have been used for wearable systems. For example, Saggio [16] used flex sensors to measure gestures in a sensored glove. The results from their work demonstrate that the relationship between the bend angle and the flex sensor reading is not linear, a result confirmed in our experimentation.

III. System Design

This paper introduces the Edemeter, a system designed to address continuous monitoring of lower extremity edema, swelling caused by fluid retention. The Edemeter is composed of three main components: a sensored wearable ankle sleeve worn by the user, an Arduino microcontroller for processing and transmitting the sensed data, and a mobile device, running custom software for alerting the user of any events. Figure 2 displays the three components of the system, and Figure 3 provides the schematic of the components inside the wearable sleeve.

The ankle strap is sensored with flex sensors, which are lightweight (less than 3 grams), inexpensive, and bendable resistors, whose resistance and associated voltage readings vary with bending and stretching events. Bending the sensor increases the resistance, which causes the voltage readings to change.

Figure 2. Components of the Edemeter prototype (a) Sensored ankle cuff with flex sensor (b) Arduino Mini Pro microcontroller with attached Bluetooth module, along with the battery (c) Android app running on paired smart phone.

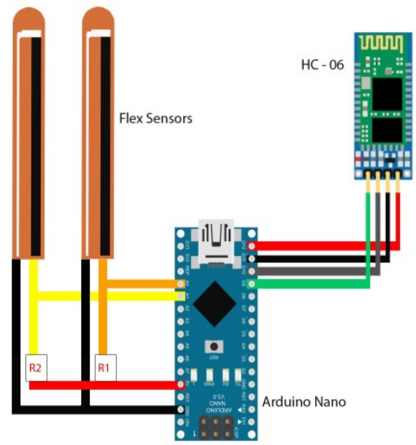

Figure 3. The schematic of the Edemeter hardware used to measure and trasmit the changes in ankle swelling, using changes in resistance registered by the flex sensors wrapped around the ankle.

An Arduino Mini Pro, a small programmable microcontroller, sends the flex sensor values to the user's phone via a Bluetooth module. The smart phone is used to alert the user of any swelling. The connection between the Arduino Mini Pro and the smart phone application leverages the Amarino 2.0 toolkit [17][18] which establishes a two-way communication between an Android phone and any microcontroller connected to a Bluetooth module.

IV. Experimental Results

In our experimentation, we examined the feasibility and accuracy of using flex sensors for determining changes in fluid retention in the ankles. We also reviewed the power consumption and its impact on battery life, for various system components and data transmission protocols. The experimental set-up and the results are presented in this section.

A. Flex Sensor Reading Accuracy

We carried out a series of experiments to determine the feasibility of using flex sensors for our intended application. Specifically, we measured the sensitivity of the flex sensor in determining changes in ankle size. The analysis examined a range of commercially available flex sensors.

We compared five flex sensors from different manufacturers and of different lengths (4.7 inches, 3 inches, and 1 inch in length). As demonstrated in Figure 4, the flex sensors were wrapped around five different cylinders and the readings were compared against the known cylinder sizes. Table 1 summarizes the sensors used in the experiments. The diameters of the cylinders ranged between 76.13 mm and 110.75 mm to replicate the size of a human ankle.

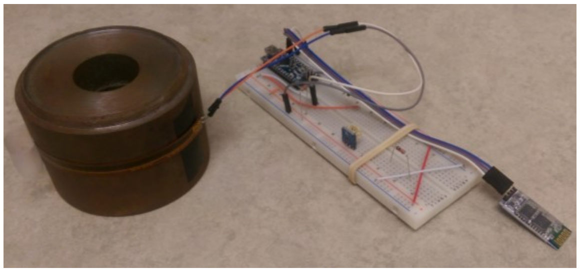

Figure 4. Experimental set-up used to measure flex sensor's sensitivity to changes in swelling. Flex sensors were wrapped around cylinders of varying diameters.

TABLE I. FLEX SENSORS AND SIZES EXPERIMENTALLY VERIFIED

Flex Sensors	Size (millimeter)
Robomesh 4.7”	119
Sparkfun 4.7”	119
Adafruit 4.7”	119
Adafruit 3”	76
Sensor Products 1”	25

The voltage readings of the flex sensor depend on resistance, which varies with the bend of the sensor. The readings range between 0 and 1023 voltage units, where 1023 represents 5 volts and 0 represents 0 volts. The flex sensor voltage units, a total of 1024 units, can be converted to volts by multiplying them by 0.0049. After setting up the sensor in the proper position, we used our application and Android's logcat to log the readings of the sensor for a period of one minute and store the values along with a timestamp.

TABLE II. FLEX SENSOR READINGS FOR A VARIETY OF CYLINDER DIAMETERS FOR FIVE DIFFERENT COMMERCIALLY AVAILABLE FLEX SENSORS (1 UNIT = 0.0049 VOLTS)

Flex Sensors	Cylinder Diameters (mm)				
	76.13	**82.57**	**88.82**	**107.4**	**110.75**
Robomesh 4.7”	482.3	491.2	505.3	516.6	527.5
Sparkfun 4.7”	530.3	536.2	542.3	559.7	566.0
Adafruit 4.7”	571.7	573.0	582.3	607.1	613.1
Adafruit 3"	286.8	293.1	299.5	322.7	321.6
Sensors Products 1”	752.2	754.61	756.8	753.7	754.8

The results presented in Table 2 provide the sensor readings measured from all five flex sensors for all five cylinders. The results indicate that swelling on the order of millimeters can be detected in some of the tested flex sensors.

For the two nearest cylinders, in terms of diameter, 107.4 mm and 110.75 mm, the large 4.7” flex sensors from Robomesh, Sparkfun, and Adafruit were able to differentiate the two cylinders, while the two smaller sensors failed to detect the difference.

B. Flex Sensors Reading Stability

TABLE III. STANDARD DEVIATION IN FLEX SENSOR READINGS ACROSS A RANGE OF FLEX SENSORS (1 UNIT = 0.0049 VOLTS)

Flex Sensors	Cylinder Diameters (mm)				
	76.13	**82.57**	**88.82**	**107.4**	**110.75**
Robomesh 4.7”	0.91	0.50	0.48	0.96	0.55
Sparkfun 4.7”	0.84	0.68	0.74	0.48	0.69
Adafruit 4.7”	0.54	0.72	0.63	0.45	0.31
Adafruit 3"	0.90	0.79	0.81	0.66	0.60
Sensors Products 1”	0.66	1.12	0.82	0.69	0.69

Five different sensors were evaluated with regards to consistency and stability of readings. For readings collected continuously for a period of one minute with a rate of roughly 8 readings per second for a fixed cylinder size, the variation in the data readings was examined. The sensor from Adafruit had the smallest standard deviation values ranging between 0.31 and 0.72 units. The smallest sensor, from Sensor Products, had the largest amount of fluctuation in the readings having a standard deviation that ranged between 0.66 and 1.12 units. It was also interesting to note that in general, the standard deviation values were smaller on the large cylinders. The results are summarized in Table 3.

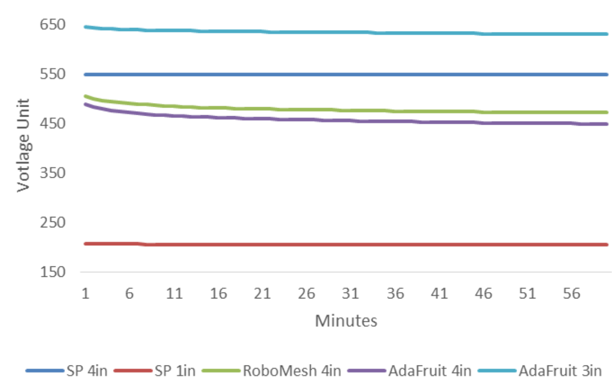

Figure 5. Average readings, taken every minute, of the 5 different flex sensors for a one hour. The actual scaling for all possible readings exist in the range from 0 as the lowest possible to a maxium value to 1023. (1 unit = 0.0049 volts)

Figure 5 demonstrates the voltage unit readings for five different sensors over a one hour period collected on the 110 cm diameter aluminum cylinder. Both the Sensor Products flex sensors (1 inch and 4 inch) maintained an almost constant value over the course of an hour. The other sensors degraded over time as their shape conformed to that of the cylinder. Thus the Sensor Products sensor was chosen for the Edemeter and used for the next set of experiments.

D. *Sensor Testing – Silicon Material Data*

To replicate the soft, compressible feel of a human ankle, cylindrical silicon molds were used for testing. Cylinders cut out of condensed foam using a computer numerical control (CNC) machine were used to cast the silicon. The range of diameters was derived from a male ankle and offsets of +3%, +5%, -3% and -5%. Those measurements are shown in Table 4.

TABLE IV. MANUFACTURED MOLDS. SILICON MATERIAL WAS USED TO REPLICATE A CYLINDRICAL SLICE OF THE HUMAN ANKLE. A PARTICIPANT'S ANKLE WAS MEASURED TO CREATE A BASELINE MOLD. OFFSETS OF THE ORIGINAL READINGS WERE USED TO INDICATE POSSIBLE INCREASED SWELLING THAT A PATIENT MAY ENDURE.

Mold	Diameter (millimeter)
+3%	86.94
+5%	85.28
Baseline Model	82.80
-3%	80.32
-5%	78.66

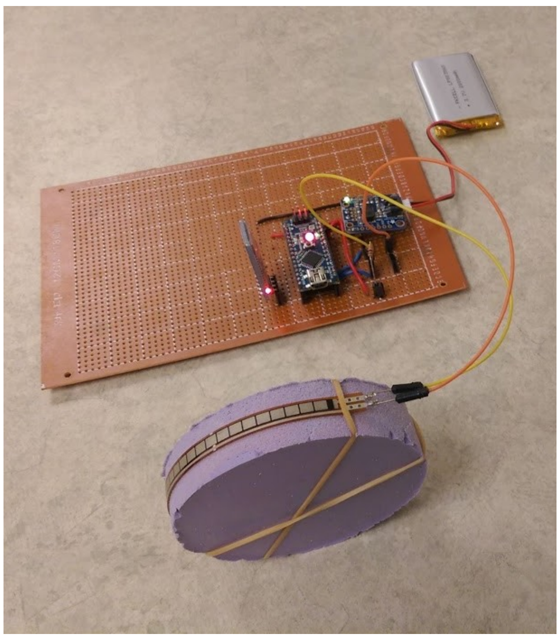

Figure 6. Photograph of the experimental setup to measure the mold circumfrance using the Edemeter.

To determine the accuracy and precision of the flex sensor in reading the various ankle circumferences, the sensors were affixed to the mold for 20 minutes. A photograph of the experimental set-up is provided in Figure 6. The results are graphed in Figure 7.

Note that the variation in the mold sizes is an order of magnitude less than that of the cylinders used in the previous experiments. Yet still, the sensor is successfully able to record the difference between the molds fairly consistently over a 20 minute period. There are a few instances where the baseline mold and the -3% mold overlap in their readings or their readings are inconsistent. Similarly for the -3% and -5% molds, there are a few instances where the readings are the same or the inverse of the expected values. Averaging the values over a fixed period of time would prevent these occasional discrepancies from disrupting the overall reading. All of the other molds are consistently differentiable.

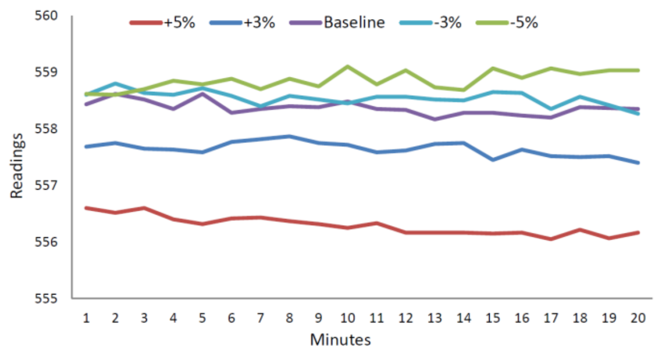

Figure 7. The data that the Edemeter received when measuring several varying molds. The data generated by the sensors indicate a successful experiment in detecting change between molds. When testing molds with larger diameters a change in resistance was generated by the flex sensors. In turn, the maximum generated voltage units that could be read decreased. The actual scaling for all possible readings exist in the range from 0 as the lowest possible to a maxium value to 1023.

Note, Figure 7 also demonstrates how the readings are consistent over time for the Sensor Products flex sensor. This was not the case for the other commercially available sensors.

C. *Power Consumption*

In our experimentation, we also evaluated the power consumption of the Edemeter components. Since the user will be wearing the device throughout the day, the battery supply should allow for at least a day of continuous use.

All the system components consume power, including powering the Arduino, powering the Bluetooth module, reading data from the flex sensor, and wirelessly transmitting the data via Bluetooth.

We measured the battery usage of the system in different states. The Bluetooth module draws varying amounts of current when disconnected, connected, and when sending data. To measure this consumption, a multimeter was attached in series with the power supply of the module to measure current intake. While disconnected, i.e. not paired to a smart phone, the device draws between 4 to 7 milliamps (mA) for a few seconds. When attempting to pair with the smart phone it draws 35 to 40 mA. When pairing with the smart phone, 35 to 40mA of current were drawn. The data transfer rate was positively correlated to the amount of current that the system needed. Once connected, the amperage decreased and varied between 25 to 29 mA while data was being sent. These results are summarized in Figure 8.

The flex sensor requires 130 microamps (µA). The Arduino took a measured 8 milliamps to function, without powering other equipment. In total and under normal conditions, the system would demand a minimum of 40 milliamps of constant current to operate.

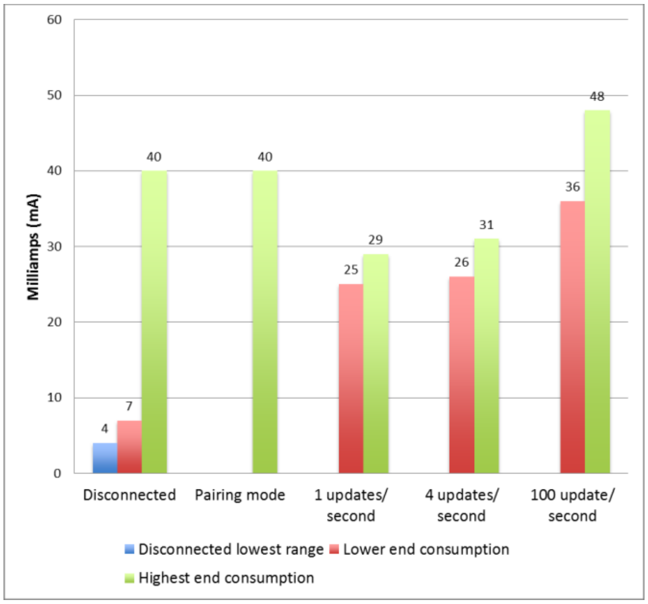

Figure 8. Current consumption of the Bluetooth module.

When and how often the smart phone is notified of readings significantly impacts battery life, since the main source of the system's power consumption is the Bluetooth module. As seen in Figure 9, power consumption is similar whether data is processed and then sent or sent as data comes in. Increasing the length of intervals between data transmission conserves power, as expected. In our experimentation 10, 20, and 60 minute in intervals were considered.

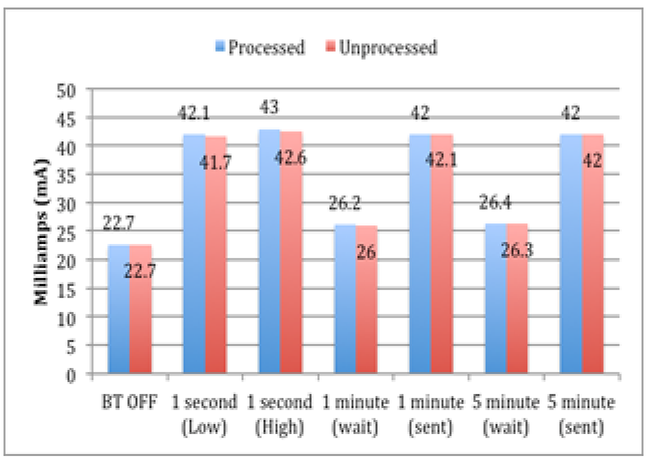

Figure 9. Power saving across various the HC-06 Bluetooth module data transmission rates.

The 'wait' bars, in Figure 9, display the power consumption of the system when information is sent after a wait period. The most energy efficient approach involves turning off the Bluetooth module when not in use, since the current draw is 22.7 mA during sleep intervals.

V. Conclusion

We presented a new wearable approach to monitoring lower extremity edema, the swelling of the ankles and feet, with an important application to prevent hospitalization of patients suffering from congestive heart failure. Experimental analysis of various factors addressing the approach feasibility were provided, including the accuracy of flex sensors in detecting small changes in ankle shape and size and the effects of data transmission and local processing on power consumption and system battery life.

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