Sensor-based system for verifying blood-pressure measurement position

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Sensor-based system for verifying blood-pressure measurement position

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Honors Thesis in Computer Science
Advisor: David Kotz
May 2012

Abstract

Mobile maternal-health programs send workers door to door to visit pregnant women in rural India and collect data such as blood pressure or weight, then send that data to doctors for review. Since the doctors do not see the data collection, ensuring correct collection methods is crucial to allow them to make good treatment decisions. However, blood-pressure measurements are sometimes taken with the patient’s arm in the wrong position, which can cause inaccurate readings. This paper describes a system consisting of an automatic blood pressure cuff with an accelerometer and force sensors attached to determine whether the arm is at the correct angle, held still, and properly supported. A user study indicated that the prototype was effective in helping untrained users take a measurement in the correct position.
1 Introduction

Though our system could have wide-ranging applications, the following scenario guided our design: A clinic in an Indian town sends health workers door to door in rural areas to visit pregnant women and collect a set of data about their health. These workers have completed a training course, but they are not doctors or nurses and may have less than a high school education. Each health worker carries a sensor kit containing, for example, a blood-pressure cuff, thermometer, spirometer, and pulse oximeter. At each house, they use each sensor to take measurements of the pregnant woman and save the data in a smartphone application. The data is later synced with the clinic’s medical records, and doctors review the data and recommend further treatment as necessary. One current example of this scenario is the E Health Point project in India’s Punjab state.¹

1.1 Provenance in mobile health

To make good treatment decisions, the doctors at the clinic must understand whom the data was collected from, how it was collected, where and when it was collected, and whether the data has been changed or preprocessed since it was collected. We call this information provenance. This project investigates one aspect of provenance: whether a blood pressure measurement was taken with the patient’s body in the correct position.

1.2 Importance of blood pressure

Studies estimate that high blood pressure causes complications in 6 to 8 percent of all pregnancies [3]. Pregnancy-induced hypertension is a sign of preeclampsia, which can cause kidney, liver, and brain problems in the mother and low birth

¹www.ehealthpoint.com
weight, premature birth, or stillbirth in the infant [4]. Therefore, monitoring blood pressure is crucial to prenatal care.

1.3 Blood pressure measurement error

Numerous studies have shown that blood-pressure measurements vary significantly when the patient’s body is in different positions. If the arm is below heart level, the reading will be too high, and if it is above heart level, it will be too low [1]. One study found that the difference between measuring with the arm hanging at the side vs. with the arm at heart level and supported was 16.35/9.81 mmHg in patients with normal blood pressure, and measurements with the arm at heart level but not supported differed from supported measurements by 7.61/2.83 mmHg [2].

The correct position (see Figure 1, Figure 6) is when the cuff is at the same level as the right atrium of the heart, which requires that the upper arm be extended forward about 45 degrees. The arm should also be still and supported at the elbow, because moving the arm or extending it without support means exerting the muscles [6]. Support may mean a stand or table, or simply the care provider holding the patient’s elbow [1].

Figure 1: Correct blood-pressure measurement position
Even in ideal medical settings with a doctor in a well-equipped office, blood-pressure measurements are often taken incorrectly. For example, a 1995 study at a major Colombian hospital found that 73% of doctors and nurses took measurements with incorrect arm positions [7]. In our scenario, with relatively untrained health workers and unpredictable settings, the risk is likely higher.

1.4 Objective

Our objective was to use sensors to determine whether a patient’s arm is in the correct position during a measurement, and provide feedback to the user so that it can be repeated if necessary. Such a system could prevent flawed data caused by incorrect arm position (by prompting the user to repeat as needed, and by teaching the correct position over time), or flag it when it does occur so doctors can take position information into account when judging a patient’s blood pressure.

1.5 Related Work

The company Omron recently released an automatic wrist blood-pressure cuff aimed at consumers, claiming that the cuff activates when at heart level, but it is unclear what mechanism is used to determine the level.² Automatic blood-pressure machines at drugstores often have the cuff in a fixed position that forces the user to take the measurement correctly, but this sort of solution is not very portable. Otherwise, efforts to improve blood-pressure measurement technique have largely focused on offering clear directions. For example, the iPhone application that comes with the Withings automatic blood pressure cuff prompts the user to click through five pages of diagrams before starting a measurement for the first time (Figure 2).

²www.omronhealthcare.com/products/7-series-wrist/
2 Implementation

From a user’s perspective, our prototype works as follows: the patient puts his arm in the cuff that is attached to an iPhone, and through a sleeve attached to the bottom of the cuff. The care provider secures the cuff around the user’s arm, then presses “start” on both an app on the iPhone and an app on a nearby desktop. The cuff inflates automatically. Throughout the measurement, the computer displays a window saying a) whether the arm is at the correct angle, b) whether the arm is still, and c) whether the arm is supported (see Table 1, Figure 8). If the patient moves, these messages update accordingly. The measurement takes about 40 seconds. When it has finished, the iPhone app displays the blood-pressure reading.

2.1 Hardware

The base of the prototype is the Withings automatic blood-pressure cuff (Figure 3), which attaches to an iPhone and includes an app that allows the user to start the automatic measurement, displays the result, and tracks data over
time. It has a metal cylinder on the front side and a Velcro lining to adjust the size.

Figure 3: A Withings cuff and iPhone application


We attached a Witilt 3-D accelerometer\(^4\) (Figure 4) to the cylinder. The Witilt sends data to the computer via Bluetooth at a 100 Hz rate in the format “X=value Y=value Z=value”, where value can be between approximately 240 and 760.

Figure 4: A Witilt 3-D accelerometer

http://makezineblog.files.wordpress.com/2006/12/witilt_img.jpg?w=500&h=419

\(^3\)www.withings.com/en/bloodpressuremonitor  
\(^4\)www.sparkfun.com/products/8563
To the bottom of the cuff, we attached a neoprene sleeve with two 1.75”x1.5” force-sensitive resistors (Figure 5) attached to the underside. When the user rests his upper forearm on something, the sensors register force. We could not find Bluetooth-enabled force sensors, so they are wired to an Arduino Uno\(^5\) that is attached to the computer via USB. Each sensor measures a value between 0 (no force) and 1023 (maximum measurable force). The Arduino is programmed to write the values of the two sensors to the serial port at a 100 Hz rate. Figure 6 shows the complete system.

Figure 5: A force-sensitive resistor

http://dlnmh9ip6v2uc.cloudfront.net/images/products/09376-1.jpg

Initially, we had hoped to use only the accelerometer, under the theory that we could tell whether the user’s arm was supported because an unsupported arm would jiggle slightly more during measurement. We tried a variety of data analysis methods, but we could not find a one that reliably distinguished a supported arm from an unsupported one, so we added force sensors to the prototype.

\(^5\)arduino.cc/en/Main/ArduinoBoardUno
2.2 Software

A Python script opens connections to the two serial ports and reads the data in one thread. A second thread repeatedly gets the data read in the last half-second, parses it, and calculates several values:

- the average $x$, $y$, and $z$ values
- the range of the values for $x$, $y$, and $z$, then the sum of these ranges
- The average values for each of the force sensors, then the maximum of these averages
We know that the arm should be still and at a 45-degree angle from vertical. However, we have not found any research on exactly how much deviation from that ideal should be considered incorrect, so our choice of thresholds was arbitrary and should be studied further. For the user study, we used $\pm 10$ degrees and a range of 200 (in the Witilt’s raw data units) in any dimension. The angles were calculated by using a protractor to place an accelerometer at 35 and 55 degrees, and observing the resulting $y$ and $z$ values. As Figure 7 shows, the $x$ value largely reflects where on the circumference of the arm the accelerometer is, rather than the angle of the arm, so it was ignored.

For the pressure threshold, we want to use a value representing the full weight of the subject’s arm, indicating that their muscles are completely relaxed. We observed the values generated by lightweight users, and set the cut-off slightly below these values, at 500 out of a maximum of 1023 (in the force sensors’ raw
data units). A value that means a 100 lb person is relaxing their arm completely might mean a 300 lb person is not, so this cut-off is also imperfect. However, if support is provided, most people will automatically relax their arm fully. For the purpose of the user study, this thread also keeps a counter that is used to calculate the percentage of the time each metric was correct at the end of the measurement.

The main thread of the script uses Tkinter to open a window. While the serial port connections are being opened, the window says “Calculating . . .” Once connected, the window displays either a confirmation message in green or an error message in red for each metric: angle, movement, and support (Figure 8). These messages change quickly when the user changes his position. Table 1 shows the possible messages:

<table>
<thead>
<tr>
<th>Metric</th>
<th>Correct</th>
<th>Incorrect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle</td>
<td>Your arm is at the correct angle.</td>
<td>Your arm should be at a 45 degree angle from your torso.</td>
</tr>
<tr>
<td>Movement</td>
<td>Your arm is still.</td>
<td>Your arm is moving too much. Try to hold it still.</td>
</tr>
<tr>
<td>Support</td>
<td>Your arm is supported.</td>
<td>Your arm is not supported. Rest your forearm on something solid.</td>
</tr>
</tbody>
</table>
3 User Study

We recruited undergraduate and graduate students for a user study of our prototype. We excluded potential participants who had significant experience taking blood-pressure measurements (for example, students who are trained as EMTs), but participants were still not an ideal representation of potential users in rural India, because they are all educated and have had their blood pressure taken at doctor’s visits all their lives. Therefore, they are more likely to know what the correct position looks like, and less likely to feel anxious or confused by the process.

In each pair, one person represented the health worker and one represented the patient. Both participants were seated in office chairs next to a desk. The researcher showed the health worker how to put the cuff on the patient’s arm and use the Withings iPhone app to start the automatic blood-pressure measurement. The researcher simultaneously started the data analysis script on the
desktop. The researcher did not provide any information about what position the patient should be in; the users were simply told to follow the computer’s instructions. An example of a common starting position is shown in Figure 9.

Figure 9: A common starting position in the user study

Participants could then adjust their position as directed by the computer and observe the feedback. When the measurement finished, the researcher stopped the script, which caused it to calculate the percentage of the time each metric was judged as correct. Each team took three consecutive measurements.

4 Results

Our user study enrolled 11 male and 9 female students in teams of two. Table 2 shows the percentage of the measurement time that each metric was correct, as measured by our program. In a few cases, the program did not produce the response we would expect from observing the user. These situations are described in the discussion.
Table 2: Percentage of measurement time in which metric was correct

<table>
<thead>
<tr>
<th>Team</th>
<th>1st run</th>
<th>2nd run</th>
<th>3rd run</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>59.5</td>
<td>95.2</td>
<td>83.3</td>
</tr>
<tr>
<td>2</td>
<td>97.8</td>
<td>97.8</td>
<td>44.4</td>
</tr>
<tr>
<td>3</td>
<td>87.0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>45.0</td>
<td>100</td>
<td>17.5</td>
</tr>
<tr>
<td>5</td>
<td>12.5</td>
<td>100</td>
<td>82.1</td>
</tr>
<tr>
<td>6</td>
<td>26.7</td>
<td>93.3</td>
<td>73.3</td>
</tr>
<tr>
<td>7</td>
<td>97.5</td>
<td>97.5</td>
<td>77.5</td>
</tr>
<tr>
<td>8</td>
<td>88.7</td>
<td>95.0</td>
<td>90.0</td>
</tr>
<tr>
<td>9</td>
<td>46.4</td>
<td>92.9</td>
<td>35.7</td>
</tr>
<tr>
<td>10</td>
<td>17.8</td>
<td>91.1</td>
<td>46.7</td>
</tr>
</tbody>
</table>

Table 3 shows the average across all teams of the percentage of the measurement time that each metric was correct, separated by run number.

Table 3: Average time correct percentage

<table>
<thead>
<tr>
<th></th>
<th>1st run</th>
<th>2nd run</th>
<th>3rd run</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle</td>
<td>58.89</td>
<td>82.02</td>
<td>92.27</td>
</tr>
<tr>
<td>Movement</td>
<td>96.28</td>
<td>96.87</td>
<td>99.84</td>
</tr>
<tr>
<td>Support</td>
<td>65.05</td>
<td>77.29</td>
<td>97.14</td>
</tr>
</tbody>
</table>

The difference between the first run and the third run for the support metric is statistically significant for $p = .005$. The difference for the angle metric just misses statistical significance: a 34.79% difference would be required for a 95% confidence level; the difference is 34.38. The difference for the movement metric is not statistically significant.

5 Discussion

The results indicate that a sensor system with immediate feedback is helpful in guiding unskilled users to take a blood-pressure measurement with their arm in the correct position. A discussion of potential improvements and adjustments for field use follows.
5.1 Study issues and improvements

For one patient with muscular forearms, the sleeve was tight enough that the force sensors registered support when the user was not resting his arm on anything. We adjusted the sleeve to make it wider so this did not happen, but as the sleeve size increases, it becomes somewhat clumsy for users with smaller arms. A second patient thought that the presence of the sleeve meant that he was not supposed to bend his elbow, making it harder for him to figure out how to support his arm. A stretchier sleeve, with force sensors that do not register force upon bending, might solve both issues. One possibility is making the whole sleeve out of conductive cloth.

In one case, the cuff was not attached securely and the part of the cuff that should be on top of the patient’s arm slipped to the side, causing the angle to register as incorrect even when the patient’s arm was in the correct position. The Withings app has some built-in protection for this situation: a measurement will not be registered if the cylinder that is supposed to be on top of the arm is too far off. However, it would be useful to try to recognize this situation from the angle of the accelerometer and adjust the UI accordingly.

Some users, when prompted to support their arm, would at first support only the lower end of their forearm, where there were no sensors, and were confused about why the program still said their arm was not supported (shown in Figure 10). The prototype could instead use a sleeve that covers the whole arm, or it could simply adjust the error message to tell the user to support their upper forearm specifically.
Two users commented that they would have learned faster if the program told them to move their arm forward or backward, rather than simply saying the angle was incorrect. Diagrams would also likely be useful.

5.2 Scenario use

A final product would be far less clumsy, with no need for a computer and multiple data transfer mechanisms. The sensors would be built into the cuff, and the data analysis and user feedback would be built into the same app that starts the cuff and stores the data. For example, this could be built on top of the open-source mobile medical record application Sana.6

The cut-off points at which the program declares that the position is invalid should be reevaluated with a medical expert’s input as to how much deviation from the ideal position is acceptable.

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6sana.mit.edu
Adding diagrams to the UI would be especially useful if the health workers are not educated, because the concept of what a 45-degree angle looks like requires a certain level of math knowledge.

In the field, it is possible that a measurement would be taken in the wrong position not by mistake, but because, for example, an ill patient is lying down and does not want to sit up. When the position is incorrect, the app should first prompt the worker to repeat the measurement. If she declines, the app should not refuse to record data in the incorrect position, but should flag it and allow the worker to add a comment about why, so that anyone reviewing the data can take that into account when making diagnoses. This system would also allow the worker to manually flag the data, for example, if the patient is extremely nervous, which can raise blood pressure by up to 30 mmHg [1]. The app could also consider the measurement in the context of other information gathered about the patient. For example, edema (swelling) is sometimes a problem for pregnant women, and a swollen arm can change the blood-pressure reading. The app might flag the blood-pressure reading if the worker notes edema.

Though our design focused on this use case, the concept could also be useful in developed countries, especially in consumer products for home use.

5.3 Limitations

There are many user factors that can affect blood-pressure readings, and some would be difficult to measure with sensors without making the device very cumbersome. For example, the system does not consider whether the patient has been moving around right before the reading, whether she is standing up or crossing her legs, whether she is stressed or nervous, whether the cuff is too big or too small, whether the measurement is taken over clothing, and so on.
6 Conclusions

A sensor-based system with immediate feedback helps people take blood-pressure measurements in the right position. To improve our prototype, the design of the sleeve containing the force sensors should be made more flexible and intuitive, and the user interface should use diagrams and text to provide more information about what action the user should take to improve his position.

References


