Version of Record: https://www.sciencedirect.com/science/article/pii/S235264831930056X
Manuscript_909fb04c4dec16cba9b878f8fc518fb5

TracKnee: Knee Angle Measurement Using Stretchable Conductive Fabric Sensors

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Abstract

Knee injuries are common and can be costly for a patient in terms of recovery time and monetary contribution. Wearable technology can be used to help monitor a patient's progress and their adherence to rehabilitation protocols. Further, estimating joint angles can help medical professionals treat their patients effectively. In this paper, we propose three models that can be used in succession to calculate knee angles from a voltage reading from a conductive fabric sensor. These models take an input of voltage, calculate the resistance of our conductive fabric sensor, then calculate the change in length across the front of the knee, and finally calculate the angle of the knee. We present TracKnee, a sensing knee sleeve designed and fabricated to unobtrusively measure knee angles. We evaluated our model and our device by conducting a user study with six participants where we collected 240 ground truth angles and sensor data from our TracKnee device. Our results show that our model is 94.86% accurate to the nearest 15^{th} degree angle and that our average error per angle is 3.69°.

Keywords: Healthcare, Wearable Technology, E-textiles

1. Introduction

Knee injuries are prevalent among all demographics of the population and the treatment of these injuries can be costly in recovery time and monetarily[1]. From 1999 to 2011, a study of more than 6.5 million knee injuries in the United States revealed that nearly 50% of the knee injuries were sports-related with adolescents making up an estimated 2.5 million sports-related knee injuries annually [2]. In the senior population, knee injuries are common due to falling and diseases such as osteoarthritis. More than 14 million individuals suffered from osteoarthritis of the knee is 2007 and 2008 in the United States[3]. Regardless of age and type of injury, a patients' recovery from a knee injury is based on their adherence to their assigned rehabilitation protocols[4][5].

Technologies such as wearable devices can be used to help monitor the patients' adherence to their rehabilitation protocols. It can be used inside and outside of a clinical setting to enhance a patient's treatment plan [6][7]. It can also be used to enhance and individually tailor each patient's protocol to best suit their needs [8]. Proper monitoring and adherence to the prescribed protocols can be used to help decrease a patient's recovery time, their overall pain, and the cost of their treatment. Further, soft wearable flexible sensors have been created to non-invasively record biometric data on patients [9].

Joint angle estimation is an important part of monitoring knee injury recovery[10]. Wearable sensors are frequently used for monitoring of joint angles. Many different sensors have been used to accomplish this task including IMU's [11][12][13], ultrasonic sensors [14][15][16], optical sensors [17][18][19] , liquid metal sensors [20][21], potentiometers [22], acoustic sensors [23] , force sensitive resistors [24], retractable string sensors [25], and galvanic coupling systems [26], and flex sensors [27][28]. Soft, flexible, wearable E-Textile sensors have also been used to monitor joint angles[29] [30] [31] [32].

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In this paper, we address the following research questions:

RQ1: How can we measure knee angles using stretchable conductive fabric?

RQ2: How can we design and fabricate a wearable device that tracks knee angles using conductive stretchable fabric and is comfortable to wear?

RQ3: How accurately can we measure knee angles with our wearable device?

To answer our first research question, we develop three models to be used in succession. First, we developed a model to calculate knee angles from the change of length across the front of the knee. To do this, we run an experiment with ten individuals of varying height in which we record the values for the change in length across the front of each of their knees at four different angles. Then we develop an Ordinary Least Squared (OLS) regression model that uses height and change in length across the front of the knee to calculate knee angles. Second, we developed a model to calculate the change in the length of conductive fabric from the resistance of the conductive fabric. To do this, we performed an experiment in which we repeatedly stretched our conductive fabric to specific lengths and recorded the resistance at each length. We then modeled this data with a third-degree polynomial regression. Third, we modeled voltage to the resistance of our fabric using a voltage divider. Overall, using these models allowed us to measure knee angles using our stretchable conductive fabric.

To answer our second research question, we designed and fabricated our TracKnee device. Our TracKnee device had the following requirements: (1) It should be able to collect data from the conductive fabric sensor and wirelessly send it to a collection location. (2) It should be comfortable to wear and be easy to put on and take off. (3) It should be washable and be able to be cleaned as needed. Our device consisted of two main parts a control patch and the sensor sleeve. The control patch houses all the non-washable electronic components needed to control the device and wirelessly connect to a smartphone to send data. The sensor sleeve houses the conductive fabric sensor and conductive fabric wiring allowing it to be washable.

To answer the third research question, we conducted a user study to collect TracKnee sensor data and ground truth angles and used that data to evaluate our models. Our user study consisted of ten participants and 240 knee angles. We collected TracKnee sensor data and ground truth angles. Then we used our models to calculate the angle of the knee from our TracKnee sensor data. We compared that angle to the ground truth angle to evaluate. Overall, we saw an accuracy of 94.86% to classify our knee angles to the nearest 15^{th} degree. The average error from the calculated angle to the ground truth is 3.69°. Following this, we evaluated our prototypes battery life. The battery life was 18 minutes and 50 seconds for a 40 mAh battery. Since the battery is removable, it can be replaced when it is fully discharged or a larger battery can be used.

Measuring human body joint angles is receiving an increasing amount of attention from the medical science and computing disciplines [33][34][35]. Since there is a growing movement to collect human motion data outside of a lab setting [6] [9] researchers have begun looking to more comfortable This enables researchers to collect more data in the real world which is essential when treating diseases. Soft, flexible, wearable E-Textile sensors allow for the comfort of the wearer while allowing still enabling the collection of critical biometric data. Our TracKnee prototype utilizes a soft conductive fabric to measure the joint angle of the knee allowing for comfort during long term use.

Our contributions are summarized as follows:

- We propose three models that can be used in series to calculate knee angles from voltage. First, we model change in length across the front of the knee to the knee angle with respect to the height of an individual. Second, we model resistance of the fabric to change in length of the conductive fabric. Third, we model voltage to the resistance of the fabric.

- We designed and fabricated a wireless sensing knee sleeve to unobtrusively measure knee angles called TracKnee. TracKnee utilizes a soft and stretchable conductive fabric sensor to monitor knee angles. We designed it to be washable by making any non-washable electronic components removable. We also designed to be easy to put on and take off so that it would be as easy for the user to wear as a non-sensing knee sleeve.

- We conducted a user with six participants where we collected ground truth angles and sensor data from our TracKnee device. To do this, we developed a data collection application on an Android smartphone to collect and store the data.

- We evaluated our models on the user study data. Our results show that our model is 94.86% accurate to the nearest 15^{th} degree angle and that our average error per angle is 3.69°.

The remainder of our paper is organized as follows. First, in Section 2, we discuss the three models that we propose to calculate knee angles. Next, in Section 3, we explain how we designed our TracKnee prototype to be comfortable, washable, and unobtrusive. Following that, we describe the data we collected and our methods for collection in Section 4. Then, in Section 5: Experimental Results, we evaluate models described in Section 2 with the data recorded in the 4. In Section 6, we discuss the Related Works. Finally, we draw our conclusions in our final section.

2. Modeling

Overall, we show that we can model knee angles based on the stretch of our conductive fabric. To do this, we need three models. First, we model the length across the front of the knee to the angle of the knee with respect to different human heights. Second, we model the length across the front of the knee to the resistance of our conductive fabric. Third, we model the resistance to the voltage that we read as an output of our voltage divider. These models can be used in a linear progression to calculate knee angles from voltage.

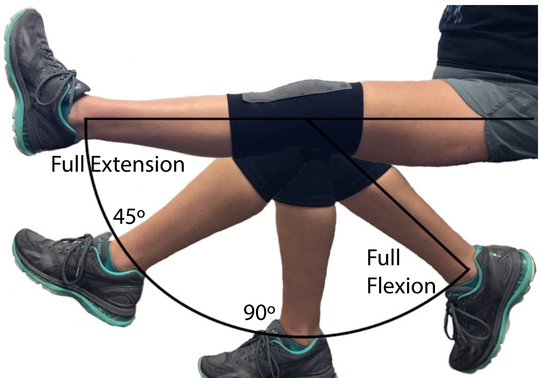


Figure 1: Measured Knee Angles

2.1. Change in Length to Angle Model

From medicine, we know that the normal range of knee motion is −10° to 130°[36]. Extension of the knee is defined as the straightening motion of the knee that results in an increase of the angle. Flexion of the knee is defined as the bending of the knee that results in a decrease of the angle. Full extension and full flexion are the max values of these motions. We illustrate these values in Figure 1. Between the full extension and the full flexion, there are many angles. To modeling the change in the length across the front of the knee and the angle of the knee, we measure the angle of the knee from full flexion to full extension in increments of 45°. To collect these values across individuals of varying height, we do the following experiment:

Our experiment comprised of ten individuals recruited from the College of William and Mary and the surrounding area. Their data is shown in Table 1. Their ages ranged from 18 to 30 with a mean of 24.5. 5 males and 5 females participated in the study. They all had healthy BMI's with an average of 23.5. Our participants' heights ranged from 4'11" to 6'6" with an average height of 5'9". Two participants had had surgeries in the past but they were more than ten years prior to this study. We started the study with a questionnaire to determine the user's age, gender, height, weight, and assessment of any knee injuries or surgeries. Following this, we collected data on their knees. For each knee, we collected their patella width, knee circumference, the max flexion angle, the max extension angle, and the change in length across the front of the knee for the following angles: max extension, 45°, 90°, max flexion. The angles of the knee that we measure are shown in Figure 1. Patella width and knee circumference were measured with a cloth tape measure while the max flexion angle and max extension angle were measured

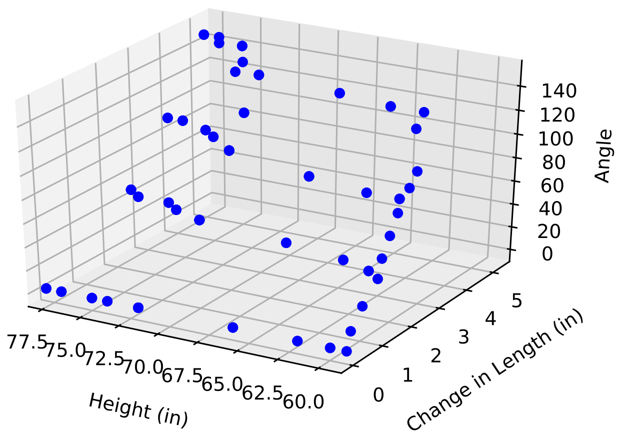


Figure 2: Change in length compared with height and knee angle of each participant.

Height	Change in Length					Angle of Maximum Flexion	
	0°	45°	90°	Full Flexion Right	Full Flexion Left	Right	Left
4’11”	0”	1”	1.625”	2.5”	2.25”	125°	119°
5’0”	0”	1.5”	2.25”	2.75”	3”	142°	148°
5’2”	0”	1.5”	2.25”	3”	3”	145°	143°
5’6”	0”	1.75”	2.5”	2.5”	3.5”	148°	146°
6’0”	0”	2”	3”	3.5”	3.5”	113°	115°
6’0”	0”	2”	3”	4”	4”	139°	137°
6’2”	0”	2.25”	3.5”	4.25”	4.5”	135°	140°
6’3”	0”	2.5”	3.75”	5”	5”	148°	148°
6’5”	0”	2.5”	4”	5.25”	5”	145°	140°
6’6”	0”	2.75”	4”	5.25”	5.25”	148°	145°

Table 1: Statistics collected for each participant in our experiment.

with a digital goniometer. A goniometer is an instrument used to measure angles of joints on the body. We show a goniometer in Figure 13. Change in length across the front of the knee for various knee angles was recorded using the goniometer and the tape measure. All participants in our study were able to extend their knee to a full 180°.

From our data, we derived the following insight. The change in length across the front of the knee is influenced by the height of the user. This can be explained by the underlying skeletal structure for the taller participants naturally being larger. We examined this insight by creating a graph, shown in Figure 2, that compares the height, knee angle, and change in the length across the front of the knee of all of our participants. From this graph, we conclude that the greater the height and knee angle, the greater the change in the length. This is highlighted by looking at the change in the length for the max flexion of our shortest and tallest participant. Our shortest participant is 59 inches tall with a change in the length across the front of their knee of 2.4 for the right knee and 2.25” for the left knee. Our tallest participant is 78 inches tall with a change in the length of 5.25” for both knees. The difference between their change in length at max flexion was 2.75” for the right knee and 3” for the left. Looking further into their data, we see that the max flexion for the change in length the length across the front of the knee for our shortest participant was not even a 45° angle for our tallest participant.

To model this data, we created an Ordinary Least Squared (OLS) Regression using Statsmodel [37]. We use height and change in length as parameters for the model. To start, we have eight coefficients and an intercept. We then train the model by removing the coefficient or intercept with the highest P value greater than the absolute value of its t-statistic while checking that the Adjusted R-squared value is not drastically decreasing. Once fully trained, the model has just three coefficients. The model has an R-Squared value of 99.3%. We graph this model in Figure 3. The model is as follows:

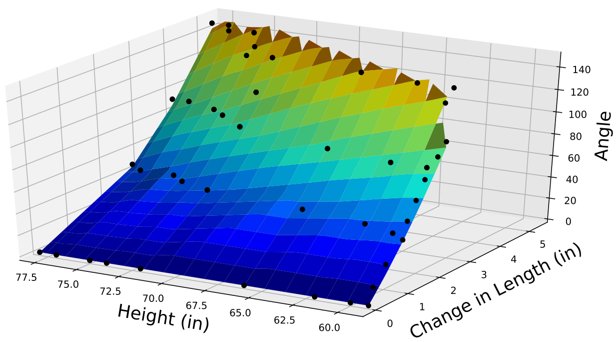


Figure 3: Change in length to angle model with height as a parameter.

For $L = Change\ in\ Length$, $H = Height$, and $A = Angle$,

$$A = 148.948L + 4.428L^2 - 1.8651LH \quad (1)$$

2.2. Resistance to Change in Length Model

In this project, we use Eonyx Conductive Stretchable Fabric [38]. This fabric shows a change in resistance when it is stretched. In our project, we use an 8.5” by 2.25” piece of fabric. To model the change in resistance as it is stretched, we performed the following experiment. We connected a digital multimeter to each end of the fabric. We then stretched the fabric four inches in total and recorded the resistance at each half of an inch. We repeated this process ten times. The results of this are shown in Figure 4. We used this data to create a third-degree polynomial regression model in Scikit-learn: Machine Learning in Python [39]. This model has a Mean Absolute Error of 0.131, a Mean Squared Error of 0.026, and a Root Mean Squared Error of 0.162. The model is shown in Figure 4. The regression is as follows:

For $R = Resistance$ and $L = Change\ in\ Length$,

$$L = -29.184 * R^3 + 282.126 * R^2 - 1005.642 * R + 1880.047 \quad (2)$$

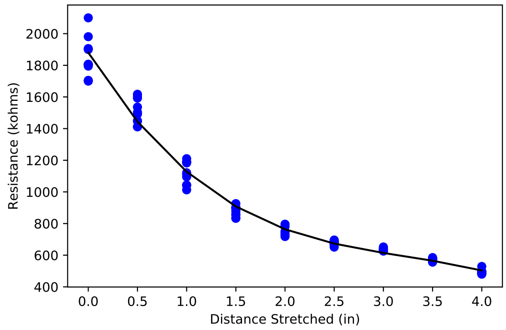


Figure 4: Fabric Resistance to Stretch Distance

2.3. Voltage to Resistance Model

Finally, we model the voltage to resistance. In our circuit, which will be discussed in more detail in the following section: TracKnee Prototype Design, we use a voltage divider. The voltage divider allowed us to read the resistance variation of the conductive fabric sensor. In Figure 5, we show the setup of the circuit that we have employed in our device. We define, $R_1 = Fixed\ Resistor$ and $R_2 = Conductive\ Fabric$. From this, we can compute the resistance from the following equation:

$$R_2 = \frac{V_1 * R_1}{V_{in} - V_1} \quad (3)$$

As this inverse function equation presents, the larger the resistance of the conductive fabric is, the smaller the voltage of $V1$. Similarly, the smaller the resistance of the conductive fabric, the larger the voltage of $V1$. The fixed resistor that is chosen to be in the middle of the variation of the resistance of conductive fabric. This allows us to calculate the resistance of the conductive fabric sensor from the voltage read on the device.

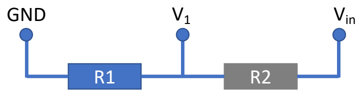


Figure 5: Voltage Divider

3. TracKnee Prototype Design

There are two main parts to our TracKnee prototype. The first is the control patch, which houses all of the non-washable electronic components. The second is the sensor sleeve, which houses out fabric sensor. When the two parts are connected, we have a full TracKnee prototype as shown in Figure 6a. As we were developing the TracKnee prototype, we kept the following requirements in mind: (1) The prototype should be able to collect data from the sensor and wirelessly send it to a collection location. (2) The prototype should be comfortable when worn and be easy to put on and take off. (3) The prototype should be washable so that it can be cleaned when it gets dirty or sweaty. In this section, we discuss the control patch, the sensor sleeve, how they come together to form our TracKnee prototype, and the lessons we learned during development.

(a) Close Up of Prototype (b) Prototype Size when Worn (c) Control Patch Connection (d) Sensor Sleeve

Figure 6: TracKnee Prototype

3.1. Control Patch

The control patch houses all of our rigid electronic components. During the development of the control patch, we addressed the following: (1) The control patch should be as small as possible so that it goes unnoticed by the user. (2) Some of the components contained in the control patch are not washable, so the control patch must be detachable from the knee sleeve. In total, the patch is 3.5 inches wide by 2.5 inches tall. The control patch is shown in Figure 7. In this subsection, we discuss the components used and the process we used to fabricate the control patch.

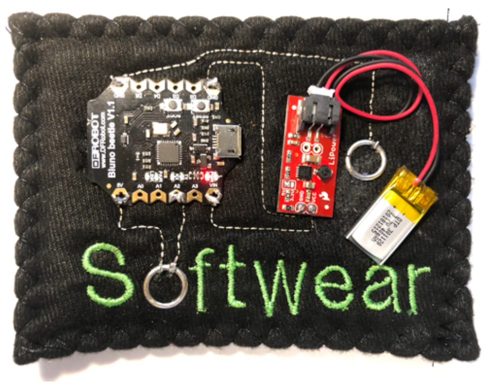


Figure 7: TracKnee Control Patch

3.1.1. Components

The components contained in the control patch are the microcontroller and Bluetooth chip combination, power supply, conductive thread wires, resistor, and snaps. We sewed all of our components to a layer of headliner foam. This gives anyone wearing the device some cushion from the rigid electronic components. In the following, we describe each of the components:

Microcontroller and Bluetooth Chip: The microcontroller that we chose is a Bluno Beetle [40]. We chose this because it is currently the smallest Arduino [41] based microcontroller with Bluetooth Low Energy. The Bluno Beetle features an ATmega328P processor and a CC2540 Bluetooth chip. It also contains four analog pins which surpasses our requirement of one analog pin.

Power Supply: The circuit is powered by a rechargeable 40 mAh lithium-ion battery. This battery outputs 3.7 volts. Since the Bluno Beetle operates in the range of five to eight volts, we use a LiPower Boost Converter [42] to boost the voltage of the battery from 3.7 volts to five volts. This battery last for about 40 minutes.

Conductive Thread: We use Syscom Advanced Materials' Amberstrand [43], a conductive thread, instead of traditional wires to connect the electronic components of our control patch. We chose this thread because it has a resistance of one ohm/foot and is solderable. It is also soft and flexible, making it a good choice for wearable devices worn on the body. Amberstrand fibers are made from Zylon which has very high in tensile strength and is resistant to heat [44]. This makes it a good choice for conductive thread wiring. The thread is coated in a combination of silver, copper, and nickel to make it conductive.

resistor: We chose a 470 ohm resistor because it is in the middle of the range of resistance values for the conductive fabric. This enhances the resolution of the data that we read from the conductive fabric sensor.

Snaps: To make the TracKnee device washable, the control patch must be removable while allowing for easy reconnection to the sensors on the shirt. To accomplish this, we used conductive nickel snaps to connect the control patch to the knee sleeve.

3.1.2. Fabrication

When fabricating the control patch, we designed it as small as possible. To accomplish this, we used a sewing machine to sew the conductive thread into the control patch. This allowed us to to get our conductive thread wires closer to each other, decreasing the space being used. We describe our sewing machine setup and then the entire procedure used to fabricate our control patch.

Figure 8: Baby Lock Verve Sewing and Embroidery Machine

Our sewing machine is a Baby Lock Verve Sewing and Embroidery Machine [45]. We show it in Figure 8. To sew conductive thread with our sewing machine, we chose installed a Schemtez Metallic embroidery needle [46]. This needle has a longer eye that gives us more room for it move around as we are sewing. This helps to prevent snags in the thread. We found that it is easier to sew our conductive thread when it is wound into a bobbin ①. When we used a spool of conductive thread on the spool pin ②, we found that it came off of the spool too fast and this would cause loose stitches to be sewn. For our prototype, we found that it was best to use the standard zig-zag foot ③ that came with the machine. We chose the 1-03 stitch for the control patch as it is small and it sews in a straight line ④. We set the tension to four ⑤. When sewing conductive thread we go as slow as possible so that we can check the thread for potential snags. To do this, we use the needle position button ⑥. This button moves the needle into the up or down position. Pushing this button twice is one stitch. For our circuit, we also need to be able to sew sharp 90° corners. To do this, once you have reached the position in which you would like to make a corner, you put the needle in the down position so that it is all the way through the foam, lift the foot with the lever ⑦, and turn the foam around the needle until you reach the desired angle. We also embroidered a logo onto our control patch. Because embroidery requires hooping the fabrics, this is done first.

Since our control patch has many different components, the procedure that we used to fully fabricate it is as follows:

(1) Layout the circuit on the back of the headliner foam. Since the conductive thread is in the bobbin we sewed with the bottom of the headliner foam facing upwards
(2) Draw out exactly where you want the wires to be. Once the circuit is live, the conductive thread is live so there cannot be any overlap in the conductive thread. This causes shorts in the circuit.
(3) Sew the conductive thread into the foam with the settings for the sewing machine as described above. At the end of each conductive thread wire, you should leave about an inch of thread. This makes it easier to attach and solder in later steps.
(4) Attach the snaps to the control patch making sure that there is contact between the conductive thread and the snap. The thread can be secured with solder or tied around the edge of the snap.
(5) Put the microchips in place. Pull the conductive thread through the correct pins on the microchip. A needle threader helps with this.
(6) Solder the conductive thread to the microchips.
(7) Cut off the remaining conductive thread.
(8) Finish the edges of the conductive foam and cut off any excess material.

3.2. *Sensor Sleeve*

The sensor sleeve contains only components that are washable so that it may be washed in the case that it gets sweaty or dirty. The sensor sleeve should accomplish the following: (1) The sleeve should not impede knee normal knee motion. (2) It should be comfortable to wear and be easy to put on and take off. (3) It should only contain components that can be washed. In this subsection, we discuss the components used and the process we used to fabricate the control patch.

3.2.1. *Components*

The components contained in the sensor sleeve are the knee sleeve, conductive fabric, conductive thread, and snaps. All of these components are washable in a washing machine. We describe the components in the following:

Knee Sleeve: We chose the Crucial Compression Premium Knee Compression Sleeve [47] as a base for our sensor sleeve. We chose this sleeve as it is easy to put on and have a good reputation for not sliding down when worn.

Conductive Fabric: We used Eonyx Conductive Stretchable Fabric [38] for the development of our knee sensor. We chose this fabric for the following reasons. It is coated in a conductive polymer that gives it piezoresistive properties. This allows us to see a change in resistance as the fabric is stretched. Additionally, the composition of the fabric is similar to that of many athletic fabrics. It is made of 72% nylon and 28% spandex. Nylon is soft and silky to the touch, quick drying, and mildew resistant. Spandex is breathable, quick drying, and moisture wicking but it additionally provides an unrestricted range of motion as it stretches with the motion of the user.

Conductive Thread: Again, we use Syscom Advanced Materials' Amberstrand [43] in place of wires. This time, the thread is hand sewn.

Snaps: We also use snaps on the sensor sleeve. The snaps from the control patch connect to these snaps when in use.

3.2.2. *Fabrication*

We could not use our sewing machine to assist with the fabrication of the sensing sleeve as we cannot lay the knee sleeve flat to sew through it. Because of this, we hand sew our conductive thread into the knee sleeve. To fabricate the sensor sleeve, we follow the following steps.

(1) Attach the conductive fabric to the knee sleeve so that it is positioned down the vertical midline of the kneecap. Secure it with spray adhesive.
(2) Attach the snaps so that they line up with the snaps on the control patch.
(3) Hand sew conductive thread in a zig-zag pattern from the top of the fabric to a snap. A zig-zag stitch is shown in Figure 10. Then sew from the bottom of the fabric to the second snap. To connect the thread to the fabric, put a stitch through the fabric and tie it off. To connect to the snap, feed the thread between the top and bottom of the snap and secure it with solder.

3.3. *TracKnee Prototype*

When we connect the control patch to the sensor sleeve, we have a full TracKnee device. The circuit diagram for this device is shown in Figure 9. Our circuit utilizes a voltage divider to incorporate our conductive fabric sensor. The voltage divider requires two resistors: our conductive fabric sensor and the 470 ohm resistor. We connect the resistor to ground and our fabric sensor to power. We read the voltage via analog pin A2 on the Bluno Beetle. So, when the conductive fabric sensor stretches, the resistance decreases and the voltage read on A2 increases. As the fabric sensor returns to its original length, the resistance increases and thus the voltage on A2 decreases.

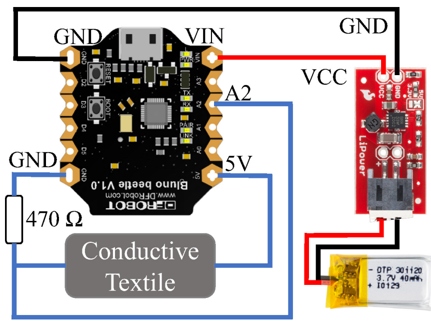


Figure 9: Circuit diagram of TracKnee

3.4. *Lessons Learned*

Through the design process for our TracKnee prototype, we learned a few lessons. The most important were the using fabric adhesives, choices of conductive thread and using different stitch patterns in different fabrics.

We tried using 505 temporary fabric adhesive to help attach our conductive fabric to our knee sleeve. This adhesive changes the resistance of the conductive fabric. When applied lightly, we saw our resistance change from being near 100 kohms to almost 600 kohms. When applied heavily, the resistance jumped again to about 1100 kohms. While there was still a readable change in resistance, we did not model nor study how this adhesive affects our conductive fabric sensor.

Initially, we chose a commonly used stainless steel conductive thread[48]. It had a resistance of twenty-seven ohms/meter. While this thread was very smooth and did not have issues with fraying, we were not able to accurately read the data coming from the elbow sensor. To fix this, we replaced this thread with the Syscom Advanced Materials' Amberstrand that had a lower resistance of one ohm/foot.

Figure 10: Stitch Patterns

Many stitch patterns can be used when sewing conductive thread. We tested two main stitch patterns for sewing on stretchy material. The first is a straight stitch and the second is a zig-zag stitch. When the fabric the stitches are sewn into is stretched, each stitch reacts differently. In Figure 10, we show the straight stitch on the left and the zig-zag stitch on the right after stretching. From this figure, we can see that the straight stitch bunches in two places while the zig-zag stitch stays in place. Thus, we learned to use a zig-zag stitch when sewing into stretchy fabrics like our knee sleeve.

4. Data Collection

In this section, we evaluate our knee angle model by collecting data from human subjects. This data collected consists of ground truth knee angles measured by a goniometer and the data collected from our TracKnee device. Our target participants were between 18 and 35 years of age and were healthy without any major knee injuries or surgeries. In this section, we discuss the equipment used in our study, the parameters, and the demographics of our participants.

4.1. Equipment

To perform our data collection study, we need to collect statistics on each participants knees, record the TracKnee device data, and record the ground truth angles. We used a Medigauge digital goniometer [49] and a fabric tape measure to collect statistics on each participants knee. We developed an android application and implemented it on a Google Pixel 2 to record our TracKnee device data. We used a goniometer to measure the angles and a camera to record the time in our application to measure the ground truth angles and label them in our TracKnee data. Next, we discuss our application.

We developed an application to collect data from our TracKnee device. This application is shown in Figure 11. Our application has four states: *Initial State*, *BLE Scan State*, *BLE Connected State*, and *Data Collection State*. The states are shown in Figure 12. Next, we describe the application states.

Initial State: When the application is launched, the user is shown the *Initial State* (Figure 11a). This state has two main components: timestamp and *Subject ID #*. The timestamp is displayed throughout the entire application. This is essential, as during our user study, we recorded with the timestamp in view of the camera so that we can label the ground truth. The *Subject ID #* is a field where the user can input the number that is assigned to each subject participating in our study. Once this field has been completed, the user can press the scan button to move the application into the second state: *BLE Scan State*.

BLE Scan State: Once in the *BLE Scan State*, the application opens the activity that scans for and displays nearby Bluetooth Low Energy devices as shown in Figure 11b. The user should select *Bluno* from the displayed list of devices. Once a device has been selected, the application displays either the *BLE Connected State* or the *Initial State*. If the Bluetooth device is correctly connected and the application is receiving data, the application moves to the third state: *BLE Connected State*. If the application does not connect to the device, it returns to the *Initial State*.

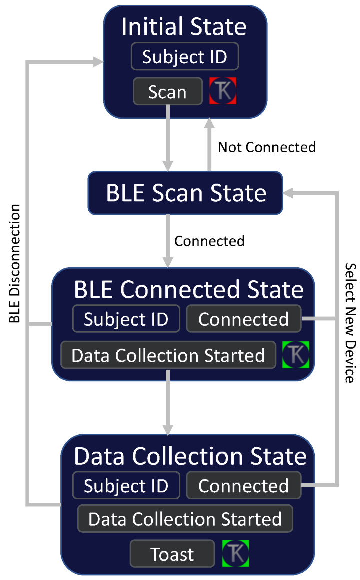
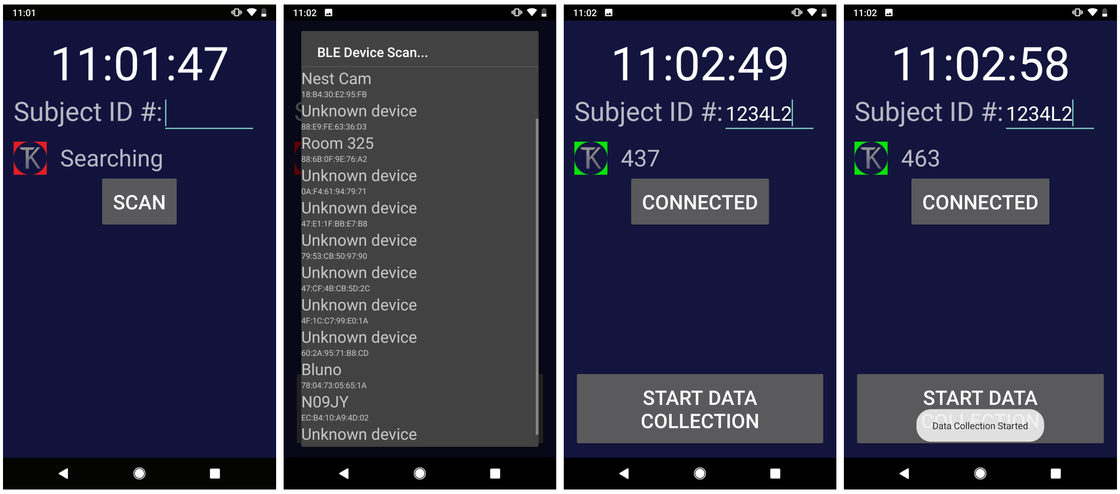


Figure 12: TracKnee Application States



(a) Initial State (b) BLE Scan State (c) BLE Connected State (d) Data Collection State

Figure 11: TracKnee Application

We based our Bluetooth connection to our Bluno device off of the BlunoBasicDemo[50] from DFRobot. This demo connects a Bluno device to an Android application and facilitates the transmission of data between the two. The android application scans for Bluetooth devices, allows the user to select a Bluno device, connects to that device, and then allows the user to send and receive data. The Bluno is coded via Arduino to receive data and send a copy of the received data back to the application.

BLE Connected State: In the *BLE Connected State*, shown in Figure 11c, the background of the TracKnee logo changes to green and the *Scan* button is renamed *Connected*. During this state, if the Bluetooth device disconnects, the application returns to the *Initial State*. If the wrong device was connected, the application still proceeds to the third state. If the application connects to the wrong device, the user can press the *Connected* button and the user is once again be presented with the *BLE Device Scan State* where they can select the correct device. At this point, the application displays the *Start Data Collection* button. This button is used in the final state.

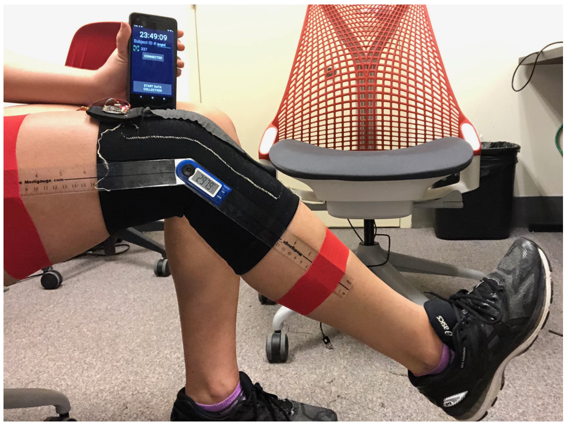


Figure 13: User Study Setup

Data Collection State: Once the device is correctly connected and the user is ready to begin logging data, the *Start Data Collection* button is displayed. To start collecting data, the user should press the *Start Data Collection* button. Once the button has been pressed, the application proceeds to the fourth state and pop up a toast message to let you know that data collection has started as shown in Figure 11d. The application logs data to a .csv file. This file is named with the *Subject ID #* and the corresponding time. The .csv consists of two values: timestamp and sensor.

4.2. Parameters

At the beginning of the study, we administered a pre-user study questionnaire. On the questionnaire, we asked for the following statistics: age, gender, height, weight, and information pertaining to previous knee injuries or surgeries. Next, we recorded the following statistics about each of their knees: width of patella, circumference of their knee (taken mid-patella), maximum flexion of their knee, maximum extension of their knee, change in length from maximum extension to maximum flexion (CLEF value), distance from top of kneecap to top of TracKnee device, and

Participant #	Height	CLEF		Maximum Extension		Maximum Flexion	
		Right	Left	Right	Left	Right	Left
1	4’11”	2.5”	2.25”	123°	120°	−1°	0°
2	5’5”	3”	2.75”	147°	145°	0°	0°
3	5’6”	2.75”	2.5”	136°	126°	−2°	−4°
4	5’7”	3”	3.25”	123°	130°	0°	−1°
5	6’0”	3.25”	3.25”	113°	116°	−10°	−8°
6	6’0”	4”	4.25”	139°	137°	0°	0°

Table 2: Statistics collected for each participant in our user study.

distance from bottom of kneecap to bottom of TracKnee device. Following that, we asked the participants to put the device on their right knee. Then, we connected the device to the data collection application and set up the camera to record the study. Following this, we asked the participant to position their knee to the following angles: 0°, 15°, 30°, 45°, 60°, 75°, 90°, 105°, 120°, and 135°. We used a goniometer to confirm the ground truth measurement of the angle of their knee. We repeated this process once on the right knee and then twice on the left knee. Overall, we recorded data for 240 knee angles.

4.3. Demographics

We recruited the participants in our study from the College of William and Mary and the surrounding area. In total, we had six participants: three male and three female. On average, our participants were 25.3 years of age with the youngest being 18 and the oldest being 32. All participants were in the normal range for BMI with an average of 21.86. The normal range for BMI is 18.5 to 25. Our participants were also free of major knee surgeries and injuries.

We show the height, CLEF value, maximum flexion, and minimum flexion for each participant in Table 2. In this table, we see that each participant’s height, maximum flexion, and minimum flexion affect the CLEF value of each knee. In general, the taller the participant the higher the CLEF value but it is also affected by how flexible each individual is. The lower the maximum flexion angle, the higher the CLEF value. For example, we had two 6’0” participants. The participant with the lower maximum flexion angle had a higher CLEF value.

5. Experiment Results

We evaluate the model that we created in Section 2 on the data collected in Section 4. We removed three outliers from our dataset as the angle calculated by the model was off by over 30°. We show our ground truth angle and our calculated angle in Figure 14. We evaluate the accuracy of the model that we created. To do this, we evaluated our model’s ability to classify an angle correctly to the nearest 15, 12.5, 10, 7.5, and 5-degree angle. Our results are shown in Table 3. Respectively, we see a 94.86% accuracy at the nearest 15^{th} degree, 84.11% at the nearest 12.5 degree, 70.09% at the nearest 10^{th} degree, 53.27% at the nearest 7.5, and 38.79% at the nearest 5^{th} degree. On average, overall, our model experiences an error of 3.69°. These results are shown in Table 3. We further analyzed our data by breaking down the accuracy by each participant. This can be seen in Table 3. From this table, we can see that the shorter participants’ angles were more accurate. In terms of average error, the shorter the participant the smaller the error.

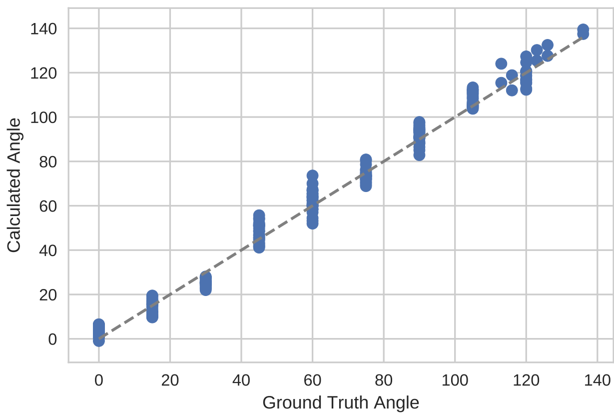


Figure 14: Comparison of Ground Truth Angle and Calculated Angle

In our study, we used a goniometer to collect ground truth angles. When used by inexperienced individuals to measure elbow angles, goniometer readings can be off by 8° to 18° [51]. This can cause variability in the actual value

Participant #	Height	Accuracy					Average Error
		15	12.5	10	7.5	5	
1	4'11"	94.44	86.11	80.56	63.89	41.67	3.29°
2	5'5"	94.29	88.57	77.14	60.00	40.00	3.34°
3	5'6"	100.00	80.55	66.67	58.33	50.00	3.35°
4	5'7"	91.67	83.33	72.22	52.78	41.66	3.79°
5	6'0"	94.44	83.33	69.44	47.22	33.33	3.99°
6	6'0"	94.29	82.86	54.29	37.14	25.71	4.42°
Overall		**94.86**	**84.11**	**70.09**	**53.27**	**38.79**	**3.69°**

Table 3: Model Accuracy by Participant

of the ground truth angles that we record. It is possible that this is the reason for the low accuracy of the nearest 5th and 7.5-degree angle. In future work, a more accurate ground truth measurement should be acquired. This can be done by using a device such as Pasport Goniometer Sensor [52] which achieves an accuracy of 2° before calibration. This sensor uses a cuff on the upper arm and forearm with the sensor positioned at the hinge of the elbow.

We recorded the voltage while discharging the rechargeable 40 mAh lithium battery. Figure 15 shows the discharging curve for the voltage change from 4.02 volts to 2.96 volts in 38 minutes and 38 seconds. In this figure, we can see that the voltage decreased quickly in the beginning and then stabilized from 3.90 volts to 3.40 volts. The average current of the main circuit can be calculated by dividing the recorded discharging time and the power, 40 mAh. The average current is 62.45 mA. The current is within the tolerance of our circuits and the microchip. We also calculated the charging time. To do this, we recorded the time it took to charge the battery fully three times. The average time for charging for the 40 mAh battery is 18 minutes and 50 seconds, which less than the half time of discharging. Since our battery disconnects from our device, we can adjust the capacity. For example, other options that are compatible with our device are 110 mAh, 400 mAh, and 850 mAh. The drawback with increasing the capacity is that the size of the battery also increases. While the 110 mAh battery is only marginally larger than the 40 mAh, the 400 mAh and 850 mAh are more than double the size.

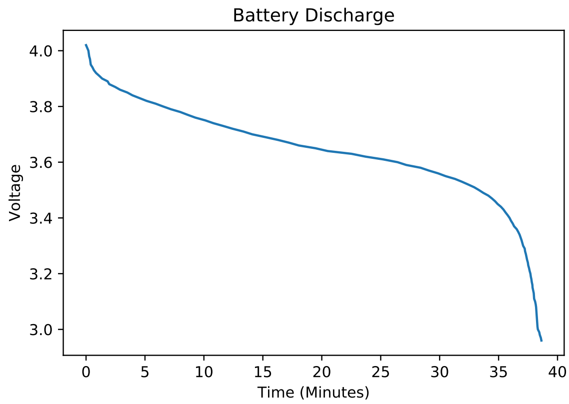


Figure 15: Voltage of Battery Over Time

6. Related Work

Enabling ubiquitous body motion tracking and modeling has received an increasing amount of attention from the medical science and computing disciplines [33][34][35][53][54]. Medical science research is mainly conducted in a lab setting [6] but there is a push to move data collection outside of the lab [9]. This will enable researchers to collect more data in the real world which is essential when treating diseases. For example, in certain diseases, such as Parkinson's, disease-specific symptoms such as freezing of gate and are challenging to reproduce in lab conditions[55]. Ubiquitous monitoring will enable the collection of more data on freezing of gate which can help to advance research on Parkinson's disease. In other diseases, such as Osteoarthritis, medical professionals see benefits in monitoring patients outside of the clinic [56] but currently, this is not widespread.

Joint angle estimation has been a focus of research in human motion tracking and modeling. Commonly, wearable sensors are used for monitoring of joint angles. The most prevalent sensing technology is the inertial measurement unit (IMU) [11][12][13][57][58][59][60][61][62]. Wireless wearable ultrasonic sensors [14][15][16], optical sensors [17][18][19] , liquid metal sensors [20][21], potentiometers [22], acoustic sensors [23] , force-sensitive resistors [24], retractable string sensors [25], and galvanic coupling systems [26] are also used but they are intrusive and not comfortable for long term wear. Flex sensors have been used [27][28] but even though they are small and flexible, they have edges that cannot seamlessly integrate into clothing.

Soft, flexible, wearable E-Textile sensors have been used for monitoring of joint angles. Shyr et al[29] used a conducive webbing made of conductive and elastic yarn do determine the flexion angle of the elbow. Bergmann et al [30] used a flexible conductive polymer material that could be attached to clothing to measure knee joint angles. Papi et al[31] designed a pair of smart leggings that used a conductive polymer strip to estimate the range of motion of the knee. Gholami et al [32] used a thermoplastic-based stretchable strain sensor to gauge its ability to estimate knee flexion and simple tasks such as walking.

7. Conclusion

In this paper, we proposed three models that can be used in succession to calculate knee angles given a voltage reading. Given a voltage reading, we first calculate the change in resistance of our conductive fabric, then its change in length, and finally the knee angle. We present TracKnee a sensing knee sleeve made with a conductive fabric sensor that unobtrusively measures knee angles. We created TracKnee device while keeping in mind the comfort of the user. Because of this, we made sure the device was comfortable, unobtrusive, and washable. We ran a user study in which we collected data on 240 knee angles from six individuals. We used this data to calculate knee angles using our models. Our results show that our model is 94.86% accurate to the nearest 15^{th} degree angle and that our average error per angle is 3.69°.

Acknowledgment

This work was supported by U.S. National Science Foundation under grant CNS-1841129 (EAGER). The authors would like to thank all of those who participated in our experiments. We would also like to thank everyone who proofread this paper and we would like to thank Victoria Cooper for her assistance with creating the images for the paper.

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It should be short collection of bullet points that convey the core findings of the article. It should include 3 to 5 bullet points (maximum 85 characters, including spaces, per bullet point.)
Please find below an example:

- We designed and fabricated a wireless soft sensing knee sleeve called TracKnee.
- TracKnee measured knee angles using a conductive fabric sensor.
- We developed three models to calculate knee angles given data from TracKnee.