# Flex Sensors: Possibility of Detecting Improper Posture of a Runner's Arm


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## ABSTRACT

According to sports coaches, the upper body posture is an important factor in running. This paper shows it is possible to detect an improper posture of a runner's arm using a flex sensor. It does this by showing how accurately a flex sensor can describe an angle. It also shows in which location on the arm the sensor should be placed. Lastly, it is shown how the sensor performed in actual running exercises, although the accuracy during these runs was not calculated due to limited resources and time.



## Keywords

Sport, running, flex sensor, joint angle, wireless sensor, body sensor network


## INTRODUCTION

In the field of sports (such as rowing, biking, climbing, basketball[1] and ice hockey[2]), a lot of research has gone into using wireless sensors to accurately describe the movement of body parts and calculating the velocity and the angle of them. This is then used to improve the performance of athletes or to notify them on poor or wrong acts; Wong et al. [3] did a complete review of the existing technology regarding wearable sensors. Most of these solutions are based on using inertial measurement units (IMU). These units consist of an accelerometer, a gyroscope and sometimes a magnetometer. A paper by Papi et al. [4] offers a replacement for IMUs to determine what a person is doing using flexible sensors.

In running, a lot of research has gone into the analysis of the lower body of a runner (e.g. running gait[5] and strife). However, sports coaches often say that the upper body is just as important: energy can be wasted if the upper body form is not correct, as the upper body would use other methods to balance itself. Therefore, sports coaches often suggest that the angle between the lower and upper arm should be close to 90 degrees and the back should be straight. A paper by Gotoda et al. [6] looks into the possibilities of using an IMU to see the changes in acceleration of an arm swing.

Not a lot of research has gone into estimating angles between the upper and lower arm of a runner, but when it comes to describing the angles between different body parts, most researchers use the accelerometer and gyroscope of the IMUs and Jacobian matrices to describe and estimate this. An example of this can be found in a paper by El-Gohary and McNames [7]. These methods can accurately describe the angles of the joints.

Flex sensors were chosen over IMUs, as IMUs have several downsides over flex sensors when it comes to determining a joint angle. A downside of using an IMU for this purpose is that it is required to have at least two IMUs and the distance between both IMUs and the elbow needs to be known [7]. While a flex sensor does need to be placed on the same position, it is easier to position one sensor on the elbow than precisely locating two sensors. It should also be noted that the direction of the accelerometer of an IMU always needs to stay the same, unless this is taken care of in the software. The gyroscope has another issue, which is measurement drifting.

## Goal and structure

The goal of this research was to explore the possibility of using flex sensors as a way to estimate the angle between the upper and lower arm at the elbow joint of a runner. This was done by looking at the accuracy of the sensor, the placement of the sensor on the arm and how the sensor performed in running exercises.

Firstly, it is shown that the sensor could accurately describe the angle between the upper and lower arm. For certain angles, the sensor took several measurements and using this data several polynomials were created. Using these polynomials, the angles were estimated and compared to each other by calculating the root-mean-square-error (RMSE). Also, it is shown that the error decreased when the sensor output was filtered. Secondly, it is justified which location on the arm was the best for the sensor. It was found that the side of the arm was the best location, due to its high accuracy. Lastly, the sensor was tested during two actual running exercises. In this section, it is also shown that the polynomials found through all experiments had the same curvature. Most importantly, it is shown that the sensor could show the improper posture of a runner's arm.

## METHODS AND APPROACH

## Prototype

The prototype built and used in this research consisted of a Raspberry Pi 3, an 8 channel 10-Bit ADC and the flex sensor itself. The sensor was reinforced with two pieces of cardboard to make sure the sensor always bent at the same point.




*SRC 2016* November 30, 2016, The Netherlands

## Error calculation

In order to answer how accurately the sensor can describe the angle between two points, the sensor was bent at multiple angles: 180, 135, 90 and 45 degrees. After the sensor was bent at these angles, it was required for it to be as steady as possible; therefore, the sensor was reinforced with pieces of cardboard and was held in the same position using two tongs. Whenever the sensor was bent at another angle, it was given five minutes to adjust to that new angle. This was done as the sensor needed some time to settle at a new angle. After these five minutes, samples were taken with a sampling frequency of 100 Hz for 10 minutes.

Using the average output of the sensor for each angle, an estimation of each angle could be made. This was done using the following equation:

$$D_{angles} = \frac{D_{sensor}(\alpha) * \overline{D_{sensor}(\alpha)}}{\alpha} \tag{1}$$

where $D_{angles}$ is the dataset containing the estimated angles, $D_{sensor}$ the output from the sensor over 10 minutes for angle $\alpha$, $\overline{D_{sensor}}$ the average of all values in $D_{sensor}$ for angle $\alpha$ and $\alpha \in \{0, 45, 90, 135, 180\}$ depending on the angle measured.

After this, three polynomials were created using the `polyfit` function in MATLAB: a $1^{st}$ , $2^{nd}$ and $3^{rd}$ order polynomial. The highest order of polynomials was at maximum three, because there were four angles measured: 45, 90, 135 and 180.

After the data was gathered, it was analyzed in MATLAB. Using the averages of the output of each angle and the found polynomials, the root-mean-square error (RMSE) was calculated several times using the following equation:

$$RMSE(\hat{\theta}) = \sqrt{E((\hat{\theta} - \theta)^2)} \tag{2}$$

where $\hat{\theta}$ is the estimator (the data from the flex sensors) and $\theta$ is the ground truth (angle determined by observation). A well-fitting polynomial had to be found, as the findings of this question were compared to the findings of the second question. Multiple orders of polynomials were considered (first to third order), but a third order polynomial was best at estimating the angle as it had the lowest RMSE (see table 1). Thus, A third order polynomial was picked to be used in the remainder of the research as it was the best.

Besides using different polynomials, the data was also filtered in two different ways: a moving average filter and an Extended Kalman filter. The RMSE of these was also calculated. The data was filtered to see if filters would greatly reduce the errors. The RMS, maximum and minimum error of every filter were compared to the RMSE of the non-filtered data. If the RMSE was greatly reduced by using a filter, this filter could also be used in the second research question.

## Possible locations on the arm

The sensor was put in three different locations on the arm: the inside, the side and the outside of the elbow. The arm was then moved in different angles and for each angle of the arm, the angle of the sensor was written down. This was done so that the sensor could be bent in the right angle later. After this, the sensor was held in place to do the measurements. These measurements were done for the nine angles in which the sensor was bent during the three different locations (see table 2).

The sensor was bent at the right angle and held there using tongs. This was done as it was hard to hold the arm in the same position for 10 minutes and as long as the sensor had the same angle it would have had on the human arm, these results would be just as valid. For every angle, the sensor was sampled with a frequency of 100 Hz. After this was done, all measurements were duplicated and one of each was filtered.

Using the raw measurements, the average sensor output was calculated by taking the mean of the measurements. Using these averages, a $3^{rd}$ order polynomial was created. It should be noted that the polynomial was created with the angles of the arm and the sensor output at that moment, meaning that if the sensor was bent at a 90-degree angle while the arm was bent at a 45-degree angle, the output of the sensor at the 45-degree angle was used to estimate the 90-degree angle of the arm. This was done as the angle of the arm needed to be determined and not the angle of the sensor this time.

The locations on the arm were then analyzed on two aspects: i) the range of angles (the highest and lowest output of the sensor) and ii) the accuracy, estimated with the RMSE (maximum, minimum and average). The RMSE was calculated between the estimated angle (using the polynomials) and the ground truth data. The sensor location with the highest range of angles with the most accurate estimation was considered the best location. It should be noted that the accuracy outweighed the range, thus if a location had a low range, but a high accuracy, this location was still considered.

## Running exercises

Two runs were conducted by the same person. One run was a "normal" run. This normal run meant that the arms were swung as if running normally - though during the run an attempt was also made to be as close to a 90-degree angle as possible. Secondly, the arm was forced at a 90-degree angle and forced to stay there during the entire run. Each run itself took 10 minutes and it should be noted that these were "stand still" runs, meaning that only the running movements were made, but the person itself did not move. These runs were picked to see how well the sensor could be used to estimate a 90-degree angle during running and to compare to normal running to offer a form of validation.

The measurements were filtered and using the found polynomial converted to angles, which were plotted against each other. A look was then taken at how the sensor performed in running exercises and if a clear difference was seen between the normal running exercise and the one where the angle was forced at a 90-degree angle. If this could be seen, the assumption could be made that the sensor could be used to improve an improper posture for the runner.

# RESULTS AND DISCUSSION

## Finding the best polynomials

Looking at how the polynomials estimated the angles (see table 1), it can be seen the $3^{rd}$ order polynomial did this the best and the $1^{st}$ order polynomial did this the worst of the three. To be more precise, the RMSE of the $1^{st}$ order polynomial was 2.94 times higher than the RMSE of the $3^{rd}$ order polynomial. The same can be said for the minimum and maximum: 2.05 and 1.13 times, respectively. However, the $3^{rd}$ order polynomial was less accurate than using equation 1: the RMSE was 1.64 times higher and

**Table 1. Summary of errors (in degrees) for the different polynomials**

| | | Raw | Moving average | Kalman |
|---|---|---|---|---|
| RMSE | Actual angle | 0.4388 | 0.1437 | 0.1417 |
| | $3^{rd}$ order | 0.7211 | 0.2775 | 0.2775 |
| | $2^{nd}$ order | 2.0675 | 1.9701 | 1.9706 |
| | $1^{st}$ order | 2.1227 | 2.0344 | 2.4739 |
| Maximum | Actual angle | 4.2723 | 0.9148 | 0.2654 |
| | $3^{rd}$ order | 7.6212 | 1.5457 | 1.1253 |
| | $2^{nd}$ order | 8.6105 | 1.9108 | 1.4570 |
| | $1^{st}$ order | 8.5941 | 2.8932 | 2.5568 |
| Minimum | Actual angle | 0.0916 | 0.0000 | 0.0000 |
| | $3^{rd}$ order | 0.1827 | 0.0000 | 0.0000 |
| | $2^{nd}$ order | 0.3941 | 1.0593 | 1.1876 |
| | $1^{st}$ order | 0.3737 | 1.0520 | 1.1123 |

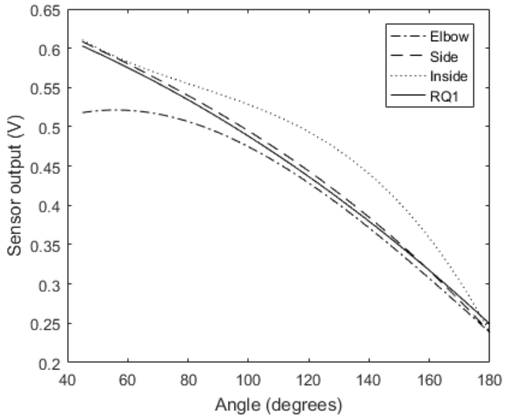


**Figure 1. Graph showing the angle estimates per position on the arm after normalizing the output for $3^{rd}$ , compared to the perfect curve (RQ1).**

the minimum and maximum error 1.99 and 1.78 times, respectively.

Equation 1 was always closest to the estimated angle as the polynomials were found using four data points: 45, 90, 135 and 180 degrees and their according sensor outputs. Equation 1 only required the actual output over the 10 minutes it was measured. This meant that the noise in the signal was taken into account when taking the average using that method, but in polynomials all this noise was seen as other angles and they are thus further away from the actual angle, resulting in a bigger error.

## Performance of the filters

It can also be seen that using filters, both the moving average and Kalman filter, reduced the error. However, when looking at the RMSE of the $3^{rd}$ order polynomial, these were only minor improvements: on average, the error was reduced by only 0.4436 degrees, granting it did decrease the minimum error to 0.0000. The $1^{st}$ and $2^{nd}$ order polynomials were more interesting to look at. It can be seen that, on average, the RMSE remained approximately the same. However, the maximum errors were reduced to 2.1166 degrees on average. Compared to the average of 8.2753 for the unfiltered data, this is a reduction of 6.1587 degrees. Interestingly enough, when looking at the minimum error, this was increased by 0.7189 degrees (1.1028 compared to 0.3839 for filtered and unfiltered, respectively). The increase in minimum error can be explained by the fact that the $1^{st}$ and $2^{nd}$ polynomials are less accurate and that the maximum error decreased: since the polynomials were making a wrong estimate in the angle, a bigger maximum error in the estimated angle may have accidentally been closer to the correct angle and thus resulted in a smaller minimum error. When the signal was smoothed out using filters, these maximum errors are reduced and thus the estimations are further away from the actual angle, resulting in the increase in minimum error. Thus, this also confirms that the $1^{st}$ and $2^{nd}$ order polynomials estimated worse than the $3^{rd}$ filter.

It can thus be concluded the sensor could accurately describe the angle between two points. The only issue was the maximum error, which for all three polynomials was between 7 and 9 degrees. However, using filters, this was reduced to a maximum of 3 degrees. For the remainder of this research, a $3^{rd}$ order polynomial was used with both filtered and unfiltered data.

**Table 2. Overview of the angles seen by the sensor compared to the actual angle of the arm**

| Arm angle | Sensor angle | | |
|---|---|---|---|
| | Elbow | Side | Inside |
| 180 | 180 | 180 | 180 |
| 135 | 145 | 135 | 120 |
| 90 | 100 | 90 | 80 |
| 45 | 90 | 45 | 40 |

## Best position on the arm

An overview of the actual angle between the lower and upper arm and how much the sensor was bent can be found in table 2. It can be seen that the elbow was inaccurate; this had to do with the fact that bone prevented the sensor from bending with the arm. The inside of the arm was more accurate, although it underestimated the angle. It should be noted that this is different for each person, as this is dependent on how much fat and muscles a person has on their arm - generally speaking, the more fat or muscles a person has, the bigger the underestimation is. This is because the muscles and fat accumulate in the inside of the arm when the arm is bent. The best location for the sensor was the side of the arm, as this accurately described the angle of the arm.

In figure 1, the $3^{rd}$ order polynomial was plotted against the best curve found previously. For the $3^{rd}$ order polynomial, it can be seen that the side of the arm came closest to the curve previously found (RQ1). Also, it can be seen that the inside of the arm underestimated the angle (a higher output means a lower angle). For angles greater than 90 degrees, the elbow was accurate, except for overestimating the angle slightly. However, for angles smaller than 90 degrees the output cannot be considered valid.

It can be concluded that the side of the arm was the best location to place the sensor in. This is because it had the smallest RMSE, minimum and maximum error when compared to the other two locations experimented with, meaning it had the highest accuracy of the three locations. When considering the range of angles that can be determined by using this sensor, the inside of the arm was slightly better than the side of the arm. However, it was less accurate than the side of the arm.

## Angle estimation in actual running

In figure 2, the $3^{rd}$ order polynomial, found using measurements for the 180, 135, 90 and 45-degree angles, is compared to the polynomials found previously. It can be seen that the found polynomial was close to the best ones found during the previous two questions. This implies the assumption can be made that the accuracy should be comparable to the RMSE found previously.

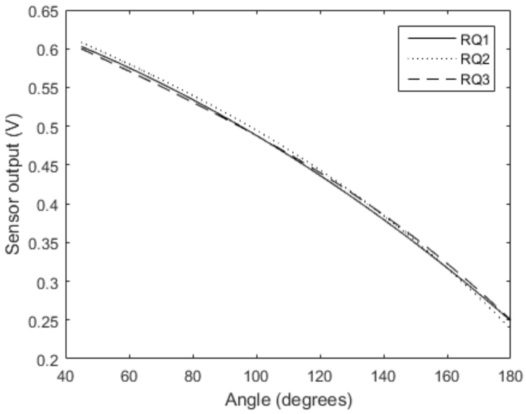


**Figure 2. Graph showing the best curves found in early phases of the research, compared to the curve found in actual research.**

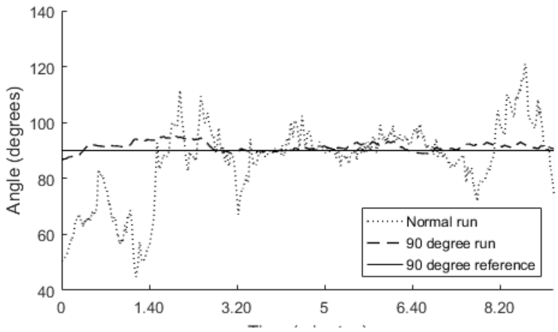


**Figure 3. Figure showing the estimated angles using the sensor.**

In figure 3, two runs are plotted against each other. It can clearly be seen that the sensor was still capable of determining the angle of the arms during these runs when the data was filtered. The run in which the arm was forced around a 90-degree angle was close to the 90-degree reference line. Any inaccuracies may be caused by the sensor moving on its own slightly, as only the arm was forced at a 90-degree angle and the sensor itself was not. The big differences in the normal run can be explained by the following: during the first part there was a struggle with the sensor, after that the run was done normally up until around 4 minutes, at which an attempt was made to be as close to an angle of 90 degrees as possible without being forced at that angle and towards the end the running session was done normally again.

In spite of the sensor being able to differentiate the runs and showing a more stable reading with the arm forced at a 90-degree angle, the accuracy could not be determined as there was no validation data of the angle of the arms to compare the estimated angles to. However, since the found polynomial was a close fit to the ones found previously, this implies that the accuracy should be comparable, though slightly less, to the results found in the previous experiments.

## CONCLUSION

It was discovered that the sensor could accurately describe the angle: the RMSE was between 0.7211 and 2.1227 degrees. When using filters, these errors were reduced even more. Therefore, it could be concluded that a $3^{rd}$ order polynomials was capable of estimating the angle between the upper and lower arm.

Although the sensor became slightly less accurate during later experiments, it was still accuracte enough to give an accurate estimation. It was discovered that the side of the arm achieved the highest accuracy. The inside of the arm had a higher range, but also a lower accuracy. On top of that, the inside of the arm was a dangerous location to put the sensor as it could be folded. It was also shown that the elbow was the worst location.

No RMSE could be calculated between the actual angle of the arm and the estimated angle due to limited time and resources. Nevertheless, it could still be seen that the sensor can be used to monitor the posture of the arm. When the assumption is made that, since the polynomials from all three research questions were close to each other and thus the estimated angle should not have a big error, the results in figure 3 should be close to the actual angle of the arm.

The goal of this research was to explore the possibility of using flex sensors to estimate the angle of the upper and lower arm at the elbow joint of a runner to detect an improper posture. Combining the research questions and their findings in this paper, this does suggest that flex sensors can be used to estimate the angle quite well and has shown that in three different running exercises, the sensor can indeed be used to detect an improper posture.

## ROLE OF THE STUDENT

The author was a Bachelor student working under the supervision of Dr. Ir. Nirvana Meratnia when the research in this report was performed. The topic was proposed by the supervisor. The student came up with the methodology, built the prototype, gathered the data, processed the results and wrote the conclusions by himself.

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