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Microprocessor-Based Athlete Health Monitoring Device based on Heart Rate and Stride Length Calculation

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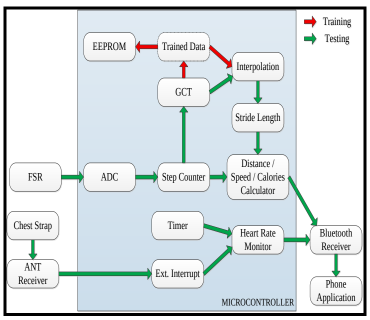
Graphical abstract



Abstract

Abnormal heart rate or low heart rate during exercise or recovery has been known to cause cardiac arrest and even sudden death in some cases. Similarly, research has shown that low step rate while running may be the causal factor for running injuries due to the force impact exerted and the extra loadings on the lower body joints. Commercial electronic devices used by athletes typically use either accelerometers or coil springs to estimate the step rate resulting in low accuracy. This paper describes the design a low-cost, wearable device that can help athletes monitor their physical activity while running or walking and report step rate, heart rate, distance covered, time elapsed and calories burnt with high accuracy. The system calculates the step rate by analyzing the signal generated from two Force Sensitive Resistors (FSRs) inserted above the insole of a running shoe which is connected to a microcontroller strapped to the athlete's ankle. According to the experimental results, the prototype was found to have an average accuracy of 97% in measuring the distance covered.

Keywords: Pedometer; activity tracker; force sensitive resistor; step rate; heart rate

Abstrak

Kadar denyutan jantung yang luar biasa semasa senaman boleh menyebabkan sakit jantung bahkan juga kematian. Begitu juga, kadar langkah yang rendah boleh menyebabkan kecederaan semasa larian disebabkan tekanan pada pada sendi kaki. Peranti elektronik komersial biasanya menggunakan sama ada pecutan atau pegas gegelung untuk menganggarkan kadar langkah yang menyebabkan ketepatan rendah. Kertas kerja ini menghuraikan reka bentuk kos rendah, peranti boleh pakai yang boleh membantu atlet memantau aktiviti fizikal mereka ketika berlari dan melaporkan kadar langkah, kadar jantung, jarak yang diliputi, masa berlalu dan kalori dibakar dengan ketepatan yang baik. Sistem mengira kadar langkah dengan menganalisis isyarat yang dijana daripada dua Perintang Sensitif Daya (FSRs) dimasukkan di atas insole kasut lari yang disambungkan kepada pengawal mikro diikat pada pergelangan kaki. Menurut keputusan eksperimen, prototaip telah didapati mempunyai ketepatan purata 97% dalam mengukur jarak larian.

Kata kunci: Pedometer; penjejak aktiviti; perintang sensitif daya; kadar langkah; kadar jantung

1.0 INTRODUCTION

The level of daily physical activity has a significant influence on an individual's health. In fact, lack of physical activity has been linked to an increased risk of the most common causes of death, such as obesity, heart disease, cancer, diabetes and high blood pressure [1]. One of the most commonly recommended physical activities by doctors is jogging or walking due to its simplicity and suitability for all ages and body types. As a result, nowadays Activity Trackers are getting more popular as a motivator and an exercise progress monitor that helps health-conscious people do more physical activity, lose weight and get fit. To quantify the level of physical activity in a day, the number of steps is among the most acceptable measures [2]. The functions and capabilities of activity trackers vary from one product to another, but when it comes to athletes, the most important functions are the step rate and the heart rate monitoring capabilities. The reasons behind the importance of the cadence and the heart rate shall be discussed in the next section.

For step rate monitoring, according to the results of a poll conducted in 2011 which was answered by 4,500 respondents revealed that about 40 percent of all running injuries are knee injuries. Furthermore, 13 percent of the runners also did suffer from knee pain in the previous year [3]. Research at University Wisconsin Madison examined the relationship between the number of steps per minute and the force impact exerted on the hip, knee and ankle joints while running. The research found out that a slight increment in the step rate has the potential to reduce the loading on the joints and it may even serve as injury prevention and treatment for several common running injuries as shown in Figure 1 [4].

Most professional coaches ask their athletes to take about 90 steps per minute for each leg. Running with a high number of steps allows the body to employ its natural shock absorption properties, which can result in transferring the ground impact from the bones to the muscles more effectively [5]. Therefore, the lower the number of steps per minute, the more the person is at risk of suffering a potential injury due to the slow and heavy force impact that is caused by each foot fall and therefore it is crucial to monitor the number of steps per minute while running.

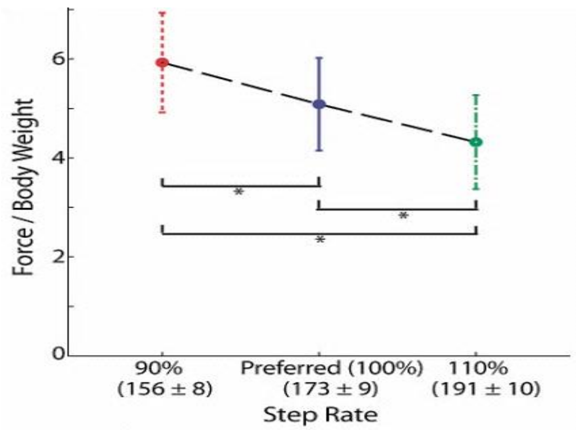


Figure 1 The relationship between patellofemoral joint (knee cap joint) pressure and step rate [6]

On the other hand monitoring the heart rate is as important as monitoring the number of steps while running because researchers have found that people with abnormal heart rate during exercise or recovery could be at risk of sudden death [7]. They also discovered that low heart rate during exercise was among the main causal factors for sudden death [8]. Other factors to be considered is that a higher risk is prevalent for people who have higher resting heart rate or whose heart rate took longer time to recover back. Thus, it is important for the athletes to monitor their heart rate during their exercise session.

Aside from that, pedometers can also motivate less active people to increase their physical activity level [9]. In fact, studies have shown that logging the physical activity and having a daily step goal will increase the physical activity of the individuals by 2500 steps approximately compared to a less active control group [10]. In order to improve the compliance with such programs the accuracy of pedometers is then essential.

There are several reasons why researchers need to accurately measure the physical activity of test subjects. For instance, to determine the percentage of people who meet the national physical activity guidelines, or to compare the physical activity among different groups of people, and most importantly to see the effect of a certain medication or surgery on the person [8].

However, athletes cannot accurately monitor their steps rate and heart rate manually while running. Furthermore, the current commercial products typically use either accelerometer or coil springs to estimate the step rate resulting readings with low accuracy. Due to that, further measurements such as speed, burnt calories and distance covered are affected as well. Whereas more expensive devices based on Global Positioning System (GPS) can calculate the distance more accurately, however they are more expensive and cannot be used indoors. Also, they cannot count the number of steps unless they are used together with a foot pod which is basically an accelerometer to be worn on the shoe laces.

This paper describes the design of a wearable athlete tracking device that consists of Force Sensitive Resistors (FSRs) in the insole of one shoe and ECG chest strap to monitor the athlete’s vital signs. The data collected by the sensors is processed by an Arduino microprocessor attached to the athlete’s ankle and transmitted wirelessly to an Android application that can be used to monitor and display the results to the user.

This paper consists of 7 sections, where section 1 consists of the introduction, section 2 discusses related works in the same field, and section 3 describes the hardware implementation of the proposed system. This is followed by section 4 which contains the microcontroller operation and section 5 which explains the device operation, section 6 discusses the results and analyses and lastly section 7 presents the conclusion.

■2.0 RELATED WORKS

2.1 Step Rate and Stride Length Measurement

Over the past few centuries, the estimation of number of steps taken and distance covered while jogging or running has been an area of interest for research. Thus, there are various ways and approaches to measure the distance, some of which have already been used in commercial products like pedometers. However, most pedometers suffer from accuracy issues.

For instance, Ali *et al.* presented a new approach in which it requires preliminary user calibration. The measuring concept was to place a magnetic object in the left shoe and a detector in the right show in order to estimate the stride length.

The movement of the magnetic object beside the detector caused a change in the inductance thus a shift in the parallel resonance frequency. As a result, it causes a change in the voltage which was amplified and sent to an Analog to Digital Converter (ADC). The digital output was computed and displayed through the microcontroller where the output is the speed and distance travelled with an error rate of 0.33% [11].

Jang *et al.* provided a new method to measure the distance traveled by humans while running or walking in which they used an ultrasonic sensor. The system was composed of a receiver (MA40S4R) and transmitter (MA40S4S) module to be placed on the shoes where both modules are controlled by an ATmega128 microcontroller. The system is initiated by an interrupt signal which causes the microcontroller to send a control signal to both the transmitter and the receiver. Then the control signal causes the transmitter to emit a 40KHZ ultrasonic signal into the air. After that the ultrasonic signal will arrive at the receiver module with a time delay proportional to the distance between the receiver and the transmitter. Finally, the microcontroller will use the timer delay to calculate the distance between the two legs. The experimental results for this work obtained an accuracy of 90% [12].

Zhao [1] proposed a technique to count the number of steps, measure the distance as well as the calories burned by using a 3-axis ADXL345 accelerometer. The ADXL345 is an accelerometer with low power consumer proprietary 32-level first-in, first-out (FIFO) buffer which can store data and process it for the pedometer applications in order to minimize the host processor computation and as a result, reduce the power usage of the device. The ADXL345 is connected to an ADuC7024 microcontroller which reads the data from the module, processes it and sends the result back with reasonable accuracy to the PC through a UART cable. The advantage of combining the 3-axis output feature is that it gives the ability to wear the pedometer in any location or position. As a result, the system counts steps with about 90% accuracy when walking or running [1].

2.2 Heart Rate Measurement

Another important feature of the Activity tracker is the ability to measure the heart rate of the person or athlete while walking or running. Heart rate monitors work by reading the electrical signals from the heart that causes a change in voltage which can be used to determine the number of beats per minute.

The first wireless Electrocardiogram (ECG) heart rate monitor was invented in 1977 by Polar Electro and it was used by the Finnish National Cross Country Ski team as a training aid [13]. Later in the 1980s more research and development were done to that monitor where the transmitter got the ability to be attached to an elastic chest belt and the receiver to be on a watch in order to display the data [14]. In this project a similar type of heart rate monitor is used, due to being small in size, accurate and wireless.

Similarly, Textronics Inc. had invented a NuMetrex sport bra in December 2005. The bra has heart sensors embedded into its designed from a specific material which can sense the heart rate and a data transmitter. Furthermore the transmitter can send data to a wrist receiver and it is also compatible with the polar link monitoring receivers. The design is similar to the commonly used elastic chest strap but the only drawback is that it is only for women.

[15] presented a real-time system called CaszOxiSys for monitoring physiological signals while exercising. Unlike most fitness monitoring systems which focus on one-to-one training, this system allows both the users and the trainers to monitor the user performance level wirelessly. The system consists of light emitting diode and a photodiode which are wirelessly connected through Bluetooth to the computer which analyses the physiological data like the user's heart rate and oxygen saturation level and display it in real time to the users in an informative way.

■3.0 HARDWARE IMPLEMENTATION

The proposed activity tracker system is based on six main elements: an Arduino Nano microcontroller, two FSRs, heart rate chest strap, ANT+ receiver, a Bluetooth transmitter module and an Android phone. The system calculates the accurate number of steps per minute while exercising by analyzing the analog signal generated from a single FSR sensor inserted in one of the shoes. Heart rate is monitored by using a heart rate chest strap, attached to the athlete's chest, The ANT+ receiver receives the wireless transmitted data from the chest strap and feed it into the microcontroller. In order to accurately measure the distance covered while running, an algorithm is developed to train the device where the athlete has to train the device in three different speed modes in the initial phase before using the device. Workout duration is calculated using the timer interrupt in the microcontroller itself. Finally, an Android application is developed to display the microcontroller output. The application allows the athletes to train the device, change the running mode and start the workout with ease. Figure 2 shows the interconnection among the project components.

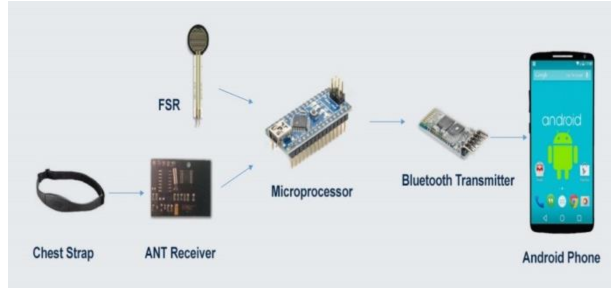


Figure 2 Block diagram of the proposed activity tracker system

Arduino Nano has been used in this project due to being small and compact. It has the ability of being programmed using C language which is relatively easier than programming using assembly language. It reads the data fed from the heart rate chest strap and the FSR, process them accordingly and relay the output through the Bluetooth module to the Android phone application. The connection of the components to the microcontroller is discussed in Table 1.

Table 1 Arduino nano pin connection with the sensors

Arduino-Nano Microcontroller	FSR 1 and FSR 2
Analog Pin 2	FSR 1 Pin 2
Analog Pin 4	FSR 2 Pin 2
	ANT Receiver
Digital Pin 10	EN Pin
Digital Pin 3 (External Interrupt)	Pulse Pin
	Bluetooth Transmitter
RX Pin	TX Pin
TX Pin	RX Pin
Vin Pin	9v Rechargeable battery + end
5V Pin	Both FSR Pin 1 , Bluetooth and ANT VCC Pins
GND Pin	9v Rechargeable battery – end , Both FSR Resistors , Bluetooth and ANT GND Pins

The FSR is a very important part of the design, as it is used to detect the steps while running due to the force exerted on them. Two sensors are placed in the right shoe's insole, so that every time the athlete takes a step, a change in the resistance will occur thus the microcontroller will process the signal and increment the number of steps. The advantage of using this sensor is that it is very light, flexible and durable. Unlike the accelerometer, this sensor has the ability to detect the actual number of steps instead of estimating it according to the movement of the accelerometer.

The chest strap heart rate monitor comprises of two elements: a chest strap transmitter and a wrist receiver or mobile phone. It senses the electrical activity of the heart due to the sensor which is placed on it just like an ECG. Transmits the signal detected wirelessly through ANT transmission protocol [14]. That is why in order to read the data transmitted from it, we need an ANT receiver module that can receive the signal transmitted from the chest strap into the microcontroller. It is important for the strap to be in direct contact with the skin, or else it will give wild readings. To achieve good contact the athlete needs to either tighten the strap well or use a conductive gel as shown in Figure 3. The chest strap does not have any ON or OFF buttons, it will be active when the receiver is active. And it comes with a small 3V battery inside.

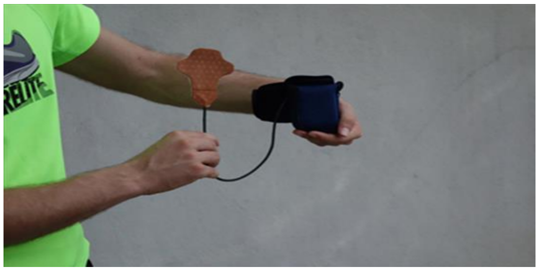


Figure 3 Insole containing FSR sensor and Microprocessor

The purpose of using Bluetooth in the design is to allow the data output to be transmitted wirelessly from the microcontroller to the Android application on the phone and thus display the data in real-time on it. The transmission distance can reach up to 20 meters with low power consumption. Before being used with the microcontroller it has to be paired first with the phone, when pairing is done the two devices are ready to communicate. Data is sent to the phone on a speed of 9600 bits per second, which is fast enough to show the results on the phone without any noticeable lag or delay via casual observation.

Modern activity tracker devices available in the market range in price from MYR 30 up to MYR 500. However, all activity trackers which have high quality sensors to accurately track number of steps and additional calculation modules are priced upwards of MYR 400. The cost of this prototype was MYR 306 and it can be concluded that the cost of commercialized device would likely be even lower.

■4.0 MICROCONTROLLER OPERATION

The microcontroller reads the data from the FSR, then it converts the analog signal into digital signal using (ADC). The digital signal is analyzed and the number of steps can be counted from it. As every time the athlete takes a step, it will cause the FSR resistance to drop, analog voltage output increases giving a higher digital reading.

By measuring the time of how long does the force remains exerted on the FSR, we can estimate the ground contact time. The ground contact time is a useful variable that can be used to estimate the speed of the athlete [16]. The faster the athlete's running speed the lower the ground contact time he has.

The ground contact time and steps counter modules are essential parts for the device training to work. Device training will be discussed in section 5.0. By training the device initially, the microcontroller will be able to assign a suitable variable value of the stride length that varies with the speed of the athlete while he is running or walking.

Distance covered is calculated by multiplying the number of steps with the stride length, whereas the calories burnt is calculated based on the athlete's weight in pounds, Metabolic Equivalent Value (MET) and the distance covered in miles as seen in Equations 1 and 2 [17].

Distance Covered (m) = Step Rate × Stride Length (cm) × 1(m)/100(cm) (1)

Calories Burnt = weight(pounds) × 0.75 × Distance(mile) (2)

Using the timer1, the time between the pulses sent by the chest heart rate monitor strap can be measured. Knowing the time between the pulses we can calculate the frequency, or in other words the heart rate in beats per minute. The timer was set to count the target time in seconds using Equation 3.

Heart Rate (bpm) = (Timer Resolution × (#TimerCounts + 1))/60 (3)

The results are then transmitted serially to the phone through the Bluetooth module. The microcontroller operational blocks are depicted in Figure 4.

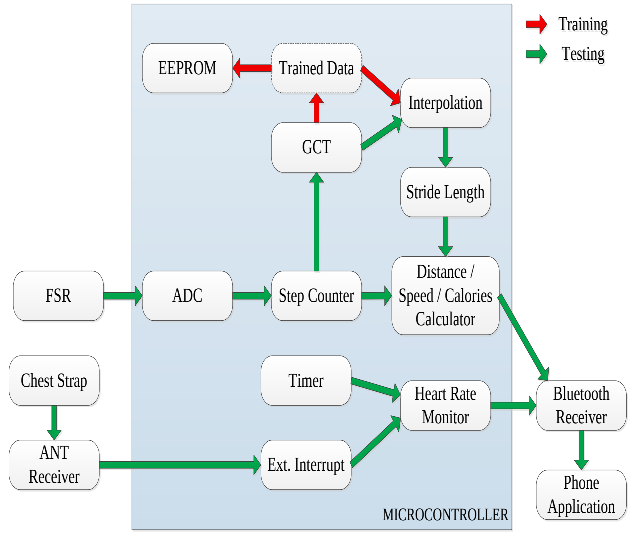


Figure 4 Microcontroller operation block diagram

■5.0 DEVICE TRAINING OPERATION

In order to get more accurate results when running/walking in terms of distance and calories calculated, the device has to be trained initially for one time only. To train the device, the user has to run twice for 30 meters, one time at a slow speed and the other time at a fast speed. From the two runs, the device will obtain two values for each of the stride length and the Ground Contact Time (GCT). As the ground contact time has an inversely proportional relationship with the stride length. The higher the ground the contact time, the smaller the stride length is. After that the values obtained will be stored in the EEPROM.

When the athlete is running, the microcontroller will check the current ground contact time every 20 steps and do interpolation using the values obtained initially from the device training as show in Equation (4), in order to obtain the suitable value for the stride length that suits the athlete's current speed as shown in the Figure 5, where *x* is for the GCT and *y* is for the Stride Length.

$$y = y_1 + \frac{(x - x_1)(y_2 - y_1)}{(x_2 - x_1)} \quad (4)$$

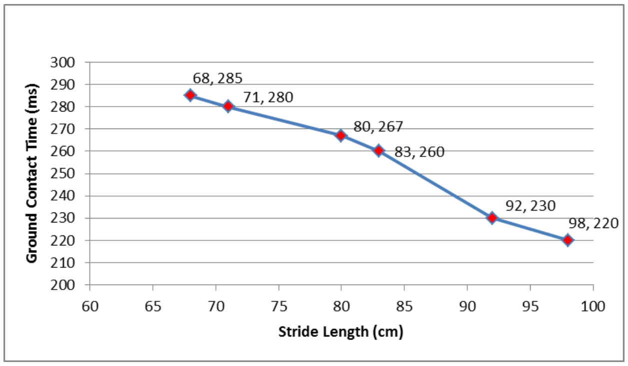


Figure 5 Relationships between GCT and stride length

■6.0 PROTOTYPE DISTANCE CALCULATION RESULTS AND DISCUSSIONS

In order to verify the calculated distance accuracy of the proposed prototype and how much it deviates from the actual distance which has been measured manually, ten test trials was done using different methods and techniques for a total running distance of six kilometers (km). Initially during the trials, the stride length obtained for the slow calibration mode was 55.56 centimeters (cm), and the Ground Contact Time (GCT) was 260.59 milliseconds (ms). Whereas the stride length obtained for the Fast calibration mode was 83.33 cm, and the Ground Contact time was 222.67 ms.

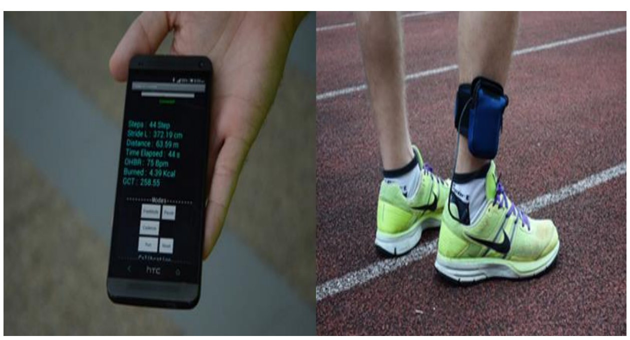


Figure 6 The proposed prototype phone application and the device

The prototype was tested by an athlete who ran at different running speeds simulating actual running conditions. Five tests were done, each for 600 m and done for two trials. The first test was done by running with slow speed (69.5 cm stride, 282.5 GCT) initially and maintained until the end of the trial. The second test was done by starting running with slow speed initially and increasing it to maximum until the end of the trial. The third test was done by running with slow speed initially and inversely changing it every 60 meters between slow and fast until the end of the trial. The fourth test was done by running with medium speed (81.5 cm stride, 263.5 GCT) initially and maintaining it until the end of the trial. The last test was done by running with fast speed (95.0cm stride, 225.0 GCT) initially and maintaining it until the end of the trial.

Figure 7 shows a summary of the ten trials that have been carried out, presenting the average error percentage for every trial. The error rate is calculated by deducting measured distance from the actual distance in meters and converting to percentage. Where starting with medium speed had the lowest average error percentage and the worst error was when the athlete ran with various speeds every 60 meters.

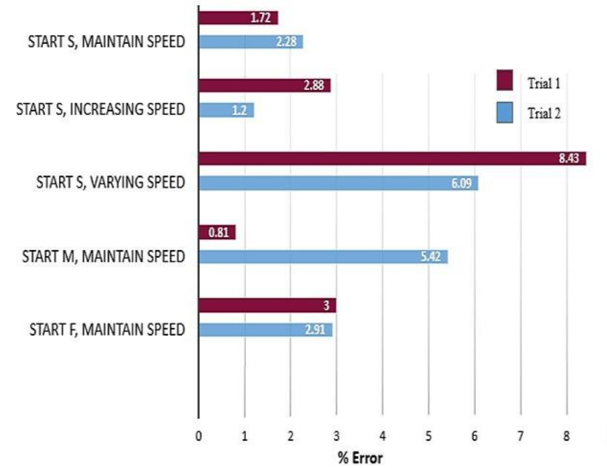


Figure 7 Error rate for the five tests

Based on the results obtained in the five test cases described previously, the findings are analyzed and discussed below.

1. From the ten trials that have been conducted, the most accurate trial was the one where the runner did not vary his speed but maintained it.
2. Running with the fast stride length or the medium stride length as the initial stride length for the first twenty steps often causes the calculated distance to be higher than the actual distance, whereas running with the slow stride length as the initial stride length often leads to the calculated distance being less than the actual distance.
3. Running with varying speeds represents the extreme case to see how wrong the reading can go, the faster the runner runs, the more the value deviates from the actual distance.
4. It is noticed that initializing the stride length closer to the target running speed gives the most accurate results.
5. Beginning with a slow speed or maintaining the same running speed was found to give the accurate results for measuring the running distance while varying speed caused reduction in accuracy.

The device prototype has been tested and compared with Ipod Nano 6th generation and an Android application called Runtastic Pedometer Application. The Ipod Nano is a portable media player designed by Apple Inc. that has an accelerometer built in to help the device function as a pedometer. Whereas Runtastic Pedometer Application is one of the bestselling applications on the Google PlayStore and it utilizes the phone’s built in accelerometer to function as a pedometer too.

The comparison was done in two parts. The first part was to compare the distance measured by the three devices including the proposed prototype, where the actual distance for the test area was 720 meters, the second part of the test was to compare the number of the steps detected by each device. In order to make sure the three devices fair comparison, all of them were tested on the same day, conditions, and location. Each device was tested by using it during a 720 meters distance run with varying the speed gradually from slow to fast.

Table 2 shows the results obtained from the test. From the comparison we can see how Runtastic Pedometer Application performed the worst in terms of distance calculation when running, with an average error rate of 26.86% while iPod Nano followed by an average error rate of 25.02%. On the other hand, the proposed prototype performed with a 3.03% average error which is by far much better than the other compared products. The reason for the better accuracy of the proposed device includes the stride length adjustment performed according to the speed of the athlete instead of remaining fixed the whole time.

Table 2 Distance measured for the three devices

Speed	Actual Distance	iPod Nano			Runtastic Pedometer Application			Proposed Prototype		
		Dist. (m)	Error		Dist. (m)	Error		Dist. (m)	Error	
			(m)	(%)		(m)	(%)		(m)	(%)
Slow	60	70	10	16.7	80	20	33.3	63	3	5
	120	150	30	25	160	40	33.3	130	10	8.3
	180	230	50	27.8	240	60	33.3	190	10	5.6
	240	310	70	29.2	320	80	33.3	247	7	2.9
Medium	300	380	80	26.7	390	90	30	307	7	2.3
	360	450	90	25	460	100	27.8	365	5	1.4
	420	530	110	26.2	530	110	26.2	417	3	0.7
	480	600	120	25	600	120	25	477	3	0.6
Fast	540	680	140	25.9	660	120	22.2	531	9	1.7
	600	750	150	25	720	120	20	589	11	1.8
	660	820	160	24.2	790	130	19.7	643	17	2.6
	720	890	170	23.6	850	130	18.1	695	25	3.5
Average Error		25.02%			26.86%			3.03%		

Figure 8 shows the accuracy level for all the three devices compared, where the highest accurate one in terms of measuring the distance while running was the proposed prototype with 96.97% accuracy, followed by the iPod Nano with an accuracy of 74.98% and at last Runtastic Pedometer Application with an accuracy of 73.14%.

For the second test, the athlete ran again under the same conditions for the same distance again. But this time to compare the number of steps detected while running with various speeds for 720 meters. As accuracy in detecting the number of steps is crucial for determining the distance covered while running for non-GPS devices. Since the distance covered is basically the number of steps times the stride length.

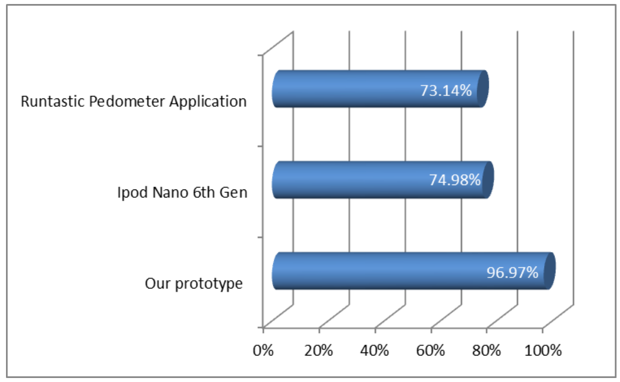


Figure 8 Distance measurement accuracy for the three devices

Note that unlike the Runtastic Pedometer Application and the proposed prototype the iPod Nano does not display the step rate while running. Therefore, the step rate for the Ipod Nano is shown NIL as in Table 3. Again the proposed prototype had the lowest error percentage that's due to the fact that the steps are being detected using a force sensor instead of estimating them using accelerometers.

Table 3 Steps detection for the three devices

Speed	Actual Steps	iPod Nano	Runtastic Pedometer Application			Proposed Prototype		
			Steps	Error		Steps	Error	
				Steps	(%)		Steps	(%)
Slow	84	NIL	83	1	1.19	84	0	0
	164	NIL	161	3	1.82	164	0	0
	244	NIL	239	5	2.08	243	0	0
	326	NIL	320	6	1.84	326	0	0
Medium	400	NIL	391	9	2.25	400	0	0
	474	NIL	461	13	2.74	476	0	0
	542	NIL	532	10	1.85	542	0	0
	614	NIL	599	15	2.44	614	0	0
Fast	680	NIL	663	17	2.51	680	0	0
	746	NIL	724	22	2.95	746	0	0
	816	NIL	790	26	3.19	816	0	0
	886	NIL	856	30	3.39	886	0	0
Average Error		NIL	2.35%			0%		

7.0 CONCLUSION

This paper described the implementation of a microcontroller based multifunction activity tracker that can help the athletes monitor their activity while running or walking. The prototype is worn around the ankle while the FSR sensor is placed inside the shoes insole and display parameters such as distance covered, heart rate, steps rate and calories burnt via an Android application on a smartphone. From the experiments conducted in this project which consisted of running for the length of 60m at varying speeds, the accuracy of the device was found to be 96.53% on average. Future improvement for this project require further testing with a larger database of users and designing a more compact prototype for ease of use.

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