Wireless Integrated Gait Analysis System for Heel-Strike and Toe-Off Measurement

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***Abstract*—This paper presents the development of a wireless system for gait analysis. Nowadays, gait analysis becoming an important tool to diagnosis or evaluate certain diseases. It has a lot of improvements since the introduction of biomechanics and gait analysis has to be more precise. A lot of studies had been made to determine the measuring of the gait parameters. However, only a few of them specify the measurement of "heel-strike" and "toe-off" timing parameters. Even though there is a research center providing the stated quantitative information, it has been done in a highly accurate computer laboratory. This super computer method is very expensive and not affordable. While in the medical world, the gait parameters analyzed without any guarantee of the results obtained. Therefore, there is a need of the system that is not only low cost but also can produce a real-time feedback. The main objective of this new insole system is to design and implemented a low cost and wearable solution for "heel-strike" and "toe-off" timing parameters using the Force Sensing Resistor (FSR) sensor. The design of this new insole system consisting of six FSR sensors that will deliver a convenient result in the stated gait parameters and offer an additional function which is the gait symmetry observation. The advantage of this project is that it would be a great achievement in the new gait analysis system by introducing the concept of portable wireless and real time feedback device (self–monitor). In conclusion, the design of this new insole system is predicted to help clinician and researchers to develop a new model of gait analysis system.**

***Index Terms*—Gait Analysis; Gait Parameters; Shoe System; Sensor Network System.**

I. INTRODUCTION

Walking skills is the greatest gift in human life. Every normal human being began to learn how to walk as soon as they reach the age of one year [1]. Nobody wants to refuse to walk normally. Nevertheless, that is the reality that needs to be faced by millions of people who face the gait disorder problems. Gait disorder, which is included in one of 600 neurological disorders have several causes [2]. A study made in 2004 reported that in every 60% of gait disorder patients, stroke disease is the most frequently diagnosed by 21% of the patients [3]. This is the main reason why the term of gait analysis introduced by Aristotle (384 – 322 BCE) before it was experimentally tested by Giovanni Borelli (1608 – 1679) [4].

Gait analysis is a study of the human walking pattern [5]. After the introduction of an advanced computer system, the applications of the gait analysis are also greatly expanded based on its parameters as tabulated in Table 1 [6]. Presently, the concept of gait analysis is extensively applied in footwear design, sports performance analysis and injury prevention, improvement in balance control, and diagnosing disease [7].

Currently, this gait analysis comes in two methods. The first method of gait analysis is carried out in motion laboratories that provide a full analysis of the motion body segments using a super highly accurate computer, but it is very expensive and not affordable for everyone indeed it requires quite a lot of maintenance to maintain the accuracy [8]. The second method is visual observation conducted by clinicians. It is more economical with inexpensive equipment, but still, has some significant weakness such as requiring a more frequent visit to the clinic for appropriate gait analysis [8].

This gait analysis study can be a learning paradigm in the conservation industry to improve their knowledge and skills as well. Results from this project into a new development or achievement for gait analysis. Notwithstanding the foregoing methods, the design of this research paper will increase the sense of humanity to analyze gait parameters practically. This design contains all the considerations on gait analysis system using wearable sensors. It focuses on a new lifestyle, in which new products must be in accordance with the concept of integrated wireless systems and mobile design.

Table 1
Gait Parameters and Its Applications

Gait Parameter	Application		
	Clinical	Sports	Recognition
Stride length	X	X	X
Step length	X	X	X
Cadence	X	X	X
Step width	X	X	X
Step angle	X	X	X
Step time	X		
Stop duration	X		
Gait phase	X	X	X
Muscle force	X	X	X
Ground reaction force	X	X	X

Thus, the main objective of this project is to design and develop a new concept of gait analysis system using a new concept of insole system focusing on two gait parameters; heel strike to toe off timing and gait asymmetry observation in the form of Gait Shoe. This objective followed by several requirements of the design, which are to provide a real–time analysis and feedback, wearability and easy system to install, low cost and low power consumption.

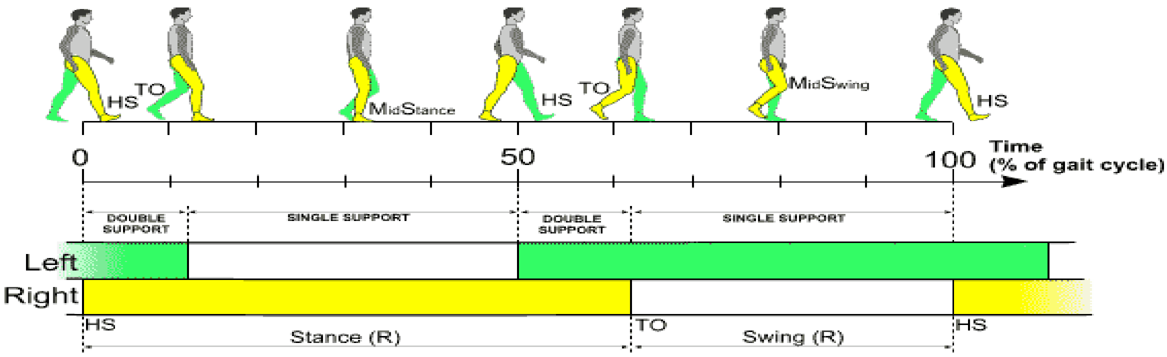

Figure 1: Schematic of heel strike to toe off timing

The general purpose of this study is to understand and study the appropriate gait parameters in which to be able to extract the data from FSR sensor. The output result then analyzed to design the subsystem of this new insole system development.

This research study focusing on the development of new insole system using FSR sensor in order to analyze two gait parameters that associate with force measurement; heel strike to toe off timing (HSTO) and gait asymmetry.

Heel strike to toe off timing occur during the stance phase in gait cycle which is approximately 60 percent of initial foot's contact to the end of the contact. HSTO measured in second (s) from heel strike to foot flat condition, continued by mid-stance condition and end with the heel off before the toe off from the contact as summarized in Figure 1. [9].

While the gait asymmetry parameters evaluated by comparing the heel strike to toe off the timing between the both of feet. A good gait asymmetry will produce a result of zero in term of symmetry index (SI). But, the condition will change depending on the dominant legs following a certain normal ratio. Gait asymmetry helps in determining the gait stability of human. The new insole system also concentrating on a new way of delivering the result of gait analysis to the end user in term of real time feedback and easily accessed.

This paper has the structure as follows. Section I providing the general information for the Gait Shoe project such as the introduction, problem statement, objectives and some of literature review part. Section II describes the methods used including the hardware and system designed for this project. All the collected data or results presented and discussed in Section III. Section IV explaining the conclusion of this project.

II. Design Methodology

A. *Flow of System*

This system operated with the analysis of six FSR sensors as the input signal that collected and sampled by using some specific algorithms to obtain the force values. The flow of this system started by collecting the analog signal from FSR sensors.

Then, all the signals analyzed in Arduino UNO microcontroller to obtain the force value for each sensor. The values of the force were compared between both of feet. The microcontroller initiating the timing once the forces were compared each to record the heel strike to toe off timing parameters.

The gait asymmetry obtained after the heel strike to toe off timing recorded. Gait asymmetry calculated by comparing the heel strike to toe off timing for both of feet. The output result of the system delivered to the database via smartphone connection. The system ended by displaying the user data to the Android application and the Gait Analyzer Monitoring System. The summary of the flow system is shown in the block diagram of Figure 2.

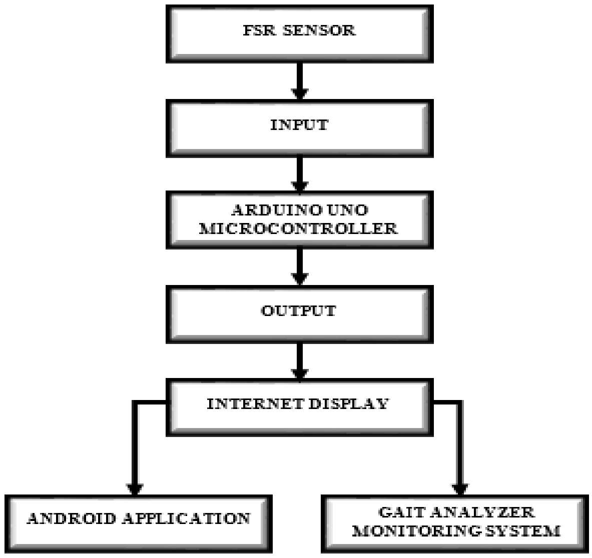

Figure 2: Block diagram of hardware flow of system

Figure 3 shows the flowchart of gait analysis system operation. The system got an input command from the android application to the heel strike to toe off timing and gait asymmetry test controlled by the user. After receiving the input command of the android application, UNO microcontroller started analyzing the collection and sampling process of the FSR signal.

Inside the microcontroller, the signal was processed to obtain the output in form of force values for the timing parameters. The generated force values between both of legs compared continuously before the timing parameters could be sorted out.

The process of obtaining data continued by calculating the gait asymmetry using the gained the heel strikes to toe off timing in both of legs. Both of heels strike timing to toe off timing and the gait asymmetry parameters stored in the online database for the monitoring purpose.

After the output data was successfully stored in the database, then, the user of this gait shoe would get a real feedback result through the android application. At the same time, the recorded history of gait analyzer monitoring system also updated with the newly inserted data. The stored data could be accessed any time by the user to improve their own walking pattern.

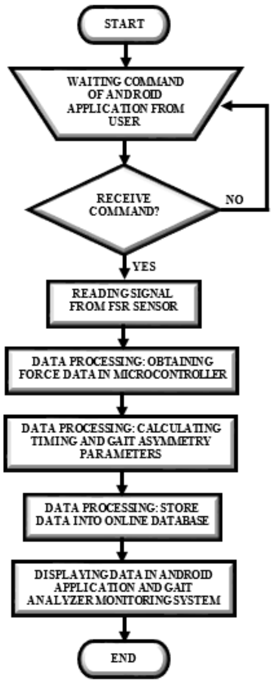

Figure 3: Flowchart of gait analysis system operation

The sensors implemented for this project selected specifically for the particular gait parameters. This study projected to analyze the heel strike to toe off timing parameters and also the gait asymmetry observation. The location of the FSR sensors studied thoroughly to reduce the error percentage of the output result to be compared with real data from the gait analysis system that using the super computer as the machine operation. The arrangement of those sensors oriented in Figure 4 [10] [11].

In order to analyze the heel strike to toe off timing and gait asymmetry parameters, two FSR-402 and one FSR-400 placed beneath right and left metatarsal and underneath heel pad consecutively. The sensor that manufactured by Interlink was placed after configuring them by using an eight size of normal shoe. FSR sensor functions to detect force from 1 Newton (N) to 100N in that location before analyzed for the heel strike to toe off timing and gait asymmetry parameters [12].

The implementation of FSR sensors required a lot of arrangement scale to make sure the sensors positioned at the right place. In order to place the sensor, the FSR sensors were smeared with a marker pen and affixed under its feet in both of metatarsal and heel. Then, the effects of markers for the site had been marked before attaching the FSR sensor. The implementation of the FSR sensor for the hardware interfacing is shown in Figure 5.

B. Sensors Placement and Implementation

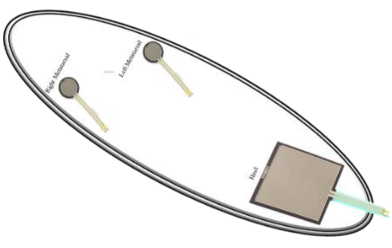

Figure 4: Sensor placement orientation

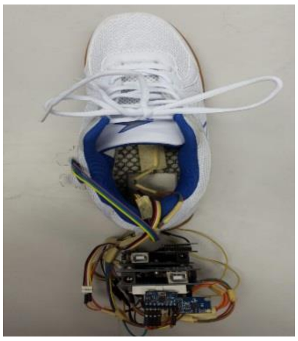

Figure 5: The implementation of FSR sensor

C. Sensors Placement and Implementation

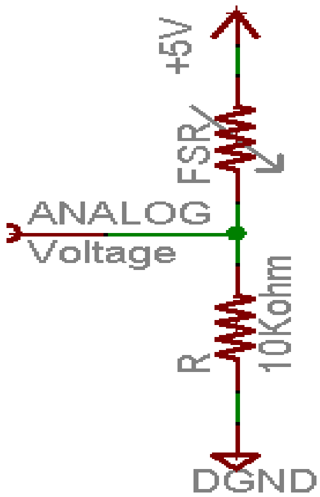

Figure 6: Circuit for FSR implementation

Both of heel strike to toe off timing and gait asymmetry extracted from the force comparison. Thus, in order to obtain the gait parameters, the equation to find the force values using FSR sensor must be selected in the first place. Figure 6 [13] shows the circuit used for the design implementation before preceding the gait parameters extraction.

$$Vout = \left(\frac{R + Rfsr}{Rfsr} \right) .Vcc \qquad (1)$$

Basically, the force values started to be analyzed by using the equation of voltage divider as shown in Equation (1). From the equation, the resistance of the FSR sensors calculated as described by

$$Rfsr = \left(\frac{Vcc - Vout}{Vout} \right) .R \qquad (2)$$

The next process of obtaining the force values is by following the relationship between conductance and the applied force in Newton. The relationship determined as

$$G(fsr) = \left(\frac{1}{Rfsr} \right) \qquad (3)$$

$$F = \left(\frac{G(fsr) - 1000}{30} \right) \qquad (4)$$

After the value of force obtained from Equations (4), (3), (2) and (1) [14], the force was compared between both of legs to gain the heel strike to toe off timing and gait asymmetry parameters. For make an easy observation, the force value converted into a digital signal which is logic '1' for the highest force, and logic '0' for the lowest signal.

The timing parameter is taken from the difference of timing in both of legs. The first timing counted when the force of one of the foot read higher than the other one. Then, the difference of the timing calculated when the other foot produced the larger force value after one gait cycle.

In the other hand, gait asymmetry calculated by using the Equation (5) [15].

$$SI = \left(\frac{X1 + X2}{0.5(X1 + X2)} \right).100 \tag{5}$$

SI representing the symmetry index where the dominant legs usually used as the 'X1'. The dominant legs in this study found the legs that received the highest average of the heel strike to toe off timing.

D. Android Application

An android application called "GaitAnalyzer" created for this gait analysis system. The android application created for the user to control the test for every gait parameter. The user must first to register in the register section to use this application. Figure 7 shows the flowchart of operation "GaitAnalyzer" android application.

For the first-time user, they need to register first in the register section before can log in to the application as shown in Figure 8. This system designed so that the health care center can really take a real data for a real user. Then, the user can start using the gait analysis system by clicking the button for the gait test. After finishing the test, the user can get the real-time feedback that displayed on the monitor of the application.

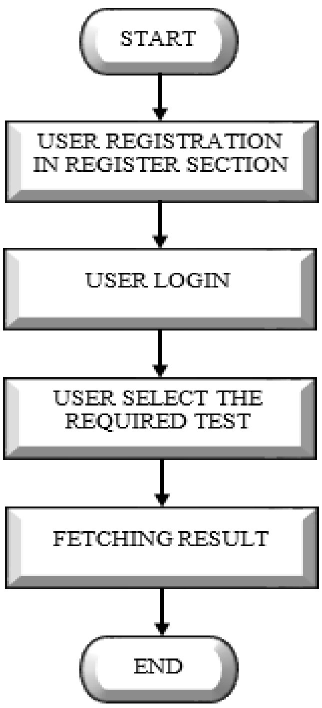

Figure 7: Flowchart of operation "GaitAnalyzer" Android application

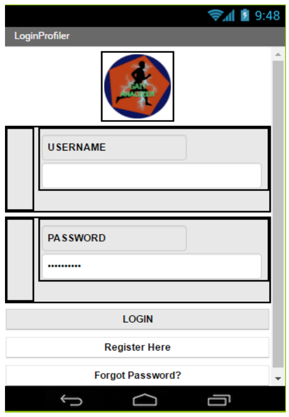

Figure 8: Login page to "GaitAnalyzer" Android application

III. RESULTS AND DISCUSSION

Table 2
Summary of Subject Characteristic

Type / Subject	Age	Height	Weight	Gait Status
Subject 1	25	1.71	68	Normal
Subject 2	26	1.72	73	Normal
Subject 3	45	1.72	64	Abnormal walking pattern with diabetes
Subject 4	52	1.68	76	Abnormal walking pattern with diabetes
Average	37	1.7075	70.25	

A. System Testing

During system testing, few volunteers were recruited to test the validation of the Gait Shoe system. This system basically requires the user to equip them with instrumented Gait Shoe. All the selected volunteers have one similarity, which is the gait size of 8 since the Gait Shoe has been fixed.

B. Overview of Participants

After the implementation and finishing up the system gait analyzer system monitoring, there are a group of 4 volunteers called to test and initialize this system. The details of the volunteers summarized in Table 2.

C. Sensor Analysis

All the volunteers had been explained in details about the gait parameters that will be extracted during the data collecting process. The purpose of selecting two by two of subjects that have the normal gait and abnormal gait is to check if the system fully functions, as it should be.

Due to the limitation of time, only three readings for each gait parameters were sampled. The system also altered so that it can start automatically and stop in a certain of time duration by ignoring the function of the controller at the android application.

The first stage of the analyzing process, the subject was asked to stand steadily so that calibration process could be performed to obtain a correct measurement with less number of the error. The subjects were then asked to walk properly as they having their daily walking pattern to allow data streamed and collected from the Gait Shoe itself.

Gait parameter data from the Gait Shoe were analyzed. This is an essential step to validate whether our system is able to provide the same result and value as nowadays Gait Analysis system that using the high-speed camera. The results of timing parameter and gait asymmetry are described in Table 3 and 4 respectively.

Table 3
Heel Strike to Toe Off Timing Result for Each Subject for Both Legs

	Heel Strike to Toe Off Timing (Right Foot) (seconds, s)				Heel Strike to Toe Off Timing (Left Foot) (seconds, s)			
	S1	S2	S3	S4	S1	S2	S3	S4
R 1	0. 32	0. 35	0. 45	0. 47	0. 30	0. 38	0. 41	0. 43
R 2	0. 28	0. 36	0. 49	0. 47	0. 31	0. 37	0. 40	0. 44
R 3	0. 33	0. 35	0. 47	0. 46	0. 29	0. 36	0. 41	0. 42
Mean,µ	0. 31	0. 35	0. 47	0. 47	0.3	0. 37	0. 41	0. 43

All the sampled data was determined based on the reference value of 0.3 seconds from Run3D shoe analysis system [16]. However, 0.3 seconds is the average value for the runner. In this system, the average of walking must be higher than the 0.3 seconds to be valid. Figure 9 shows the graph of the entire means for each subject compared to the data from the Run3D shoe. All the timing was measured when the force at logic ‘1’.

Based on the data, it was confirmed that this new insole system produced the standard range of normal value compared to the Run3d shoe, which is popular in Europe country. The mean for subject 1 and subject 2 is approximately achieving the normal timing range of normal walking pattern for a both of legs. The normal timing range is from 0.3 to 0.4 seconds.

In the other hand, for subject 3 and 4, the mean reading is higher than normal values, which are 0.41 and 0.43 in left foot, while obtained the same value of 0.47 in right foot. This value is abnormal since the test subjects already have the gait disorder problems related to diabetes problem. Thus, the results were gained perfectly for this gait analysis system.

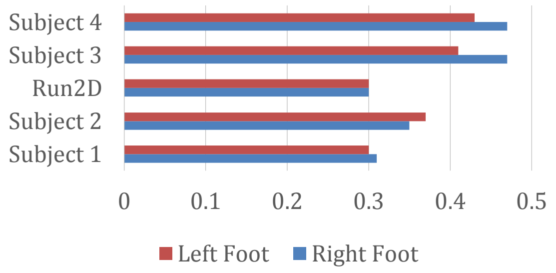

Figure 9: The comparison data for each subject for both of legs to the data from Run3D shoe

Table 4
Gait Asymmetry for Each Subject

Subject	Symmetry Index, SI (%)
Subject 1	3.28
Subject 2	5.55
Subject 3	13.67
Subject 4	8.88

Table 4 shows the gait asymmetry for each subject. There are no specific details about the gait asymmetry parameters. It is a measurement to observe the human body balancing either they walked with more load on the right foot or vice versa.

Gait asymmetry could be measured using ground force distribution (GFD) or timing parameters. In this study, the determination of the gait asymmetry used the heel strike to toe off timing parameter. The symmetry index of gait asymmetry is obtained by Equation (5) in methodology section where the legs dominant determined by the highest timing parameter between two legs.

D. Android Application

Basically, there are two stages of process occur simultaneously depending on user need. The first stage is user may really want to see the result of analysis immediately, and thus using the “GaitAnalyzer” android application as shown in Figure 10 to control an Arduino Microcontroller to obtain gait result at an instant is an option. The data first will be stored into Health Care Center Cloud service and then Gait Analyzer application will retrieve data from the database and display it on the mobile.

However, at the second stage, the user will wear the Gait Shoe and start walking without worrying too much about the Android application to control and Arduino microcontroller since it has an ability to perform gait analysis automatically.

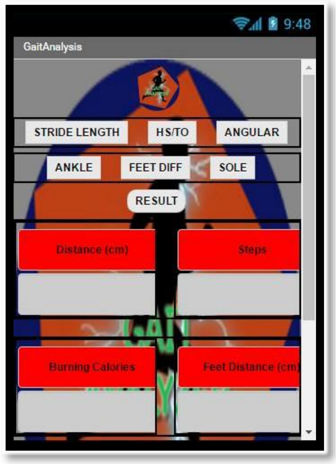

Figure 10: Result display for “GaitAnalyzer” Android application

IV. Conclusion and Recommendation

As a conclusion, it can be concluded that Integrated and Real-Time Gait Analysis System for Heel-Strike and Toe-Off Measurement resulted in a wireless wearable system that capable to analyze and characterize gait parameter in term of heel strike to toe off timing and also the gait asymmetry observation. As a system created to provide a real-time analysis and feedback, wearability and easy system to install, low cost and low power consumption, it also is able to retrieve data in real time. This new concept of gait analysis system also programmed to record all the gait information in various condition. For instances, the subject or the patient still can do the daily routine life without interruption. Furthermore, this gait shoe system also able to display results from the analysis and sent it directly to the medical specialist through the database to the data center analysis and at the same time the patient also can monitor via mobile phone. For the future recommendation, this system will be expanded to the iPhone operating system (iOS) since the current development is only limited to Android user. Besides, it is expected to be able to define types of gait and the relating diseases using this new insole gait analysis system.

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