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Development of wearable gait analysis device based on vertical ground reaction forces

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ABSTRACT: Gait analysis system is widely used in the field of biomechanics and sports sciences. It is a sophisticated system that requires high costs to develop and run. This system also requires trained people to handle the system. Besides, the current wearable gait analysis device faced limitations such as low durability and repeatability, big size and heavy weight, and limited data storage and usage time. Based on these conditions, this project was created to overcome the stated problems by initiating a pilot work on developing a reliable and cost-effective device. This initial gait analysis device only focused on the vertical ground reaction force (vGRF) and analyzed the human gait pattern during normal walking activity. This project was designed with wireless capability that makes handling and monitoring the device easier. This project is a prototype-based gait analysis system with the idea to develop a low-cost system that can be integrated and enhance the existing system. Resistive force sensors were placed at three locations representing the most pressurized on foot based on a previous study to measure the vGRFs. The device was tested by conducting experiments to analyzethe gait pattern of ten healthy subjects during normal walking activity. The results were verified according to the standard gait data obtained from the previous study. The results showed that the developed wearable gait analysis device able to produce similar curve patterns as the standard vGRF with 94.5 % accuracy. With the high repeatability and accuracy, this device can be further expanded by including the lateral and longitudinal ground reaction forces, performing more activities, and conducting an experimental studyfrom different subjects' backgrounds.

KEYWORDS: Gait analysis, vertical ground reaction force, wearable device, walking pattern.

I. INTRODUCTION

Walking is a movementwith high coordination controlled by the central nervous system and involves a very complex system. Walking is a very stable movement using two legs known as bipedal locomotion. Normal walking conditions require only a small amount of work on the muscles of the limbs. Forward movement is the most important movement during walking due to the acceleration and deceleration of the limb and muscles when performing the activity.

Gait analysis is the assessment of the walking pattern. Biomechanical analysis of a gait pattern employs various methods such as kinematic analysis, pressure measurement, dynamic electromyography and many other techniques. One of the most applicable methods is the kinetic analysis based on the assessment of the ground reaction forces (GRFs) recorded on two force plates [1]. The primary function of the gait analysis is to measure the degree of pronation in which the natural inward rolls act as a shock absorber for the leg and body by optimally distributing the force of the impact when the heel hits the ground. It would be helpful to have a wearable device to analyze the gait variability for monitoring or analyzing the gait pattern that can be used for therapy and to detect any abnormalities of the gait cycle at an early stage.

In the field of biomedical engineering, gait analysis has been a fundamental method and assistive tool to characterize human locomotion. A standard gait analysis method based on the multi-camera motion capture system and force platform with the capability of measuring ground-reaction forces has been successfully developed and applied in several gait laboratories [2]. However, thisgait analysis requires specialized labs, expensive equipment, and long-time processing. Additionally, it requires a large area to perform the task. An alternative gait analysis method based on wearable sensors, which can be used outside the laboratory environment, has been introduced to overcome this problem. This condition has been studied and shown excellent prospects for the past two decades.

The previous study has shown significant results on the development of gait analysis instrumented force shoes and pressure insoles [3]–[6]. Later, the combination of inertial measurement units and linked segmental models have paved the way for ambulatory assessment kinetics of knee and ankle [7], [8]. Even though these studies achieved high accuracy with low root mean square (RMS) errors of (1.1±0.1)%, certain limitations have to be addressed [9]. Low repeatability and durability, big size and heavyweight, limited data storage, and experimental duration are some of the issues this research study wants to overcome. Therefore, this project is intended to enhance the existing technology's capability and make it affordable for all segments of society in the world.

II. MATERIALS AND METHODS

Figure 1 shows the block diagram of the project. The project consistsof two main parts:the hardware and software parts. A sensor is the most important part of this project. The selection of sensors was made after considering the criteria that are required for the system based on the durability, lightweight, small size and ease to embed on the shoes. As for this project, the most suitable and affordable sensor is the Flexiforce sensor (FFS). These sensors were used to record the pressure of the load when the subject steps on it. The sensors were mounted on the insole to collect data for each step of walking. The placements of the sensors are shown in **Figure 2**. Based on the previous study, these locations represent the most pressurized on foot to measure the vGRFs[9].

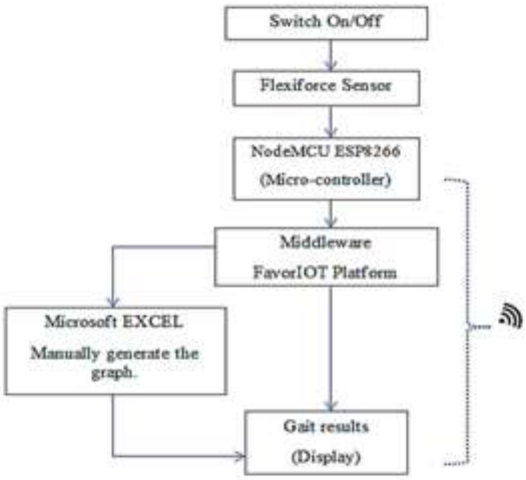

Figure 1: Block diagram of the project

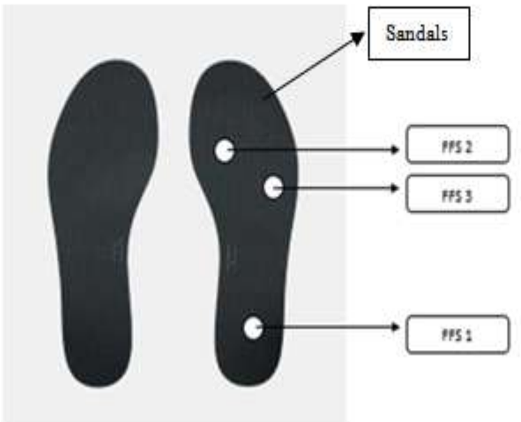

Figure 2: The location of the pressure sensors

The second essential hardware for this project is the micro-controller. This device utilized NodeMCU as a controller and interface between the insole and computer. Its wireless capability and small size are the advantages of using this component. The small size makes it easier to be mounted on the insole. NodeMCU is firmware based on ESP8266. It is an open-source IoT. The NodeMCU was programmed via Arduino IDE software since it is the most suitable for long-term planning to manipulate the coding to suit the future expansion of the project. The final design of the device is shown in **Figure 3**.

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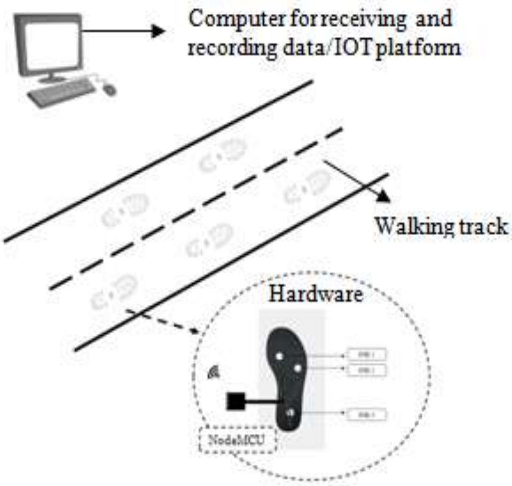

Figure 3: Hardware final design Figure 4: The experimental setup (walking track**)**

III. EXPERIMENTATION

Figure 4 shows the walking track used for the experiment. This project's analysis was conducted based on the designated walking track. The walking track was set to 5-meter in length by considering the limited space in the laboratory and the subject able to produce at least two complete gait cycles (1.5 m per stride). The subject was asked to walk at a normal working pace during the testing. This walking track was fabricated using tape and paper marked on the ground

The procedures include the steps for the preparationuntil the end of the experiment.

Step 1: The subject needs to read and fill in the consent form.
Step 2: Record the name and weight of the subject.
Step 3: Prepare the insole for the subject. The subject must adequately wear the insole.
Step 4: Check the walking track and make sure it is clearof any hazards.
Step 5: The subject starts walking on the track for 2 minutes.
Step 6: Save data and display iton the computer.
Step 7: Analyze the results.

IV. RESULT AND DISCUSSION

The individual demographic information of the subjects who participated in the experiment is shown in Table 1. The difference in the subjects' body weights can significantly influence the force and gaitpattern during walking, and this criterion can be used to validate the results of the study.

No	Name	Age	Gender	Weight(kg)
1.	Subject 1	26	Female	38
2.	Subject 2	26	Female	47
3.	Subject 3	27	Male	83
4.	Subject 4	27	Male	80
5.	Subject 5	26	Female	56
6.	Subject 6	27	Male	72
7.	Subject 7	27	Female	96
8.	Subject 8	26	Female	43
9.	Subject 9	26	Female	85
10.	Subject 10	24	Female	45

Table 1: Demographic information of subjects

DATA STREAM ON THEFavorIOT

The data obtained from the force sensors were sent wirelessly to the computer. Figure 5 shows how the results were displayed in the FavorIOT platform. The FavorIOT platform allows the user to directly access the data without requiring a manual data transfer from a memory card

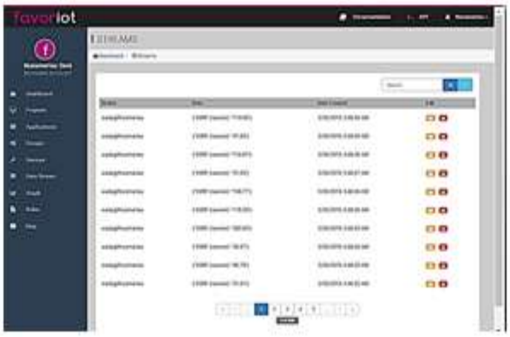

Figure 5: Data stream on FavorIOT platform

STANDARD VGRF DIAGRAM

The purpose of developing this project is to analyze the gait data obtained from the experiment. This is to ensure that the outcomes of this project are highly reliable and accurate. For that purpose, this project was tested on several subjects who had different weights and gender. The results of the analysis were evaluated by referring to the standard diagram of vGRF for normal gait, as shown in figure[10].

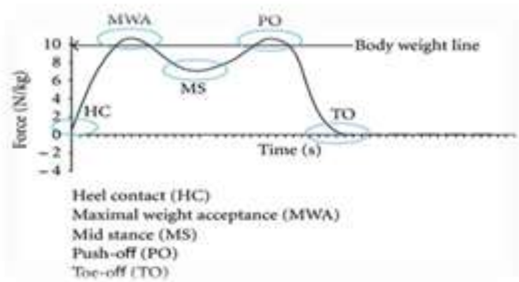

Figure 6: Vertical ground reaction forces (VGRF) [10]

Based on the figure, the gait events are divided into five significant events, which are heel contact (HC), maximal weight acceptance (MWA), mid stance (MS), push-off (PO), and toe-off (TO). These gait events are crucial in determining and assessing an individual's gait pattern. As a rule of thumb, a normal and healthy individual should have a similar curve pattern as exhibited in Figure 6. However, the x-axis has to be normalized to 100% of the gait cycle in order to ease the comparison between the vGRF curves patterns produced from the different subjects.

GAIT DATA ANALYSIS

The vGRF value and percentage of the gait cycle were calculated using the formula in equations (1) and (2). Next, the vGRF graph was then plotted, as shown in Figure 7. The example of the subject data for one complete gait cycle is shown in Table 2

$$V_{grf} = \frac{Output\ value\ (N)}{weight\ of\ subject\ (kg)} \quad (1)$$

$$\%\ gait\ cycle = \left(\frac{time(s)}{total\ time\ (s)}\right) \times 100 \quad (2)$$

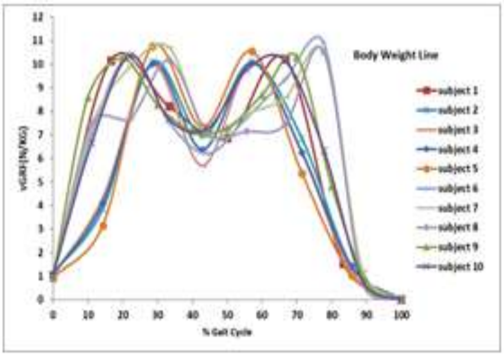

Figure 7: vGRF graph of 10 different subjects

Time (s)	Subject 1 (38kg)	% Gait Cycle	vGRF (N/Kg)
0	63.05	0.0	1.66
1	407.32	16.7	10.72
2	311.9	33.3	8.21
3	260.76	50.0	6.86
4	388.71	66.7	10.23
5	58.42	83.3	1.54
6	0	100.0	0.00

Table 2: Complete gait cycle data of Subject 1

The percentage difference between the recorded and standard data of the vGRF was calculated for each gait event, as shown in Tables 3 to 6. Based on the results, further analysis can be obtained to investigate the accuracy of the developed device.

Table 3: Heel contact reading

Subject	Standard value (N/kg)	Device reading (N/kg)	% difference
1	1	1.05	5
2	1	1.09	9
3	1	0.98	2
4	1	1.06	6
5	1	0.92	8
6	1	1.03	3
7	1	0.96	4
8	1	0.92	8
9	1	0.96	4
10	1	1.03	3

Table 4: Maximum weight acceptance reading

Subject	Standard value (N/kg)	Reading value (N/kg)	% difference
1	11	10.16	8
2	11	10.08	8
3	11	9.96	9
4	11	10.02	10
5	11	10.77	2
6	11	10.43	5
7	11	10.72	3
8	11	10.17	8
9	11	10.28	7
10	11	10.37	6

Table 5: Mid-stance reading

Subject	Standard value (N/kg)	Reading value (N/kg)	% difference
1	11	10.23	7
2	11	10.09	7
3	11	10.04	9
4	11	10.05	9
5	11	10.55	4
6	11	10.88	1
7	11	10.46	5
8	11	10.53	4
9	11	10.31	6
10	11	10.14	8

Table 6: Push off reading

Subject	Standard value (N/kg)	Reading value (N/kg)	% difference
1	7	6.86	2
2	7	6.97	0
3	7	5.7	9
4	7	6.37	9
5	7	7.34	5
6	7	7.54	8
7	7	6.94	1
8	7	7.06	1
9	7	7.16	2
10	7	7.28	4

Based on the graphs and tables presented, in general, the vGRF patterns for all subjects exhibited a similar curve pattern as the standard vGRF as reported by Bouffard et al. [10]. However, the vGRF values for each subject for each gait event showed a significant difference, but the difference was still in the acceptable range. This is based on the fact that the percentage difference between the measured and the standard gait data is less than 10% for each of the observed gait event. According to Handžic and Reed [11], the acceptable range is within ± 25% between the measured and standard gait data [11]. In average the percentage difference is 5.5%, or in other words, we could say that this device is 94.5% accurate. In addition, this device can still produce good results based on the ten data samples taken from the different subjects with different body weights.

Many factors can affect the accuracy of the device. This condition might be due to the variability of the walking style between the subjects. An individual's walking style is greatly influenced by the body mass index (BMI), walking speed, stride length, and many other factors that are classified as a kinematics adaptation of human locomotion [12]. The variability of the walking pattern is essential in order to maintain the skeletal health of an individual when performing daily living activities

V. CONCLUSION

The development of the gait analysis device based on vGRF has shown a great potential to be further expanded in order to develop a more accurate and cost-effective device. This device has achieved 94.5% accuracy and demonstrated good repeatability. The accuracy of the device has been validated by comparing the result obtained from the experiment with standard gait pattern as presented by Bouffard et al. [10]. In addition, all of the gait data can be transferred wirelessly and can be further analyzed to examine the performance of the gait.

In future, this study can be further expanded by including the analysis of longitudinal and lateral ground reaction forces. The performance of the device can also be improved by conducting an experiment involving subjects from different BMI, such asoverweight and obese subjects, and applying different types of activities such as stairs ascending and descending. Last but not least, automatic gait analysis can also be explored to substitute manual computation that is believed can reduce the computation time and error in analyzing the gait data.

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