Gait Cycle Ground Reaction Force Measurement Using Piezoelectric Sensor Attached to Shoe-Insole System

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Abstract. This study presents a wearable system that mainly consisted of piezoelectric sensors, filter circuit and data logger in order to measure the vertical ground reaction force (VGRF) and study its profile. The proposed system establishes base information to improve the portable gait analysis systems and make them easier in use also to be able to get more outdoor data. The experiments were done by a young healthy person without physical disabilities or nervous disorders and the experimental protocol was explained to the participant before the performing. The experiment involved the walking with self-selected speed along 15 meter track of paved ground. The system was set on (200 Hertz) sampling rate in order to achieve the required data resolution. The produced information was about the events of the gait cycle (Heel-Strike, Stance, Heel-Off and Swing) and their durations also for the VGRF profile of each step and stride which compared with the VGRF profile of force plate. The results of VGRF of sensor-insole system clarified a high similarity with the VGRF produced by force plate system. Despite the system having many features, there are some limitations which can be avoided after improving the system.

1. Introduction
Gait cycle analysis is an important subject in time being, this subject was discussed in many researches using different means to serve various purposes. The analyzing of the gait cycle depends on collecting required data of spatial and temporal parameters such as (the length of stride and step, the duration of stride and step, speed and cadence). Also, there are some complicated parameters like kinematic data that can found using more sensing instrument that includes the position of joint centers, joint angles, center of mass and angular velocities. Then other kinetic data (that includes Ground Reaction Force (GRF), Center of Pressure (COP), joint power, muscle torque and muscle power) all these parameters could be extracted through utilizing specific devices and sensors [1]. The collected data are considered essential to be used in different fields such as designing of footwear [2, 3], especially in sports applications in order to avoid the probable accidents and injuries and to improve athletes’ performance [4], or in medical applications to improve foot comfort for patients which have some diseases as arthritis, ulceration of diabetes and plantar fasciitis [5]. Also, the collected data from these sensors can contribute directly in the technologies of mechatronics applications [6]. In addition, it can be used to improve some gait assistance instruments as orthotics used for states of cerebral palsy toe walking or foot drop [7] so as to help patients, disables and elderly people to improve their mobility. Finally, gait cycle analysis is important in treating, assisting, evaluating and diagnosing the gait defects, moreover, informing surgeries’ procedure [8, 9].
In the current study, the vertical ground reaction force (VGRF) was investigated using a wearable system to obtain these data. One of the conventional methods is by using force plate system [10] that represents the golden standard to find VGRF parameters [11], but it has some disadvantages like immobility and heaviness to be used [12, 13], besides that it’s expensive, needs to a trained persons to perform the tests [11, 12], requires a lab dedicated for motion and the collected data for short distances [14]. During recent decade, many researchers developed new wearable electronic instruments and sensors with the aim of monitoring, diagnosing and collecting the information about human subjects in daily activities and in an unobtrusive way. For example of these methods is F-scan (Tekscan Inc., South Boston, MA, USA) mobile system which is consisted of many sensors incorporated within insole [7]. In spite of these systems being effective in the applications of gait analysis, they have some limitations as they are time-consuming, as they need some time to calibrate it for a specific and each subject patient [15], or do some activities, for instance, the participants should walk for about 10 minutes so as to achieve a temperature equilibrium of the insoles [16, 17]. Finally, in some of these systems, the generated data are stored in an internal memory because they do not provide on-line transferring data to remote storing or analyzing unit, so the data are not analyzed in real-time [18, 19].

In this study, some of the gait parameters are studied by using a set of sensors attached to the shoe insole, where these piezoelectric sensors are generating voltage signals. Then these signals are passing through an electronic circuit which contains a band-pass filter circuit that allowing a certain range of signal frequencies to pass and rejects the others. The electronic circuit also contains a potentiometer that controls the signal value to the specified limit which can be compatible to the data logger. After that the signals are collected by a multi-channel wireless data logger, the data are transferred to a personal computer through Wi-Fi connection in order to manipulate the collected data, also this data logger system was provided with a power bank so to make the system portable. Later on, some of the gait information could be extracted from the collecting data, like some of the gait cycle main events (Heel Strike, Stance, Heel Off and Swing) these events can be found from the (VGRF) profile which present the state of the foot during the step. And from gait events information, the cadence of the steps could be calculated for the walking in self-selected speed. Also, the collected data is compared with the (VGRF) profile produced by force plate system.

The aim of this study is to validate the proposed system. So, it can be used for analyzing range of the gait cycle activities and find out what its advantages, disadvantage and limitations.

2. Method

2.1 Subject

The one male participant who performed the experimental protocol has the following properties; 178 cm in tall, 79 kg in weight and he’s 26 years old. Also, he has healthy body without gait abnormalities or any problems in the nervous and musculoskeletal systems. However, the protocol of the experiment was explained to him before taking part.

2.2 System’s Constituents

The system that used to collect the data of gait cycle consisted of the following parts which are connected together as shown in figure (1).
In the beginning, a piezoelectric sensor (LDT1-028K PIEZO SENSOR, TE connectivity Ltd., Schaffhausen, Switzerland) which used in this system is a multi-purpose piezoelectric sensor; it could be used for different application detecting physical phenomena such as the impact or vibration [20]. When the piezo-signal generate due to the pressure between the foot and the ground, the signal pass through a band-pass filter circuit which allow a specific range of signals frequency to pass through this filter to the data logger [21]. The filter electronic circuit is shown in figure (2) as used in this study [22].

The filtered signals was collected, then sent to the computer wirelessly through (WiFi) connection, this process done by a multi-channel data logger (labJack T7-PRO, LabJack corporation, Colorado, USA). Another important item is the power source of this system, where the power bank (ANKER Power Core +13400, Anker Technology Co., Ltd.) with a capacity of 13400 mAh was used in order to make the system portable and movable. Finally, the data stored in the personal computer in order to be processed and analyzed to find the required gait cycle data as in the following section.
2.3 The Protocol
In the beginning two sensors were placed on the insole of shoes, the first sensor is located at the heel and the second sensor is positioned at the metatarsal area as shown in figure (3). The positions of these sensors are strategically important because of high-pressure distributions generated at these areas during normal actions for different stages of ages (elderly, young and children people) [23].

![Sensors attached to insole, (a) Heel position sensor, (b) Instep position sensor.](image)

To perform this test, the insole of the right foot is equipped with the sensors then it was put in a sports shoe, the subject wore the shoes and he was asked to walk freely for few minutes to be familiar with the equipment that attached on his body [15]. The experiment was performed on the paved ground without any obstacles, and the participant walked along a track with 15 meter (m) long with a self-selected speed of walking. However, the test was repeated for six times with the same speed and the same track. The wireless connection between the data logger and the personal computer was done using Wi-Fi connection by a local router, besides that the sampling rate for the data logger was set to be on 200 Hertz (Hz). Additionally, a force plate AMTI force platform (Advanced Mechanical Technology, Inc., Waltham Street, Watertown, MA, USA) was used to compare between the VGRF profile that resulted from the force plate and the piezo-sensors attached to the shoe insole. Finally, the left foot insole was also equipped with two sensors, then the tests were repeated in the same manner by using both insoles to study the VGRF characteristics of both feet.

2.4 Data processing
After collecting and storing the data in a personal computer, these data should be processed to transform them into beneficial information which represents the vertical ground reaction force. The raw stored data (generated voltage from the piezoelectric sensor) acts as the strain rate [21, 22], as illustrated in figure (4), where (v1) and (v2) are the data of the sensors at heel and instep positions respectively.
Figure 4. Raw data (strain rate) of three steps

The strain rate data was used to find the force values that generated during the gait cycle as shown in figure (5). So, numerical integration is needed in order to transfer the strain rate data to strain. In which the strain values were considered to be proportional with force values during the walking cycle. The process of numerical integration was performed on a personal computer by using Microsoft Excel application, and the formula that was used is General Trapezoidal Numerical Integration Formula, which clarified as follows:

$$ε=\int_{t=a}^{t=b} ε' \, dt \rightarrow F=\sum_{t=a}^{t=b} \left( (ε'_{(t)}) + (ε'_{(t+1)}) \right) / 2 \, Δt$$

Where: $ε$= strain, $ε'$= strain rate, $a$= the time of stepping beginning, $b$= the time when the strain required to be found, $t$= time and $Δt$= time interval [24].

Figure 5. Normalized VGRF with time.

The produced profiles forms by processed data in this system have been compared with the data collected from the gait profile produced from the force plate. This comparison was utilized in order to validate the sensor-insole system as it will be discussed later.
2.5 Data analysis
The processed data have been analyzed to calculate some parameters of the gait cycle, then to describe the step events which are Heel Strike (HS), Stance (ST), Heel off (HO) and Swing (SW) [23]. Figure (6) illustrates the main step events (HS, ST, HO and SW) and their descriptions are:
Heel Strike (HS): it is the duration when the heel touches the ground till the instep region strikes the ground; (The sensor of the instep region is unloaded)
Stance (ST): it is the duration in which the heel and instep regions are touching the ground; (Both sensors are loaded)
Heel Off (HO): it is the duration that the heel takes off the ground and the sensor of that position is unloaded; (The sensor in the heel area is unloaded)
Swing (SW): it is the duration when the whole foot away from the ground and there is no contact between them [25]. (Both sensors are unloaded)

Another parameter could be calculated which is the cadence (C) of steps for the right foot and the calculation of this parameter is done by the following formula C= 1/ (HS + ST + HO + SW), where the cadence expressed in Hertz (Hz) [15]. The analysis of the processed data should be achieved for steps in steady-state. So, the information for two steps at the beginning and the end of the motion was eliminated for all trials, whereas the duration between two heel strikes for the same foot is gait cycle [25]. Additionally, in the case of using both the right and left sensorized insoles, there is a phase called Double-Support (DS) in which both feet touch the ground in a certain duration [15]. So, it could be determined by calculating the duration between the beginning of the heel-strike phase of the front foot and the end of the heel-off phase of the rear foot as shown in figure (7).
3. Results

3.1 VGRF profile

The profile graph of processed data of the insole that equipped with two sensors for the right subject’s foot is shown in figure (7). (The VGRF data of this profile is the average value of all steps and strides data for 15 m track) it’s obvious that the signal of heel sensor (S1) begins when the heel striking the ground then the value goes up to the peak (maximum loading at the heel sensor). After that, the signal value decreases dramatically close to zero. On the other hand, the same trend occurs in the instep sensor signal (S2), but in general the peak value for the signal of instep sensor is higher than the heel sensor peak value. The pattern of this trend also produced in other researches but has some differences [26-30]. A resulted behavior of double peak; M-shape profile; or dual hump shape [15, 28, 29 and 31] means that the first peak represents the end of the stage of weight-acceptance, while the second peak expresses the push-off stage [15]. A resultant signal (Sr) in green color as illustrated in figure (8) could be produced by combining the two signals (S1 and S2). Thus, this signal is compared with the VGRF profile resulted from the force plate, and there is enough similarity found between the two patterns of VGRFs profiles for the sensor-insole system and the force plate. The values of the force plate signal are expressed in Newton (N) unit as clarified in figure (9).

![Normalized VGRF of sensorized insole for a Stride](image1)

**Figure 7.** Normalized VGRF of sensorized insole for a Stride.

![The resultant signal (Sr) of Normalized VGRF](image2)

**Figure 8.** The resultant signal (Sr) of Normalized VGRF.
3.2 Gait parameters
In the sections 2.4 and 2.5, the parameters of the gait cycle were listed, illustrated and explained how to process the collected data. Figure (10) shows the form of the gait cycle events (HS, ST, HO and SW) and their durations, whereas stages 1, 2, 3 and 4 represent the HS, ST, HO and SW respectively. It was noticed from the graph in figure (10) that the duration of stage 2 is longer than the other stages in which both of the heel and the instep positions are in touch with the ground, while the stage 4 (swing phase) is the second longest duration during the gait events. As well as, it was observed that the four phases are repeated in the same manner, but each stride has peaks values differ from the other strides. Another important parameter that could be calculated is the speed of walking, whereas its average value was about 0.907 meter/second for the steady-state walking.
On the other hand, the results of using left and right insoles illustrate the repetition four phases of the gait cycle for each foot as well as the Double support (DS) phase regularly without abnormalities in the signals of the sensors.

Table 1 Parameters of the gait cycle.

| Parameter | Value          |
|-----------|----------------|
| HS (Sec.) [100%] | 0.081 Sec. [6.05%] |
| ST (Sec.) [100%] | 0.625 Sec. [50.61%] |
| HO (Sec.) [100%] | 0.13 Sec. [10.43%] |
| SW (Sec.) [100%] | 0.41 Sec. [32.9%] |
| DS (Sec.) [100%] | 0.168 Sec. [13.48 %] |
| C (Hz)    | 0.803 Hz       |
4. Discussion

4.1 The VGRF and the events of Gait cycle
The performed tests clarify the profile of the gait cycle in self-selected walking speed. The VGRF profile of the sensor-insole system has a physiological pattern similar to the force plate VGRF profile. It can be noticed that both of them produced a double-peak or an M-shape trend. Where the first and second peaks express the weight acceptance and push-off phases respectively [15]. Besides that, the values of the amplitudes (first peak, second peak and the drop between them) and gait pattern could be influenced by changing the swing of the arm [28] and increasing of motion (walking or running) speed [26-28]. Despite the similarity between the profiles, there is a difference in the middle region (the drop) that existed between the two peaks. The middle region of the VGRF profile which resulted from the force plate has a higher value than the sensor-insole system profile because there is no sensor covers the generated force from the region between instep and heel positions. Additionally, during the use of both insoles, the signals of four sensors were generated without abnormalities and the Double support phase was generated regularly. As observed from the results for the gait events, the algorithm of walking repeats itself in the same way with only minor differences, such as the height of the peaks changes especially the push-off peak in each stride during the walking.

4.2 The advantages of the system
This system has many advantages which are mentioned as follows; In the beginning the wear-ability of the system is important, the participant could wear the shoes which has sensor-insole system without any discomfort during the walking because the sensor is flexible, lightweight and thin with (157 micrometers) thickness [20, 32], as well as the system parts (data logger, electronic circuit and power bank) were light in weight and could be attached on the leg by belt or could be held in pocket of clothes. Furthermore, the sensors could operate normally in a wide range of temperature (0 to 70 in Celsius (C°)) [20, 32], in contrast with some existing systems in which the temperature increase is one of the major limitations that effect on their sensitivity [15]. Finally, this system achieves portability and movability by transferring the data wirelessly and stored directly on a personal computer, as well as the data logger has many ports, therefore many sensors could be used to cover almost the entire area.

4.3 The limitations of the system
This system was evaluated preliminarily as a commercial, wearable and portable system. So, there are some limitations have raised to be avoided in the future in order to make this system more affordable and available. One of the important limitations is time-consuming because the raw data are processed manually after storing. So, a software should be developed to transform the raw collected data into the required information with more time effective procedure. Also, spending much time during adjusting the positions of the sensors on the required area of insoles for each subject, it is considered crucial because each participant has a different foot size. The piezo-sensor is widely used in various sensing applications using range of installation methods and load values [32], in other meaning, each way of piezo-sensor installation will produce specific type of signals which serves a certain application. For gait analysis sensors should be positioned where the load is concentrated. Since the sensors' dimensions are (41.4 mm in length and 16.26 mm in width [20]), they were positioned under the instep and heel areas as the sensor area can cover them. Also these positions were chosen to avoid any severe bending in the sensors which can be happened somewhere else that can terminate the sensor.

5. Conclusion
The collected VGRF data from the piezoelectric sensor-insole system which is proposed in this study has close trend to the data collected from a standard force pleat system. From this similarity in the data profile the proposed system was validated and calibrated, so this system can be used in more tests. These tests can be utilized in different conditions such as, walking of unhealthy subjects, patients with diseases that affect their gait cycle, or healthy subjects in different walking conditions; range of speeds or terrains, subjects who taking the stairs or walking on slopes. All these test condition and more can be utilized using the wearable and mobile testing kit which is proposed in this study.
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