GAIT ANALYSIS USING IMU SENSOR

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***Abstract*—Inertial Measurement Unit (IMU) based systems that employ gyroscopes has a growing interest in gait analysis. We described the IMU-based gait analysis method that uses angles obtained from an accelerometer and gyroscope sensor within MPU6050 to identify phases of each gait cycle during walking. The gait analysis algorithm is composed of Heel strike and Toe off factors detection observed by means of detection of initial contact(IC) and terminal contact(TC) so that gait parameters are calculated from those gait details. Most of the present gait phase detection strategies use multiple sensor modules connected to every segment of lower body. We have used two MPU6050 sensors placed on a shank of both legs to collect gait signals. For experimental purpose, each participant was asked to walk for a distance of 40 meters for the straight corridor at a normal speed. These gait signal data measured by using Arduino uno micro-controller is then transmitted to an android app 'Blueterm' wirelessly via the HC-05 Bluetooth module. Collected data by the app is stored as a text file in a device containing app. This database is further processed to an algorithm that has been developed using MATLAB to extract a period of events that happened during walking such as stride time, stance time, step time, cadence, etc. The results are useful in identifying the bio-mechanical stability of patients post surgery. Basically, this paper presents a wearable IMU sensor-based system and its associated gait analysis algorithm to obtain quantitative measurements of the individual's gait parameters to monitor patient progress in orthopedics and rehabilitation.**

***Index Terms*—Gait cycle analysis, Inertial Measurement Unit(IMU) sensor, Gyro-sensor MPU6050, Bluetooth module, Gait parameters.**

I. INTRODUCTION

Gait analysis is the systemic study of locomotion of human being during walking [1]. Gait analysis plays an important role in detecting abnormality in the human walking pattern [2]. Changes in gait styles implies important information of a person's fitness that would be used for assessing or analysis individuals with pathological situations that have an effect on their ability to walk and the complete biomechanic system [3]. Traditionally gait analysis carried by a human observer but this was further augmented with video recording, wherein the recording could be reviewed in slow movement to permit more accurate assessment of the gait cycle. This technique of qualitative analysis remains extensively used nowadays. However, this method is labour intensive, requires a exceptionally skilled clinician and is not accurate as methods that quantify motion analysis.

A more objective way of assessing gait is required. There are a variety of wearable sensors including accelerometer, gyroscope, magnetometer, foot pressure sensor, inclinometer, and goniometer that are generally used to measure various characteristics of human gait. IMU sensors have been used in different gait analysis techniques such as monitoring postoperative gait abnormalities, detection of falls, nature of Parkinson gait, auto detection of daily activities of older adults and human walking foot trajectory [4]. These sensors are directly worn or attached directly or indirectly to different body locations such as foot, wrist, chest, thigh, and shank, & are attached using belts, clips or other accessories [4]. Gait analysis system has many clinical applications which consists of external prosthesis adjustment for amputees, or outcome evaluation after knee and hip replacement. In elderly subjects, it can also be proposed as a diagnostic tool for abnormal gait analysis, as a predictor tool for fall risk estimation, or as a monitoring tool to assess progress through rehabilitation. In this paper, we've implemented and explored the functionality of a system which is totally based on an IMU sensor, includes use of two mpu6050 sensors. Those sensors are connected to the shank of both the leg to sense the motion of the leg. The raw data obtained from sensors is processed in microcontroller and then sent wirelessly via Bluetooth HC-05 module to an android app. Collected data is further processed for calculating gait parameters by using a developed gait phase detection algorithm in MATLAB. The gait phase detection algorithm consists of detection of Heel strike i.e. initial contact(IC) and toe-off i.e. terminal contact(TC) points to decompose a gait cycle into stance and swing phase and acquire several other spatiotemporal gait parameters. This paper is organized as follows: In section II- Brief discussion about gait cycle, various gait phases, gait parameters, gait analysis and it's importance. Section III consists of system design in which we have described hardware and software required, experimental set-up, proposed gait phase detection algorithm on gait signals collected from IMU sensors mounted on the shank, section IV described results obtained from developed algorithm has been explained. Section V and VI consist of conclusion and future scope respectively.

II. THEORY

A. Normal Gait

Definition- A Series of rhythmical, alternating movements of the lower extremities which results in the forward progression of the body.

A gait cycle starts when heel strike i.e when heel contacts the ground and end at the next heel strike of the same leg. Single gait cycle is called as a stride.

A gait cycle or stride consists of two main phase: stance phase & swing phase. In a single gait cycle stance phase comprises of approximately 62% of the gait cycle, which begins when a heel strike of one foot and ends with toe off of the same foot. The foot is in weight bearing phase during this phase. The average duration of the stance phase is approximately 0.59 to 0.67 seconds. The remaining 38% is the second phase which is known as a swing phase. During this phase foot is in non-weight bearing, as it moves from one step to another [5]. This phase lasts, on average, 0.38 to 0.42 seconds. The reference foot is in contact with the ground during stance while the other foot is in swing, and swing is where the reference foot is swinging over the ground while the other foot is in contact with the ground as shown in Fig.1

1) Stance phase is further divided into:

- Heel contact:- 'Initial contact', the moment when heel of the reference leg touches the ground while other leg is in terminating stance phase.
- Foot flat:- 'Loading response ', the period when the reference foot is in fully contact with the ground and other leg is in initiating swing phase i.e. pre-swing.
- Midstance:- Body weight is completely falls on refernece leg during mid-stance while other leg is initial swing and mid-swing phases.
- Heel-off:- 'Terminal stance', it begins as soon as the heel of the reference leg starts moving away from ground but toe is still in contact with the ground and the other leg follows the terminal swing.
- Toe-off:-'Pre-swing', when the reference foot start moving further keeping toe in contact with ground while the other leg having loading response [6].

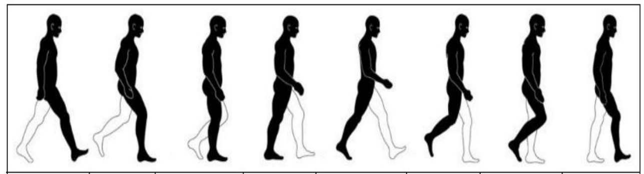
2) Swing phase:

- Acceleration:- 'Initial swing'During acceleration forward motion of the limb starts with knee flexion and foot looses the contact with ground.
- Midswing:- Reference leg is in the air and thigh is at its maximum flexion for advancement of limb.
- Deceleration:- 'Terminal swing', the shank is at the final advancement and the reference foot is positioned for initial foot contact to start the next gait cycle.

Fig.1 shows the eight sub phases of the human gait cycle.

B. Gait parameters

i. Stride time:- It is the time duration between heel strike /toe-off to the next heel strike/toe-off of the same leg. (1.09$\pm$0.06 sec = 1.15 sec).
ii. Stance time:- Time period during the foot is in contact with the ground, i.e. time taken from the heel strike point to the toe-off point within each gait cycle [9]. (0.8 $\pm$ 0.02 sec)
iii. Swing time:- While the foot completely off the ground, that duration is known as swing time. (0.4 $\pm$ 0.05sec)



Right heel strike	Left toe-off			Left heel strike	Right toe-off		
	Stance phase(60%)					Swing phase(40%)	
Heel strike	Foot flat	Mid-stance	Heel-off	Toe-off	Initial swing	Mid swing	Terminal swing

Fig. 1. Phases of gait cycle

iv. Step time:- Time interval between successive foot contact with the floor of the opposite feet (0.8 sec)
v. Stride length:- Distance covered during successive heel strike of the same foot. (Approximately = 130 cm $\pm$ 15 cm)
vi. Step length:- It is the linear distance in the plane of progression between two successive points of foot floor contact of the opposite feet. (Approximately = 60 cm $\pm$ 10 cm)
vii. Gait speed:- It is calculated by distance covered in a given time. The instantaneous speed varies from one instant to another during the walking cycle, but the average speed is the product of the cadence and the stride length.
viii. Cadence:- The cadence is the number of steps taken per minute, there are two steps in a single gait cycle, and the cadence is a measure of half-cycles [7]. (100 $\pm$ 6 steps /min)
Slow: 60-70 Steps / min
Medium: 80-90 Steps / min
Fast: 120 Steps / min

C. Gait analysis and it's importance

Gait Analysis can be defined as the 'study of the biomechanics of human locomotion to quantify the factors which helps to check the functionality of the lower limb'. This is fundamental for the detection of gait disorders. Gait analysis can also be defined as the systemic study of human movements during walking or running(locomotion) [3]. In a broader sense, gait analysis includes assessment, planning and treating people with conditions affecting their gait. So gait analysis allows assessing the gait pattern of a person to identify different walking disorders. For assessment and treatment of individual having certain(pathological) conditions which affects their walking ability and entire muscular-skeletal system accurate gait analysis is most useful.

Importance of gait analysis:

- Gait cycle analysis is used in the study of human locomotion
- As reduced gait quality can lead to severe reductions in patient mobility and quality of life, it is important to quantify, detect and treat gait impairments as early as possible [2]

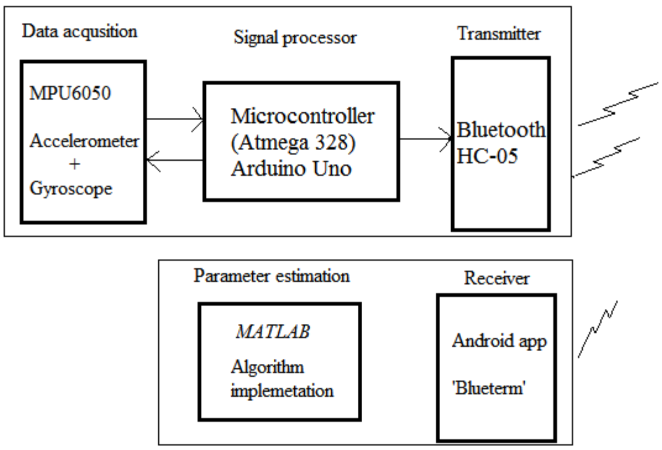


Fig. 2. Schematic diagram of designed system

- to identify the loss of the person's ability to walk also it can be helpful to implement and evaluate treatments to correct abnormalities within an individual.

III. System Design

In this section, we implement the proposed algorithm for human gait phase detection. The overall system design of the gait cycle analysis system can be categorized into two parts, the hardware and software requirements.

A. Hardware Used

The system we have developed for gait analysis is composed of two IMU sensor MPU6050, which consist of triaxial accelerometer & triaxial gyroscope, a microcontroller (Arduino uno), and a Bluetooth module HC-05. During walking motion acceleration signals are generated, and detected by the MPU6050 sensor. Then it will measure the angular rate of the shank motion with respect to ground. The angle is generated by combining gyroscope and accelerometer data related through complementary filter [8]. The sensors on the shank had a full scale range of accelerometer $2g$ with Sensitivity Scale Factor of $16,384LSB(Count)/g$ & Gyroscope full scale range of $\pm500/s$ with sensitivity scale factor of $65.5LSB(Count)/^{\circ}/s$. Furthermore, the digital signals generated by the MPU6050 sensor from both the shank through an I2C interface is collected by an Arduino Uno. Also, a HC-05 Bluetooth module is connected to microcontroller for wireless communication. The output signals of the accelerometer and gyroscopes are all sampled at 400 kHz by a 12-bit analog to digital converter(ADC). Simultaneously these data is sent wirelessly to an android app 'Blueterm' via HC-05 Bluetooth module. Obtained data was stored as a text file in the android app. The power consumed by the wearable hardware device is 30 mA at 5 V. The schematic diagram of the designed system is as shown in Fig.2.

B. Software used

Software that we used to implement the gait phase detection algorithm is MATLAB. It is a high-level language and interactive environment for numerical computation, visualization, and programming. Gait signal data is imported in MATLAB and by using all the required mathematical calculations, algorithm to extract gait parameters has developed.

C. Experimental setup

Data was collected from a group of six people was selected for gait analysis. They were asked to walk for 40 meters on a straight line at a normal speed. During the walking trials, two IMU sensors MPU6050 that measures the angular rate of the rotations were attached on the anterior side of the lower limbs: one on each shank. Velcro belts were used to fix the sensors such that the sensor does not slip or move during walking. The sensors were aligned to the mediolateral axis, hence, measuring rotation in the sagittal plane. The sensors on the shank had a full scale range of accelerometer $\pm2g$ with Sensitivity Scale Factor of $16,384LSB(Count)/g$ & Gyroscope full scale range of $\pm500/s$ with sensitivity scale factor of $65.5LSB(Count)/^{\circ}/s$. Data was recorded with a sampling rate of 400 khz. Simultaneously these data was sent to an android app 'Blueterm' via HC-05 Bluetooth module. Collected data was stored as a text file in the Blueterm app. This file is imported in MATLAB and using proposed algorithm gait parameters were extracted.

D. Proposed algorithm

The proposed gait phase detection algorithm is developed to acquire the gait parameters from the angular rate signal generated by the IMU sensors from walking motions of the person. The following steps describes the proposed algorithm in detail.

1) Data collection: In natural walking the hips, knee and ankle are synchronized in a smooth bouncing vertical motion with each step. This vertical motion is in the same direction as gravitational force. Legs do majority of movement while walking because the joints produce greater levels of motion to transport the body ahead in horizontal direction [4]. This rhythmic, repetitive movement involves steps and strides known as the gait cycle. This movement produces angular deflection, which is investigated in this study. An MPU6050 sensor consisting of an accelerometer and gyroscope is used to collect measurement of the angular rate about x, y and z-axes of the sensor frame due to horizontal movement. Data are analyzed using our proposed algorithm to find strides, stance and swing event information. The sample data from the individual is as shown in Fig.3

2) Selection of sensitive axis: 3D data derived from the gyro-sensor demonstrate different characteristic according to the walking activities of the individual. Therefore it is of great importance to select the most sensitive axis in the sense that the corresponding data are closely correlated with the activity and it is advisable to select the axis whose data has the maximum magnitude. Y-axis(in sagittal plane direction) of the angular rate signals are used to detect the HS and TO points during walking movements for further calculating gait parameters [9].

3) Heel strike and Toe off points detection: Using signals from the shanks gait cycles and related events were detected and spatiotemporal parameter estimated. In this first step was to detect heel strike i.e. initial contact (IC) and Toe off i.e. terminal contact (TC) of the foot with respect to ground. By simultaneously recording the signals using the body attached IMU MPU6050 sensors, the intervals where these events occurred were determined based on the shank angle rate. The heel strike of a gait cycle is characterized by a negative angle reaching its highest values at stance phase initiation. After this, the TC is characterized by a maximum positive angle. With different populations of normal and pathologic, young and elderly subjects, the angular rate can be different. By using these precise instances of heel strike and Toe off, maximum and minimum peaks of the signal are detected from the data signal obtained by right and left shank.

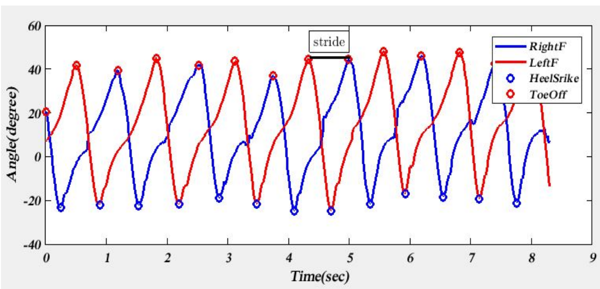


Fig. 3. Shank angles obtained by sensors from Saggital plane

4) Calculation of Gait Parameters: Using the right foot as a reference to apply the spatiotemporal gait parameter measurement, we categorize the gait cycle into two phases, i.e. stance phase and swing phase [10]. Heel strike denotes the initiation of stance phase whereas the swing phase starts at the toe off of the same foot [6]. Once the toe off and heel strike points of each gait cycle are found, we can calculate the following gait parameters. The gait parameters are computed as follows [11]:

(i) Stride duration (time between HS of stride i and HS of stride i+1)

$$Stride(i) = HS(i+1) - HS(i); \tag{1}$$

(ii) Stance duration (time between HS and TO during stride i)

$$Stance(i) = TO(i) - HS(i); \tag{2}$$

(iii) Swing duration:- time between TO of stride i and HS of stride i+1

$$Swing(i) = HS(i+1) - TO(i); \tag{3}$$

(iv) Right step duration:- time between left HS (HS_{left}) of stride i and of right HS (HS_{right}) stride i+1

$$Rightstep(i) = HS_{righ}t(i+1) - HS_{left}(i); \tag{4}$$

(v) Left step duration (time between HS_{right} and HS_{left} during stride i)

$$Leftstep(i) = HS_{left}(i) - HS_{right}(i); \tag{5}$$

TABLE I
GAIT CYCLE PARAMETERS OBTAINED FROM SUBJECTS

	F	M	M	F	M	M
Age(years)	24	26	28	29	24	26
Height(cm)	164	180	176	155	157	171
Stride time(sec)	1.23	1.21	1.16	1.12	1.11	1.20
Stance time(sec)	0.89	0.86	0.82	0.81	0.83	0.89
Swing time(sec)	0.34	0.34	0.33	0.31	0.28	0.31
Right step time(sec)	0.60	0.59	0.56	0.54	0.55	0.58
stride length(m)	1.02	1.11	1.08	1.13	0.93	1.05
step length(m)	0.51	0.55	0.54	0.56	0.46	0.52
Gait speed(m/s)	0.80	0.88	0.90	0.94	0.81	0.85
Cadence	98	101	105	109	107	102

(vi) Stride legth:- the distance covered from IC to IC of the same foot
Average Stride length

$$= Totaldistance/TotalNo.ofstride \tag{6}$$

(vii) Step length:- Distance covered during single step.

(viii) Cadence:- Total number of strides per minute.

IV. RESULTS AND DISCUSSIONS

In this paper, we have exhibited the created system dependent on IMU sensor and related algorithm to perform gait analysis. Relevant gait events are calculated from the gait data of 6 healthy volunteers. Measured gait parameters values validated against the standard values of the same for healthy adults. Our result value has matched with the standard gait parameters values as mentioned in II-B. Fig.3 shows the gait data obtained in terms of the angular rotation of the IMU sensors attached on the shanks of the body. Using the algorithm we obtained two different series of samples HS and TO for data obtained from the attached sensor. From these points and using appropriate calculation we have obtained gait parameters like time duration of stride, stance, swing, right step also stride length and step length. We have obtained the total number of strides within a particular time, & from this information we calculated the cadence of the individual. Table I Shows the results obtained from the 6 healthy subjects participated.

V. CONCLUSION

The results of the experiment demonstrate that the chosen sensor is effective for the data acquisition & it improves the accuracy for gait analysis. The IMU accelerometer and gyroscope data had been analyzed using our developed system which is used to extract gait parameters: stance time, stride time, swing time, step time, stride length, step length, Cadence, and gait speed. The focus of the research was to develop low cost effective & simple technique by considering person comfort to walk which can be used for gait analysis, and it is possible through use of mountable sensors like gyrosensor. At standard gait, there is a uniform repetitive flexion and extension of joints present compared to a person with certain deformity. The appropriate methodology of analysis can serve as an appropriate rehabilitation process for a patient with gait malfunction.

VI. Future scope

Our future work will aim to make wireless, fully automatic real-time gait feature extraction system which can be used for a long duration to continuous monitoring and to identify the abnormal gait patterns for the assessment of elderly fall risk, rehabilitation, athlete's application. The next step would be to validate this method on subjects with atypical gait and see if there is enough sensitivity to detect gait abnormalities.

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