Design and Development of Kinematic Analysis System

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Abstract — **This paper presents a study on the Design and development of a kinematic analysis system for lower limb disorders. The main objectives of the project are to design a sensor system with a cost-efficient and intelligent IMU sensor that can measure the gait parameters and help clinicians to diagnose. A kinematic analysis system is used for the detection in abnormal gait and rehabilitation of human gait. In the early days, gait analysis of the lower limb of the human body is done by an optical motion analysis system using high-speed definition cameras which is high cost and complex which cannot be easily applied to clinical. Some companies like Xsens, Invensens, etc made their IMU sensor gait analysis system, but the cost of these systems is also very high, which cannot be afforded.**

***Keywords*— Gait phases; Wearable sensor system; Gait cycle; Kinematic analysis system; Gait disorders.**

1. Introduction

A gait, a human everyday behavior, contains an abundance of data that could show an individual's gender, identity, health status, etc. The techniques for the walk analysis might be commonly isolated into two sections: kinematic evaluation and kinematic analysis. With the advancement of the sensors and the improvement of the calculations, the exploration interests in stride have focused on the kinematic evaluation for the restoration and clinical. The gait analysis applied in the clinical field mainly focuses on the diagnosis of the gate disorders. The appearance of the gait disorders indicates the dysfunction of a system or part of human a body such as the orthopedic diseases and the nervous system diseases. In the medical field, these gait disorders could be defined as pathological gait. There are four stages of events in the general gait cycle: heel strike, heel off, foot flat, swing. The classic parameters and features extracted from the gait include the stride length, stride frequency, stride time, stride velocity, stance phase time and swing phase time, etc., which could offer the reference to the judgment of the gait disorder or plan for the further rehabilitation. Also, to compare these parameters between the patients with abnormal gait and a normal person will help the clinicians understand the patient's physical condition further [1] [2] [3]. The earliest research on gait analysis back the nineteenth century and its application in biomedical arranging started with the accessibility of video camera systems. Although the data captured from the video system may be precious, the long-term monitoring under the video leads to the uncomfortable and aggression to the patient resulting from its little use in the clinical application but popular in the laboratory. Besides, the IMU sensors are also commonly used. Kinematic analysis is a method of determining kinematic quantities that describe motion. It tells about acceleration, velocity, angular velocity, angular acceleration, etc. Human gait tells about the motion of the human body due to movement of the lower limb. Kinematic analysis is applicable to fields like biomedical and gaming industry applications. In biomedical application, the kinematic analysis system is utilized in help patients as well as doctors in identifying lower limb disorders such as Parkinson, Hemiplegic etc., while in game industry it is used to create a virtual world and to operate a game character.

2. Literature Survey

The Usual method used to measure the human gait is optical motion analysis using high-definition cameras to capture human motion. The integration of three-dimensional motion movement utilizing multi-camera frameworks and response power estimation utilizing power plates has been developed to following human body parts and performing a dynamic analysis of their physical movements in a complex situation. Optical motion analysis needs more workspace and high-speed graphic signal processing devices and using high-definition cameras, the devices required for this analysis are so expensive, and analysis of recorded videos is complex and time-consuming. This method is limited to laboratory research purposes. A wearable sensor system with properties of lower-cost, benevolent activity, and less impact on human is turning into a significant theme in biomechanics and clinical applications. To take locally situated recovery and telerehabilitation, a few analysts have created many sorts of wearable sensor frameworks depend on single accelerometers or multi-accelerometer and gyroscope combination. Additionally, for monitoring everyday living of impaired people, new techniques utilizing various sorts of walking sensor frameworks can useful outside of a laboratory. In our research on wearable sensor systems for biomedical applications can be divided into two major directions: one is about state recognition on daily physical activities including walking feature assessment, walking condition classification and gait phase detection, in which the kinematic data obtained from inertial sensors (accelerometer or gyroscope) are directly used as inputs of some inference techniques; and another direction is for accurate measurement of human motion such as joint angle, body segment 3D position and orientation, in which measurement calibration and data fusing of different inertial sensors are important to decrease errors of the quantitative human motion analysis. Besides, the IMU sensors are also commonly used. Kinematic analysis is a method of determining kinematic quantities that describe motion [3] [4]. It tells about acceleration, velocity, angular velocity, angular acceleration etc. Human gait tells about motion of human body due to movement of lower limb. Kinematic analysis is applicable for fields like biomedical and gaming industry applications [5]. In biomedical application, kinematic analysis system is utilized in help patients as well as doctors in identifying lower limb disorders.

3. Stance Phase

The swing phase is that portion of the gait cycle which comprises 60 percent of the total gait cycle. In this phase, one leg is taken as reference to do analysis. Generally, the referenced foot or leg will be in contact with the ground. The stance phase is divided into five sections and Fig.1 shows the different stages in the stance phase: -

- Initial contact.
- Loading response.
- Mid stance.
- Terminal stance.
- Pre swing.

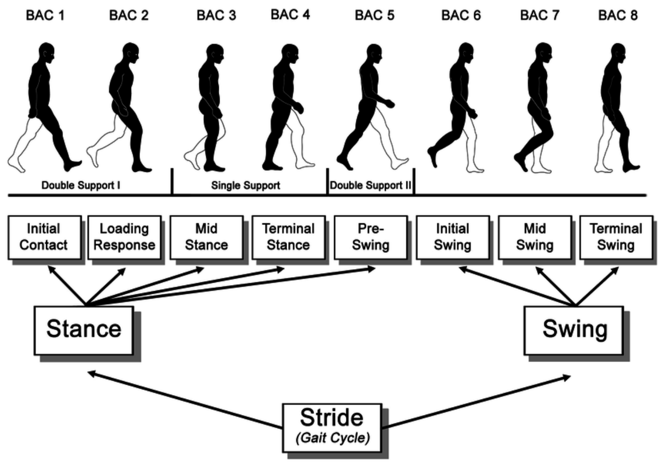

Fig.1 Different stage of gait cycle.

1) Initial Contact: It is that portion of the stance phase, which referenced leg, foot heel will be in touch with the ground. This portion is also called a heel strike.

2) Loading Response: It is the portion of the stance phase in which full body weight will be transferred to the referenced leg, it is helpful in weight holding, shock bearing, and forward movement. This is also called as foot flat.

3) Mid Stance: It is the midpoint of the stance phase, which concludes arrangement and adjustment of whole-body weight to the referenced leg perpendicular to the ground.

4) Terminal Stance: It is that portion of the stance phase in which the referenced foot will start leaving the ground while the toe of the referenced foot will still in contact with the ground.

5) Pre-Swing: It is that portion of the stance phase in which the referenced foot raises up and swings in the air. This is also known as the start of the phase.

4. Swing Phase

The swing phase is that portion of the gait cycle which comprises 40 percent of the total gait cycle. In this phase of gait movement, one leg will in full contact with the ground and another leg will hauls or swings in the air. Fig.2 showing the graphical representation of swing phase. The swing phase is divided into three sections: -

- Initial Swing.
- Mid Swing.
- Terminal Swing.

1) Initial Swing: In this section of the swing phase referenced leg, lifted their toes from the ground while keeping thigh bend at the hips.

2) Mid Swing: It is also called as the midpoint of the swing phase; the thigh of the swinging leg reached its peak point.

3) Terminal Swing: In this section of the swing phase, the shank of the swinging leg takes final advancement. The foot is kept positioned at initial contact to start the next cycle.

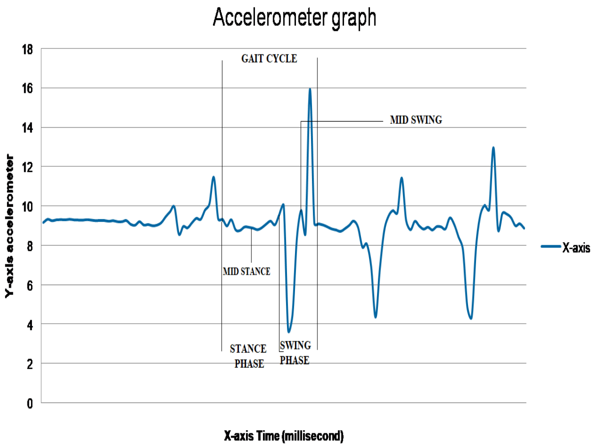

Fig.2 Graphical representation of gait cycle. From the graph it can be observed that stance phase occupies 60 percentage of gait cycle and swing phase occupies 40 percentage of gait-cycle.

5. Muscle Activity at Different Stages

1) Initial Contact: The ankle is neutral or slight plantar flexion; pretibial muscles contribute to internal dorsiflexion torque. The foot is positioned for loading response [6].

2) Loading Response: - Initial contact with opposite toe off. 5 degrees of rapid plantar flexion, External plantar flexion is decreasing and disappears at the end of LR. Pretibial muscles eccentrically to prevent foot drop, heel rocker preserves forward momentum.

3) Mid Stance: - Opposite toe-off to hell rise of reference limb, ankle dorsiflexes to 5 degrees, and external dorsiflexion torque increases rapidly. The ankle rocker maintains momentum.

4) Terminal Stance: Heel rise to opposite initial contact; ankle dorsiflexes to 10 degrees MTPs extend to 30 degrees. Forefoot rocker produces a maximal forward progression and adequate step length.

5) Pre-Swing: Opposite initial contact to toe-off, ankle moves to 5 degrees of plantarflexion, pretibial muscles concentrically to move the foot into dorsiflexion. Foot clearance contributes to swing limb advancement.

6) Mid Swing: Feet adjacent to tibia vertical, ankle moves to neutral. Low-level external plantar flexion torque due to the weight on the foot. Pretibial muscles concentrically to move the foot into dorsiflexion. Foot clearance contributes to swing limb advancement.

7) Terminal Swing: Tibia vertical to next initial contact, the ankle remains in neutral, and external plantar flexion torque decreases to zero. Some isometric pretibial muscles to maintain foot position. The neutral foot position assures heel contact at initial contact.

6. System Design

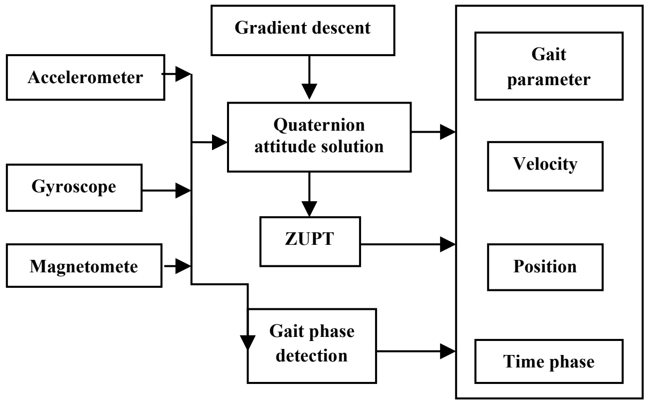

Fig.3 Overall system algorithm

Orientation estimation via the fusion of sensor data: In this gait system we are using the Zero velocity update algorithm, the quaternion attitude update for the calculation of the attitude of the human foot in the walking. The quaternion attitude update gives more accurate results. The quaternion is divided into scalar and vector parts i.e.

$$q = (q_r , q_v), q_r \in R, q_v \in R^3 \quad (1)$$

With $|q| = 1$. Assuming a three-dimensional space arrange framework b, given a vector $r_b \in b$, n is acquired by pivoted through quaternion q, in the interim vector $r_n \in n$ is planned by r_b from b. Then r_n can be expressed as:

$$r_n = q^{-1} \otimes r_b \otimes q \quad (2)$$

This represents the rotation matrix using quaternion; the rotation matrix at every moment is the key step of coordinating mapping. So as to get the quaternion q at each second, the equation is expressed:

$$dq/dt = \tfrac{1}{2}\, q \otimes w^{s}_{ns} \qquad (3)$$

Where $w^{s}_{ns} = [w_x\ w_y\ w_z]^{T}$, it is the angular velocity information from gyroscope. Therefore, the matrix form of the eq. (3) can be written as:

$$\begin{bmatrix} a0 \\ a1 \\ a2 \\ a3 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 0 & -w_x & -w_y & -w_z \\ w_x & 0 & w_z & -w_y \\ w_y & -w_z & 0 & w_x \\ w_z & w_y & -w_x & 0 \end{bmatrix} \begin{bmatrix} q0 \\ q1 \\ q2 \\ q3 \end{bmatrix}$$

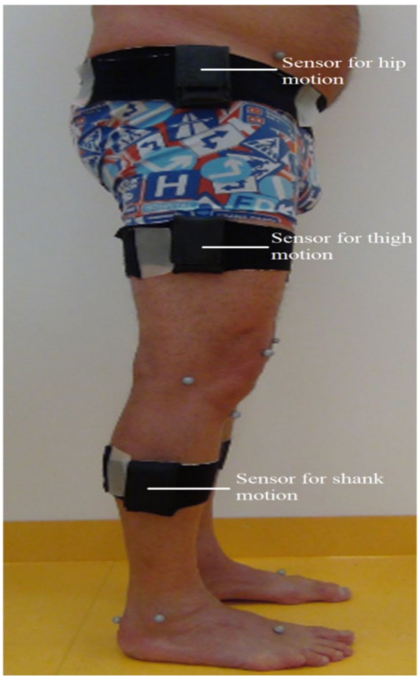

Fig.3 Placement of sensor on lower limbs

6.1 Sensor System

As shown in Fig.3 3-axis accelerometer and gyroscope are used to track the motion of the lower limbs of a human body and sensors is placed as shown. The accelerometer measures the acceleration of a body and the gyroscope to measure the rotational velocity (angular). The X-axis of the accelerometer gives the forward movement tracked data [7] shown in Fig.2.

6.2 Hardware System

The wearable sensor system includes NodeMCU ESP8266, MPU9250 (IMU sensor), and TCA9548A (multiplexer). MPU9250 of size (3x3x1)mm and sensor placement is shown in fig3. It gives information about 3-axis acceleration through the accelerometer, 3-axis rotational velocity through the gyroscope, 3-axis relative change of magnetic field through the magnetometer. The gyroscope gives information on angular velocity and Coriolis force. NodeMCU ESP8266 have Wi-Fi enabled ESP8266 development chip with TCP/IP protocols. This supports serial communication such as I2C, SPI. TCA9548A is a multiplexer made with 8-bidirectional communication channels. It can be communicated through the I2C bus and the SM bus. All of the above components can easily be operated with 3. 3V and 5V. Six IMU sensors are attached to the shank, thigh, and hip of both legs sides. SDA and SCL Pins of IMU are connected with different channels of TCA9548A. VCC and GND pins of IMU are connected to the positive and negative terminal of the battery. Vin and GND pins of TCA9548A are connected to 3V and GND pins of NodeMCU. An SDA and SCL pin of TCA9548A connects to D1 and D2 pins of NodeMCU. NodeMCU ESP8266 is connected to the desktop through a USB cable. The desktop is already installed with Arduino, TERA TERM, and required important libraries in Arduino. MPU9250 (IMU) are powered by 3.7 volts Li-ion rechargeable batteries. Data signals of inertial sensors from different lower limb parts are transferred to the TCA9548A multiplexer. Multiplexer helps to record data at the same time stamps for different lower limb parts. Data signals from different lower limb parts Pulled up by Multiplexer TCA9548A will be transferred to NodeMCU ESP8266 Through SDA and SCL pins. Raw data from NodeMCU is transferred to Arduino Serial Monitor as it is connected through a USB cable. Data Starts Streaming Arduino serial monitor. Now, data is being logged to the Excel sheet through TERA TERM software [8] [9]. It is an open-source and free terminal emulator application. It logged data to an excel sheet, which can be stored for future work. Data from different Excel sheets will be plotted and used for the analysis portion.

7. Optical Motion Analysis System

To validate the performance of the kinematic sensor system we have compared with the data obtained from the optical motion technology. In optical motion technology, we use high definition cameras and markers are attached to the subject's body. High definition cameras, track the body motions with an accuracy of 1 mm, and 50 Hz are used to track the marker position.

- The time domain of the sensor system and optical motion system results should be in identifying.
- The resultant graph from the two systems should be almost identical.

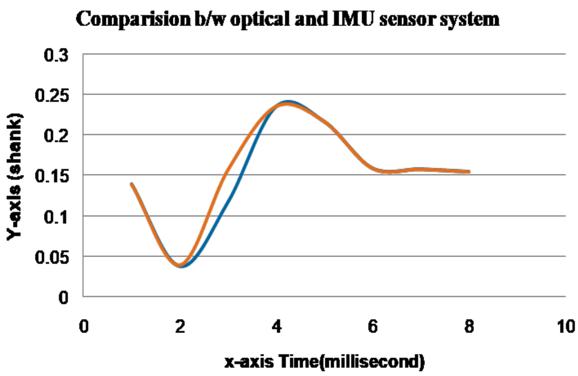

Fig.4 Shank measurement by wearable sensor system (blue line) and optical Hi-Definition Cam's (red line).

8. Experimental Analysis

Parkinson's Gait - Parkinson's is a type of gait caused by the damage of the central nervous that affects movement. A person with Parkinson's gait walks slowly, takes more steps than a normal person is shown in Fig.4. Falls frequently while taking turns and feels like being stuck in place. PD does damage to the nerves in the brain and in the body, comparatively as causing aggregates of the protein alpha-synuclein, called Lewy bodies.

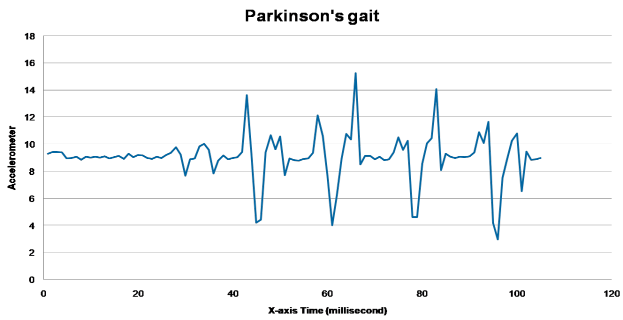

Fig.5 Parkinson's gait graphical representation, from the graph it can be observed the person with this gait has slow gait, takes more steps compared to normal gait person.

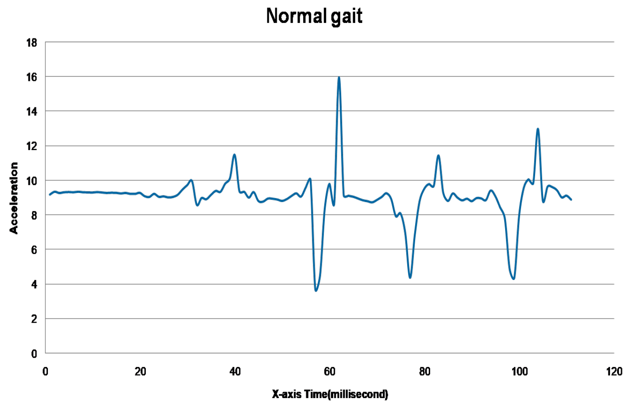

Fig.6 General (normal) gait graphical representation.

Hemiplegic Gait – In this gait, leg is stiff without flexibility at the knees and in some cases at ankle. Moves from outside, and then towards in, forming a semicircle. This gait is due to serious heart stroke in patients, paralysis, etc.

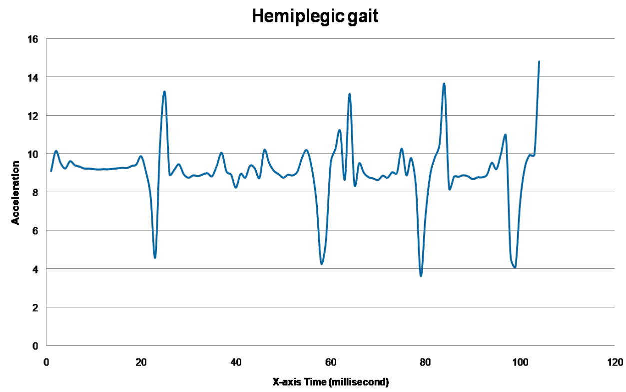

Fig.7 Hemiplegic gait graphical representation, it can be observed that gap between gait cycle is more compared to the normal gait walk. As a person moves his leg in a semicircle while walking.

TABLE I

Stride length	**Normal person**	**Patient-1**	**Patient-2**
1	0.888(m)	0.968(m)	0.793(m)
2	0.667(m)	0.714(m)	0.809(m)
3	0.784(m)	0.947(m)	0.839(m)
mean	0.779(m)	0.876(m)	0.813(m)

Stride Length

TABLE II

GAIT PHASE PARAMETERS

	S.no	Stride length	Stance phase length	Swing phase length
Normal person	1	0.63(s)	0.390(s)	0.239(s)
	2	0.62(s)	0.372(s)	0.248(s)
	3	0.78(s)	0.468(s)	0.312(s)
Patient-1	1	0.47(s)	0.282(s)	0.188(s)
	2	0.62(s)	0.384(s)	0.235(s)
	3	0.47(s)	0.291(s)	0.178(s)
Patient-2	1	0.78(s)	0.483(s)	0.296(s)
	2	0.62(s)	0.359(s)	0.260(s)
	3	0.63(s)	0.378(s)	0.252(s)

Through the analysis and comparison of the gait parameters of both abnormal and patients gait and normal person, the patient with abnormal has much longer gait cycle time than the normal person [10]. It describes that patients are lacking strength and the patient need more time to maintain a stable and balance center of gravity. It describes that patients walking ability is poor.

9. CONCLUSION

An IMU-based system that extracts gait parameters is designed and used to verify the sensitivity and effectiveness of the proposed guidelines. In this case, low-cost, intelligent wearable technologies for clinical applications have gained increasing interest from the research community without a laboratory environment. We have presented the design and graphical representation of different gait parameters of patients in this paper. The Hardware system collects the data from the IMU sensors and the collected gait parameters are sent to a personal computer for generating a graph for the particular gait. From the graph different stages of the gait cycle can be observed. It is observed that the results of the abnormal gait patients are consistent with the proposed guidelines. The extracted results are used for the diagnosis of patients and for surgery guidance.

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