WEARABLE SENSORS BASED REAL-TIME MONITORING OF GAIT KINEMATICS FOR LOWER EXTREMITY EXOSKELETONS

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ABSTRACT

This paper presents a real-time gait analyzer used to record the gait pattern of a subject which can be primary input to lower extremity exoskeletons. Studies have been carried out on walking behaviour of subjects indicating that lower extremity exoskeletons can take inputs as hip and knee joint movement angles in sagittal plane. Wearable gait motion analyzer can be used to operate lower extremity exoskeletons in two different modes: real-time gait and pre-defined gait. For pre-defined gait mode, wearable gait motion analyzer provides wearer specific gait pattern of hip and knee joint angles in sagittal plane. A comparison study on gait data obtained from gait lab and wearable gait motion analyser was carried out and showed 98% correlation match. Gyroscopes of IMU are also used to measure angular velocity of hip and knee joints to estimate specifications of exoskeleton actuators.

Keywords: gait, sagittal plane, Euler angles, inertial measurement unit (IMU), exoskeleton.

INTRODUCTION

Large number of troops are regularly deployed in the border areas having extreme environments especially in a country like India, where border areas are covering the hottest climate of deserts, humid climate of marshy areas, cold climate of high altitude areas like siachen glacier and Himalayan regions of Indian borders due to military and strategic reasons. These extreme climates are a potential threat to physiological functions and physical performance of an individual. Patrolling across the borders in a rough climate results in an increase in energy consumption and as a consequence earlier onset of fatigue [1-2]. To help soldiers perform these tasks more efficiently, exoskeletons are emerging which can not only assist but also increase the endurance of soldiers in walking longer distances with payloads without giving stress to their musculoskeletal system. Therefore, there is a need for wearable gait motion analyzer which can provide reliable inputs to lower extremity exoskeletons. This paper presents a system developed by DEBEL, DRDO to meet the above requirement.

Human Gait

Gait analysis is a study of human locomotion which generally includes walking and running. A gait cycle is the time interval between two successive occurrences of any of the repetitive events of walking. A single gait cycle is called as a stride. Scope of this study is real-time acquisition of gait data and its processing.

Real-time bio-mechanic study has been reported on subjects which shows activation of each joint in different gait cycle events for designing exoskeletons [3]. A motion capturing device has been designed elsewhere to acquire gait cycle data and graphical user interface (GUI) was used for post processing and analysis of gait cycle data [4]. Another study was conducted to compare wearable magnetic and inertial sensors with gold standard equipment and it was claimed that hip and knee joint angles measurement can be used for clinical trials [5]. A research paper published on cerebral thrombosis patients examined gait disorders with IMU based dual foot mounted gait analysis system [6].

A number of studies have been performed on normal gait acquisition of a human locomotion using portable technologies [7-10]. Gait pattern of a human subject can be distorted due to various reasons such as musculoskeletal disorders, cardiovascular & pulmonary problems; and in some cases due to psychological reasons.

Anatomical References

A standard reference position for mapping body's structure is the normal anatomical position. There are three reference planes for study of human body motion as depicted in Figure 1 [11]. The sagittal plane is a plane which divides the human body into left and right halves. The frontal plane divides the human body into front and back portions. Transverse plane divides the human body into upper and lower portions.

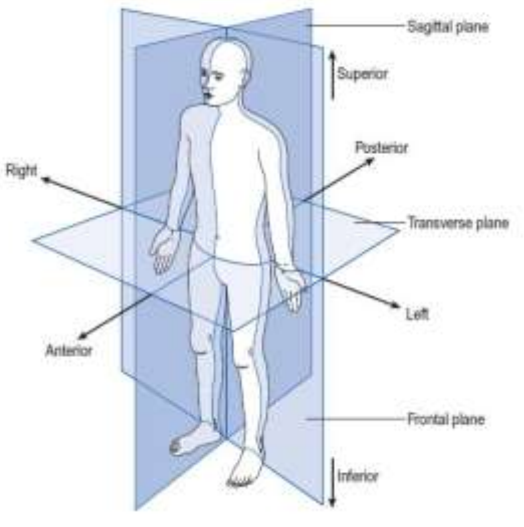

Figure 1: Anatomical references

Euler Angles

Euler angles are used to measure pitch, roll and yaw rotations of body segment about three orthogonal axes. These angles are calculated from data obtained from accelerometer and gyroscope of IMU. As human locomotion is predominantly in sagittal plane, Euler angle corresponding to pitch rotation is chosen as input to exoskeletons.

Degree of Freedom & Angular Velocity

Hip joint is the only true ball-and-socket joint in human body, the ball being the head of the femur and the socket the acetabulum of the pelvis. The joint is capable of flexion, extension, abduction, adduction, internal and external rotation. The knee joint is a hinge type synovial joint, which primarily allows flexion and extension. Wearable gait motion analyzer records flexion and extension of hip and knee joints as one degree of freedom. Flexion of hip and knee joints are considered as positive angles. Range of pitch angles were -180^{o} to 180^{o} for hip and knee joint. Figure 2 depicts formulae for hip, knee and ankle joint angle calculations.

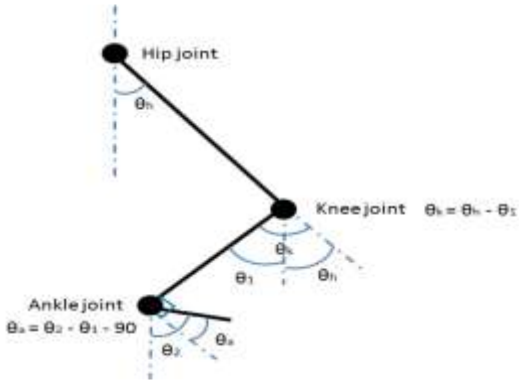

Figure 2: Sagittal plane joint angles of hip, knee and ankle

To study the sequence of muscle activation and force effectuation during walking, angular velocity is a vital parameter. Thus, wearable gait motion analyzer is designed to acquire the wearer’s angular velocity.

Lower Extremity Joint Angle Conventions and Profiles

Human gait cycle can be broadly divided into two phases: stance phase and swing phase [11]. Stance phase is the phase of gait cycle when foot is on the ground whereas during swing phase, foot is moving forward in air. The stance phase lasts from initial contact to toe off whereas swing phase lasts from toe off to the next initial contact.

Stance phase of a gait cycle can further be divided into four events as loading response, mid-stance, terminal stance and pre-swing. Similarly, swing phase of the gait cycle can further be divided into three events as initial swing, mid-swing and terminal swing. Joint angle profiles for hip, knee and ankle over one gait cycle are shown in figure 3.

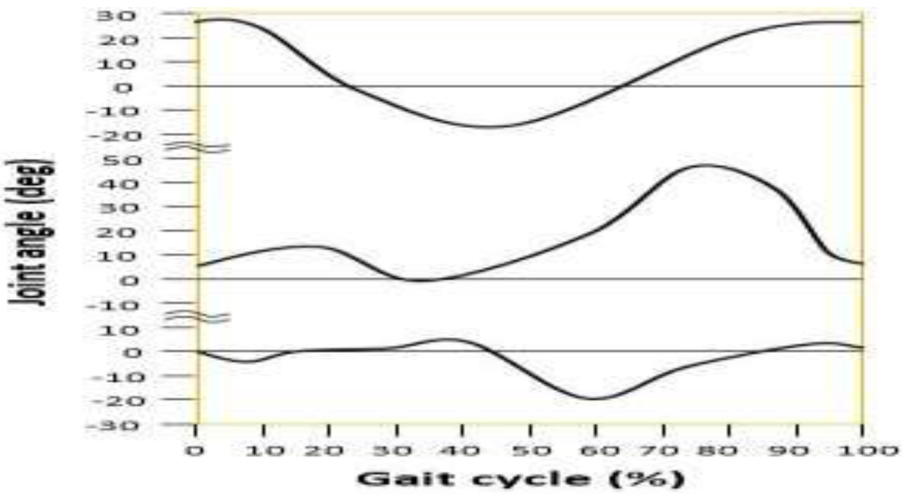

Figure 3: Sagittal plane joint angle profiles of hip, knee and ankle

Lower Extremity Exoskeletons

Lower extremity exoskeletons have been proposed as assistive devices for human locomotion which can be used for rehabilitation and military purposes. Military exoskeletons have been primarily designed to ease load carriage by providing a parallel load path to the ground surface [12-13], and augment movement of the wearer by applying torque directly to the wearer's joints. These exoskeletons are realized using rigid frames that enable bypassing the weight of payload and; rotary or linear actuators for applying external forces for desired joint movements. Rigid nature of exoskeletons also presents a number of practical challenges towards the goal of assisting locomotion such as higher interaction forces between subject & machine and increased exoskeleton mass. DEBEL has been actively involved in design and development of advanced biomechatronic technologies like powered, passive and cognitive exoskeletal machines to enhance load carrying capability of soldiers during military operations in order to support the ground soldiers.

HARDWARE DESIGN DESCRIPTION

Block Diagram

Wearable gait motion analyzer consists of central unit and IMU sensor units. Central unit is responsible for data acquisition from IMU sensor units, accelerometer & gyroscope data processing, storage and transmission. There are five IMU sensor units to acquire lower extremity joint angle movements. The system hardware is built around a 32-bit microcontroller unit (MCU) running on advanced RISC machines (ARM) core. System hardware block diagram is shown in figure 4.

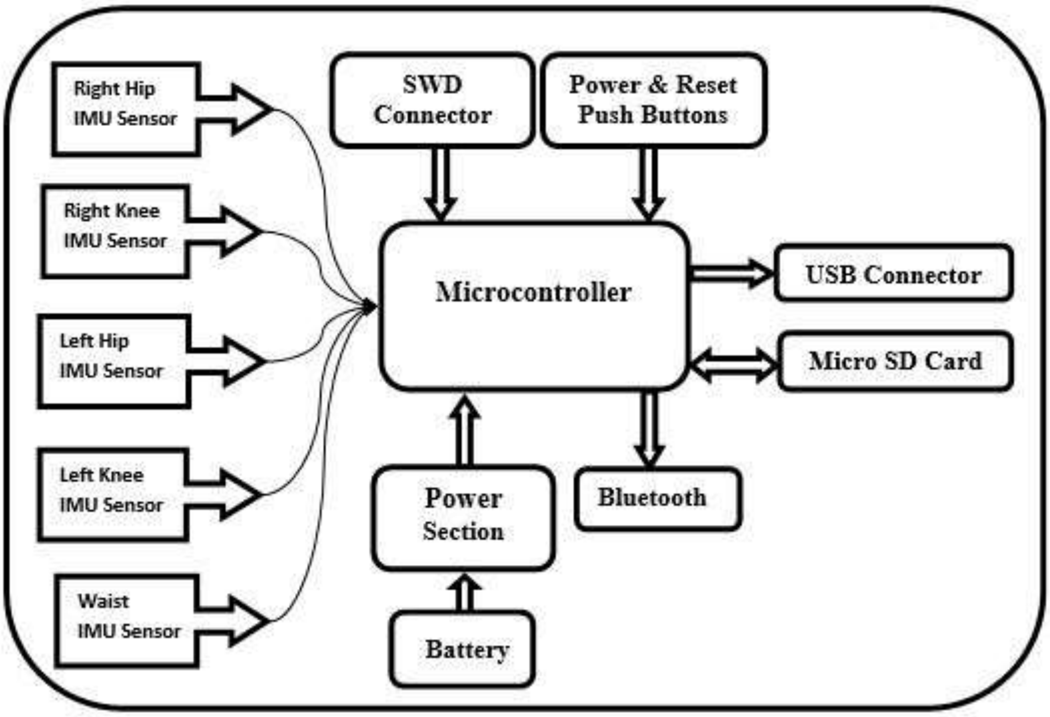

Figure 4: System hardware block diagram

Five IMU sensor units are interfaced with microcontroller of central unit through inter-integrated circuit (I2C) protocol. Microcontroller calculates Euler angle from data received through each IMU sensor unit and provides the necessary real-time gait pattern and vital gait analysis parameters. The printed circuit board (PCB) of system electronics is shown in figure 5.

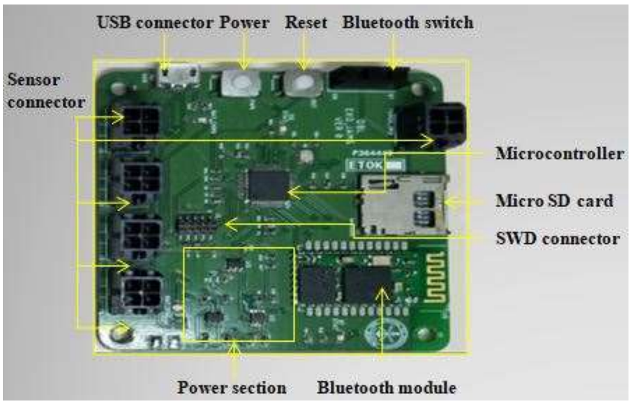

Figure 5: Printed circuit board of central unit

There are two push buttons, one for system power on-off and the other one for microcontroller reset. There are 5 light emitting diodes (LEDs) for indicating system checks, battery backup & charging and wireless module power status. An on-board micro secure digital (SD) card is also provided to enable storage of gait data. A wireless module is used to transmit real-time data wirelessly to a host system. Serial wire debug (SWD) interface is used to program the microcontroller. The system is powered through a 3.7 Volts, 500 mili-Ampere per hour rechargeable lithium polymer battery.

Sensor Placement

Central unit and a IMU sensor unit are designed to be worn around waist and the other four IMU sensor units are placed on the thigh and shank segments of each leg of the wearer. Sensors are connected to central unit by cable harness. Cable harness consist of power lines to provide power to IMU sensor units and data communication lines for I2C interface. Sensor units need to be placed in such a way that sagittal plane should be in-line with the pitch angle of the IMU sensor. A photograph of wearable gait motion analyzer is shown in figure 6.

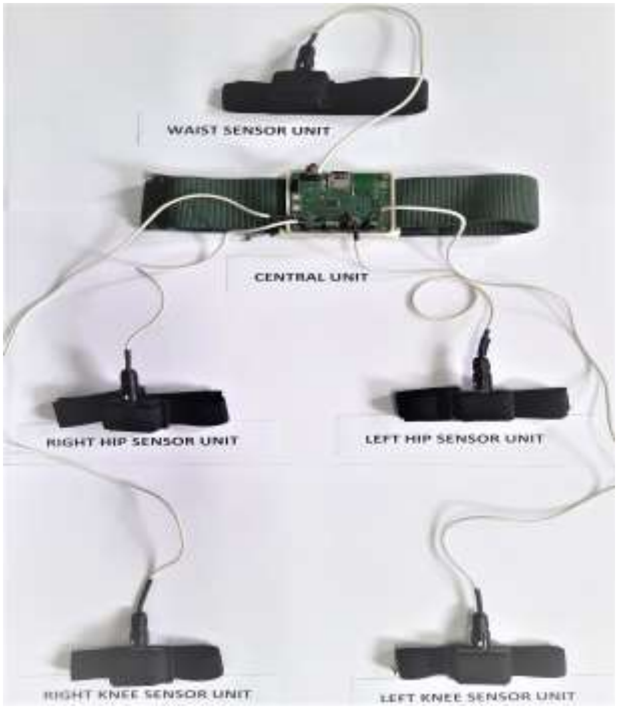

Figure 6: Wearable gait motion analyzer

SOFTWARE DESCRIPTION

Principle of Euler angle estimation

Estimation of Euler angles from gyroscope measurements alone is not possible due to accumulation of angular drift over time. Similarly, estimation of Euler angles from accelerometer measurements alone is also not possible due to high frequency noise in sensor data in dynamic conditions. Wearable gait motion analyzer estimates Euler angles of body segments by fusing both accelerometer and gyroscope data using complementary filter [14-15] as shown in figure 7.

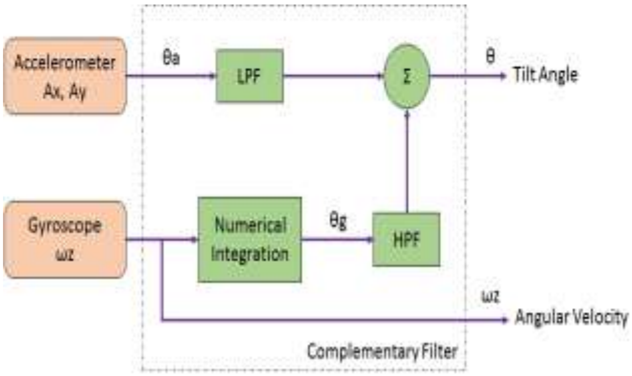

Figure 7: Complementary filter design

System Checks

System checks are a set of checks incorporated to increase the operational reliability of the system. Wearable gait motion analyzer firmware continuously monitors the potential system malfunctions like battery low, wireless connection loss and sensor unit errors. Central unit tries to recover from these error conditions automatically, otherwise it notifies these errors to the wearer. There are four system checks as described below:

A. Battery check

A hysteresis curve is programmed into the firmware to monitor the battery status. Battery voltage should be always greater than the upper threshold to start the system. A dual color LED gives indication of battery status okay or not okay respectively.

B. Sensor check

Chip identifier of each IMU sensor unit is read by central unit on start-up to verify the harness connection. Each sensor unit will then be set to IMU mode and acknowledgement of the same shall be checked by central unit to pass sensor check.

C. Micro SD card check

This is a software check included to find the presence of micro SD card in central unit, if micro SD card is not present, the device shall not pass the system check.
Once all of the above three checks are passed, the system is ready for use.

System Firmware Flowchart

Central unit runs on 48 MHz MCU clock frequency. Flowchart of system software is shown in figure 8. Upon start-up, the device initializes necessary modules such as serial peripheral interface (SPI), I2C, universal asynchronous receiver transmitter (UART) and then pairs with wireless module. The device also displays battery status and switches on system check LEDs to enable the subject to perform system checks. Once the system passes all the system checks, the software enters into a super loop for continuously reading and processing of pitch data values from all five IMU sensor units, data storage into micro SD card and transmission through wireless communication in real-time. IMU sensor units are interfaced via I2C protocol where microcontroller acts as a master and IMU sensor units act as slave devices. On start-up, first reading from each IMU sensor is taken as a reference for offset correction. During data acquisition, there is a continuous monitoring on the I2C bus, to avoid any bus collision or congestion. After successful reading from IMU sensor units and processing, data packet is stored on micro SD card via SPI protocol. Micro SD card memory pointer is introduced in firmware to keep track of the current memory location where data is to be stored.

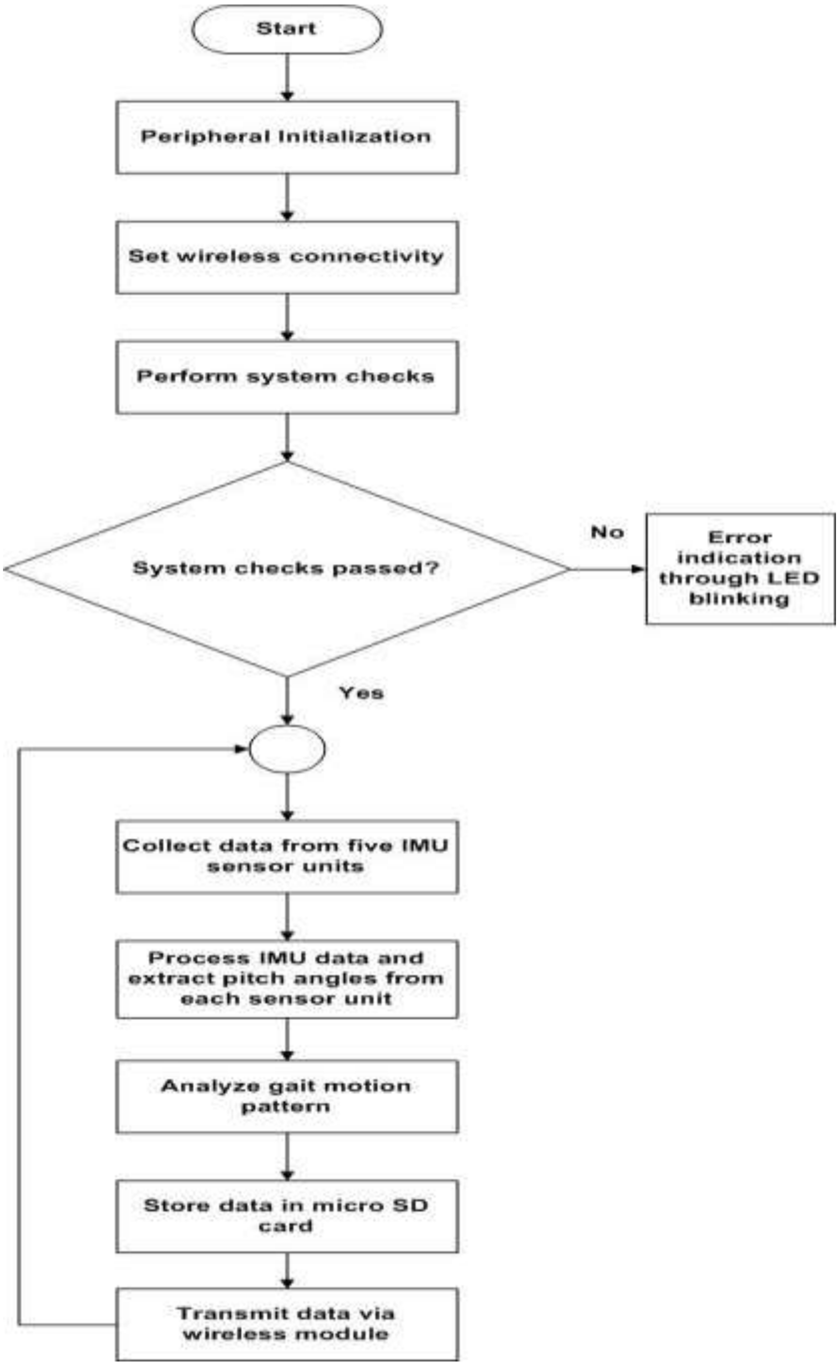

Figure 8: System software flowchart

RESULTS AND DISCUSSION

Wearable gait motion analyzer was tested in gait lab facility available at DEBEL, Bengaluru. Human gait data was collected during walking with 60 cm, 100 cm and 140 cm stride lengths. The gait patterns from wearable gait motion analyzer and gait lab were recorded and analyzed. A single gait profile for 140 cm stride length from gait lab is obtained for thigh and shank movements which are shown in figure 9 and figure 10 respectively. Similarly, gait profiles from wearable gait motion analyzer for thigh and shank are shown in figure 11 and figure 12.

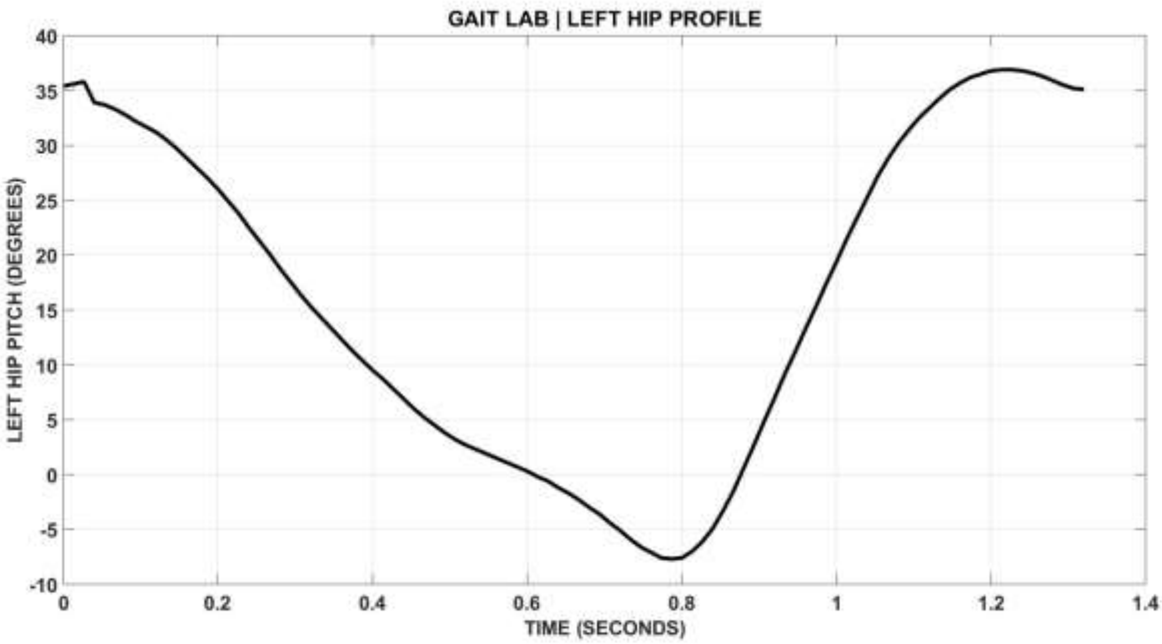

Figure 9: Gait lab: left hip gait profile

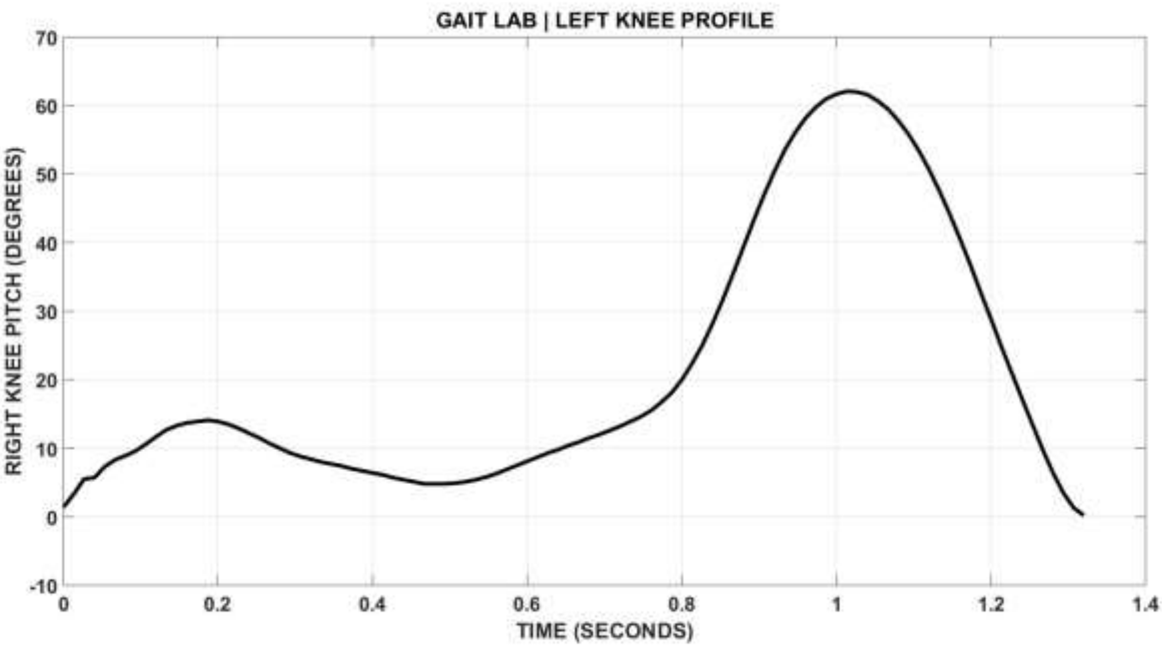

Figure 10: Gait lab: left knee gait profile

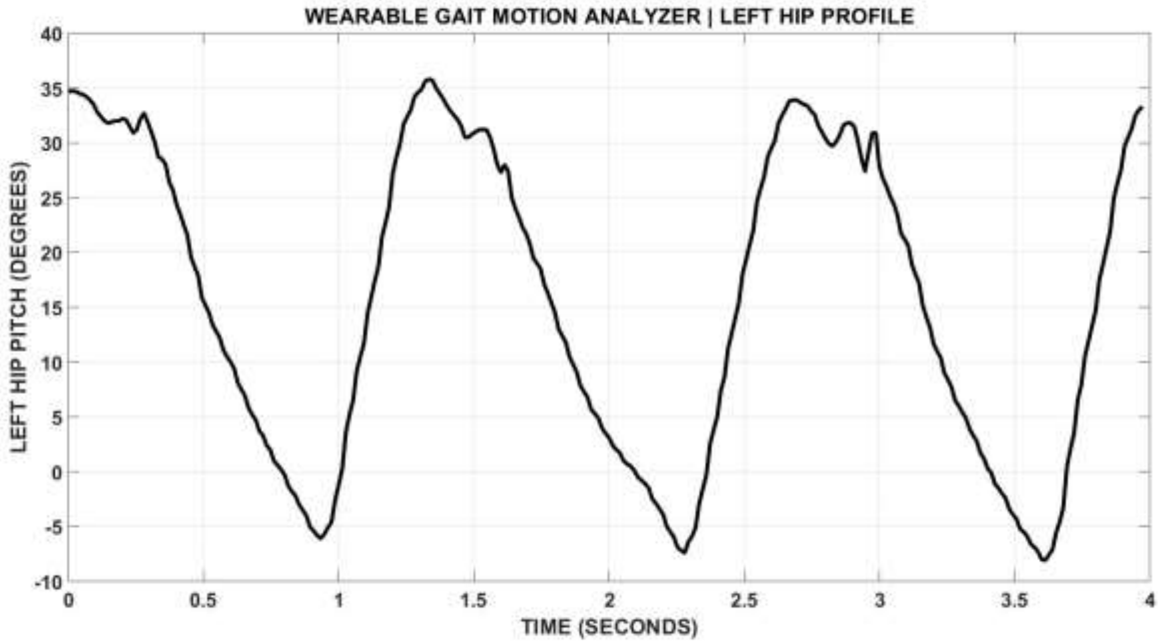

Figure 11: Wearable gait motion analyzer: left hip gait profile

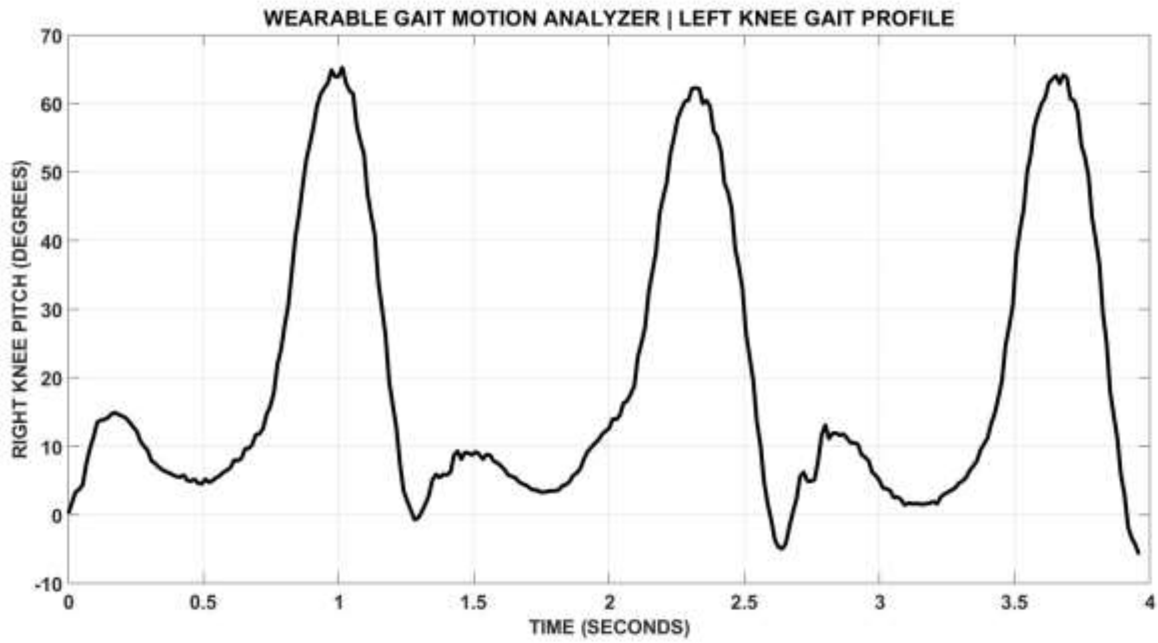

Figure 12: Wearable gait motion analyzer: left knee gait profile

Gait patterns recorded by gait lab were cross correlated with wearable gait motion analyzer data from the same subject using MATLAB. Table 1 shows the results comparing correlation coefficient, stride time and maximum angular velocity for left leg thigh and shank data. Stride time, cadence and maximum angular velocity are internally calculated by wearable gait motion analyzer.

Table 1: Gait pattern analysis results

S. No.	Parameters	Result
1.	Correlation between gait lab data and wearable gait motion analyzer data for left thigh profiles	98.72%
2.	Correlation between gait lab data and wearable gait motion analyzer data for left shank profiles	98.17%
3.	Stride time (seconds)	1.36
4.	Cadence (steps/minute)	88.23
5.	Maximum angular velocity (degrees/second)	282

Wearable gait motion analyzer was used to record data of 15 subjects from different age groups & gender. Gait patterns for real-time and pre-defined gait modes were recorded. A photograph of subject along with wearable gait motion analyzer system is shown in figure 13.

Figure 13: Subject with wearable gait motion analyzer system

Analysis of data recorded by wearable gait motion analyzer showed that the events of gait cycle such as stance phase and swing phase can be detected and given as input to operate the exoskeletons.
Wearable gait motion analyzer was also used in experiments to carry out measurement of angular velocity in addition to joint angles to estimate the necessary torques produced by lower limb joints as shown in figure 14.

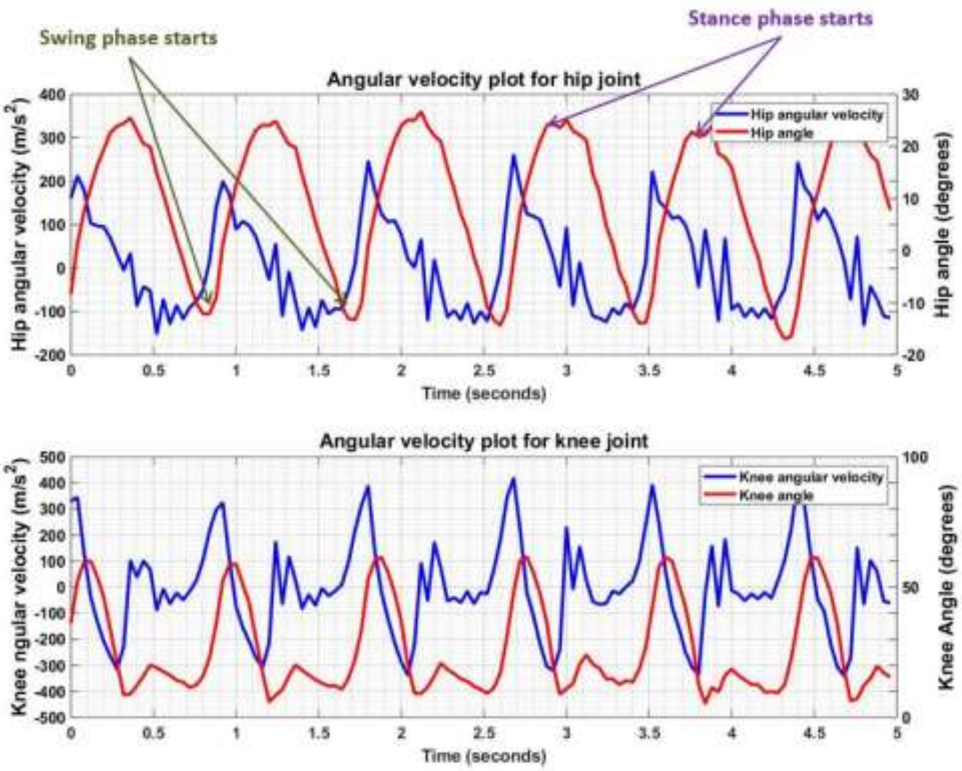

Figure 14: Angular velocity graph for torque estimation

Results obtained from wearable gait motion analyzer correlate with gait lab results by more than 98%. Gait cycle time was calculated with an accuracy of more than 99%. It can be concluded that wearable gait motion analyzer successfully records and analyzes human gait patterns.

CONCLUSION

Wearable gait motion analyzer can be used to operate lower extremity exoskeletons by means of real-time gait sensing and feeding to motor driver controllers. It can also be used as assistance to lower extremity exoskeletons for pre-defined walking which will help in rehabilitation of injured soldiers.

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