Towards a Portable Human Gait Analysis & Monitoring System

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***Abstract*—Human Gait analysis is useful in many cases, such as, detecting the underlying cause of an abnormal gait, rehabilitation of subjects suffering from motor related diseases such as Parkinson's disease or Cerebral Palsy, improving the athletic performance of sports person etc. However, gait analysis has seen limited usage, especially in developing countries, because of the high cost involved in setting up a gait laboratory. We present a portable gait analysis system using Inertial Measurement Unit (IMU) sensors to collect movement data and a Smart-phone to process it. IMU sensors has gained significant popularity in the last few years as viable option for gait analysis because its low cost, small size and ease of use.**

Using the accelerometer and gyroscope data from 3 EXL-S3 IMU sensors (on thigh, shank and foot), we measure kinematic angles in the *sagittal plane* and detect Heel Strike (HT) and Toe Off (TO) events using methods based on [11] and [4] respectively. To measure the accuracy of our system, we compare it with an *Optical Gait Analysis* system, which is the current gold standard for gait analysis [1]. We measure the gait parameters for 3 healthy individuals belonging to different age group and achieve an RMSE of $4.739° \pm 1.961°$, $3.7° \pm 3.02°$ and $4.12° \pm 1.21°$ for *Knee Flexion Extension*, *Ankle Dorsi Flexion respectively* and *Hip Flexion Extension* respectively. We measure the *Heel Strike* and *Toe Off* using shank and foot mounted sensor independently. 34.5 ± 28.3 ms and 27.5 ± 32.8 ms is the RMSE for HT calculated by shank and foot sensor w.r.t. optical system respectively. The RMSE for *Toe Off* is 36.2 ± 36.8 ms and 37.5 ± 35.9 ms for shank and foot sensor w.r.t. optical system respectively.

I. INTRODUCTION

Gait analysis is the study of gait characteristics and deviations from normal, assessed in a variety of ways, ranging from observations to more specific quantitative methods [**?**]. Nowadays, the gold standard method to assess gait parameters is the use of force-plate and optical motion capture systems. In addition, to detect the activation of muscles during the gait cycle, electromyography is used, placing the EMG electrodes on the relevant agonist/antagonist muscles and to study their correct activation [**?**]. Instrumented gait analysis is able to revel subtle gait characteristics that would not be detected by clinical examination [**?**]. In instrumented gait analysis, gait cycle parameters are usually captured monitoring few steps (5-6 steps) and then calculating the spatial and temporal gait parameters such as, Heel Strike (HS), Toe Off (TO), Kinematic angles in Sagittal, Transverse and Frontal planes.

Fig. 1: A typical Optical Gait Laboratory.
Source:http://www.mdpi.com/sensors/sensors-14-03362.

A Typical set up gold standard for performing a gait analysis is by using *Optical Sensors* as shown in the figure 1. The optical system consists of, 6 to 9 High speed infrared cameras (IR), 1 or 2 60 fps video camera, pressure mat, optical markers and a computer to process the data (usually a proprietary software from the vendor). The analysis is carried out in a lab, where lighting conditions can be controlled because of the sensitivity of the sensors to light. The subject wears the optical markers and then take a short walk in the field of view of all the IR cameras. The data captured from the cameras is processed to get the relevant gait parameters.

This is repeated a fixed number of time to get the final result which is the average of kinematic angles in the all the trials. The result is used be used by doctors and surgeons for different purpose such as, to find the underlying cause of an abnormal gait [12], [13], rehabilitation of subjects suffering from motor related diseases such as Parkinson's disease or Cerebral Palsy [16], [4], [14], improving the athletic performance of sports person [10] etc.

Despite of its usefulness, gait analysis has seen very limited use, specially in developing countries, because of the high cost incurred in the setting up a gait laboratory. Apart from the requirement of a laboratory with suitable

*: Work done by authors when they were at Indian Institute of Science.
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lighting conditions, there are some inherent problems in the optical system, such as, the field of view of the cameras is very limited and can only capture around 4-5 steps.

The biggest disadvantage of these gait analysis systems is that they do not allow evaluation and monitoring of the patient's gait during his/her everyday activities, thus extrapolating the conclusions from a short time of study that does not reflect the patient's real condition [**?**]. In addition the evaluation may be time consuming and difficult to tolerate by the subjects, mainly if in case of pathological conditions.

Recently there has been the important introduction of low cost motion sensors, usable for gait analysis, that are easy to use, portable and can be used in daily life conditions. Inertial measurement Unit sensors or IMU sensors has gain popularity in recent years as a viable option to measure human gait. A typical IMU sensor consists of 3 DOF (Degree of freedom) gyroscope, accelerometer and magnetometer [**?**]. In the present study we used EXL-S3 IMU sensors [7], which can record the data with very high accuracy and broadcast it via Bluetooth or store data locally making it ideal for long term and ubiquitous usage.

A. Related Work

There are several works aimed at using IMU sensors to measure gait parameters. [11] provides a way to calibrate the sensors to detect the axis of rotation corresponding to a joint and use that to get the Knee Flexion Extension, Ankle Dorsiflexion and Plantarlfexixon angles. Drift creeps into the result obtained using the integration method because of the noise present in data recorded by gyroscope, which adds up over the time. [15] and [3] provide a method to remove the drift from the results, using concept of Double Derivate and Integration (DDI) method and Zero Velocity Updates (ZUPT) respectively. [4] provides a method to detect the Heel Strike an Toe off events by *marking* specific patterns in the data recorded by the accelerometer and gyroscope for individuals with normal gait.

Although relevant, none of the work focuses on a complete gait system. Outwalk protocol, proposed in [5] is the only work in our knowledge which aims at doing complete gait analysis using IMU sensors. Outwalk is validated in the work [8] which shows comparable performance to the gold standard. However the methods used by them to achieve the results is not open source and is offered as paid product from Xsens [17].

B. Our Contribution

With this paper, we start the work towards our ambitious goal of building an easy to use, portable and, low cost Human gait analysis system. IMU sensors to collect the data and a smart phone for processing it to calculate the gait parameters. We do not re-invent the wheel, instead use well known and established algorithms to solve sub-problems and modify them as per requirement dictated by sensor specifications. To this end,

1) Our algorithms for measuring the gait parameters are based on algorithms from [11] and [4], with some changes, which makes it easy and portable to use. Details are given in section III.
2) We implement all the algorithms in a smart phone. Using IMU sensors specifications, we built an android application which is capable of collecting the data from the sensors and process it to generate the results in real time. Integrating the collection and processing of data on a smart phone makes it a true portable system.

(a) Portable System: EXL-S3 IMU Sensors with smart phone.

(b) Placement of IMU sensors.

Fig. 2: Portable IMU system and its usage.

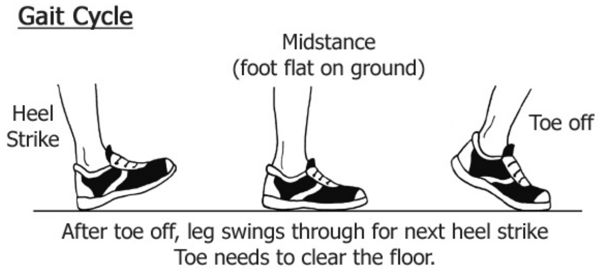


Fig. 3: Gait Cycle: As marked by Heel Strike and Toe off.
Source: http://www.drwolgin.com

Using 3 IMU sensors, placed on thigh shank and foot, we measure the gait parameters for 3 subjects belonging to different age group (a child, an adult and an elderly person) with healthy gait. We use the optical system to measure the performance of our system. The results shown are for right leg. The process is fairly straightforward and can be applied to left leg also. In terms of performance, we are able to achieve RMSE of $4.739° \pm 1.961°$, $3.7° \pm 3.02°$ and $4.12° \pm 1.21°$ for *Knee Flexion Extension*, *Ankle Dorsi Flexion* and *Hip Flexion Extension* respectively. We measure the *Heel Strike* and *Toe Off* using shank and foot mounted sensor independently. 34.5 ± 28.3 ms and 27.5 ± 32.8 ms is RMSE for HT calculated by shank and foot sensor w.r.t. optical system respectively. For *Toe Off* it is 36.2 ± 36.8 ms and 37.5 ± 35.9 ms RMSE for shank and foot sensor w.r.t. optical system respectively.

II. BACKGROUND

A. Gait Cycle

Heel Strike and *Toe Off*, as shown in the figure 3 , are points, when the heel of a leg touches and the ground and when the toe of a leg leaves the ground respectively. These event marks the start and end of a *Gait Cycle*. The final result of a gait analysis contains average of all the

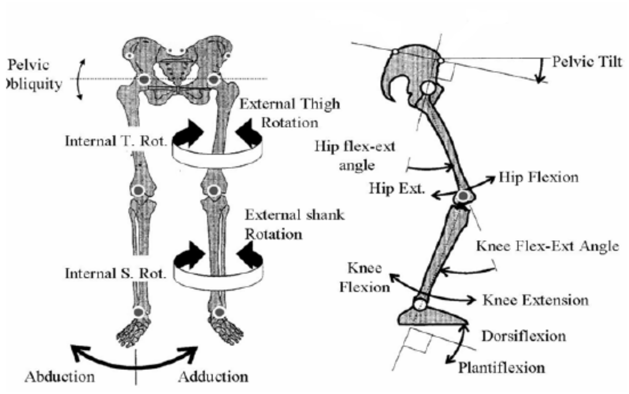
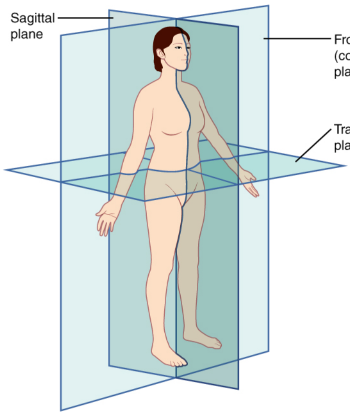
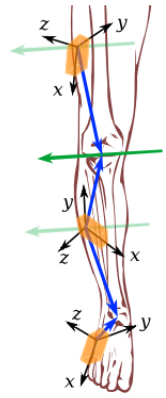


Fig. 4: Definition of Kinematic Angles.
Source:http://www.scielo.org.ve



(a) Different Planes of movement.



(b) Joint axis direction, found during calibration, shown in green arrows.

Fig. 5: Figure showing different plane of motions and the axis found by the calibration process.
Source for figure 5(a) http://upload.wikimedia.org
Source for figure 5(b) : [11]

kinematic angles, measure in all the gait cycles of every walk. This helps in smoothing out the errors.

$$Avg\ Anlge_k = \frac{1}{N * M} \sum_{i}^{i=N} \sum_{j}^{j=M} (Anlge_k^{ij}) \qquad (1)$$

where $Anglie_k^{ij}$ is kinematic angle in i^{th} gait cycle of j^{th} walking trial. N and M are number of gait cycles in a walk and total number of walks respectively.

B. Kinematic Angles

The Kinematic angles, as shown in the figure 4, are the angles formed by different joints during a walk. While walking, a pattern of these kinematic angles is repeated for every gait cycle. These patterns are similar for individuals with a healthy gait. A deviation from the norm indicates some underlying problem, which shows up in the result of gait analysis.

As shown in figure 4, *Knee Flexion Extension* angle is the angle formed between the thigh and the shank in the sagittal plane. When the leg is straight the angle is $0°$ and goes up as the shank folds towards the thigh during walking. Similarly, *Hip Flexion Extension* angle is the angle between the thigh and the pelvis in the sagittal plane. Same as Knee Flexion Extension angle, Hip Flexion Extension angle is $0°$ when the subject is standing straight and goes up as thigh raises during a walk. *Ankle Dorsiflexion Plantarflexion* is the angle formed by the foot with the horizontal axis starting from the ankle joint and moving towards the foot.

III. Algorithm

A. Calibration

We use the calibration procedure as mentioned in [11] with few modifications. The purpose of the calibration is to find two j vector , j_1, and j_2, which corresponds to the axis of rotation in the sagittal plane for the two body segments, corresponding to joints, on which sensors are attached(thigh and shank for knee joint, shank and foot for ankle joint). As majority of the motion during a walk happens in saggital plane, it gives the axes for rotation in this plane.
The constraint used for the optimization, as described in the equation [11] is as follow. Assuming *g1* and *g2* are gyroscope readings from sensors on (thigh and shank)/(shank and foot) respectively, then as explained in [11], " *for each instant t, $g_1(t)$ and $g_2(t)$ differ only by the joint angle velocity and a time variant rotation matrix. Hence their projections into the joint plane have the same lengths for each instant in time* " which can be represented as:

$$\|g_1(t) \times j_1\|_2 - \|g_2(t) \times j_2\|_2 = 0, \forall t \qquad (2)$$

Calibration is basically an optimization problem which is to find the axes along which maximum rotation happens, subject to the condition specified by equation 2.

The authors in [11] introduces calibration as an additional step where the subject, prior to walking has to do some predefined movements which essentially calculates the j vectors and use it to calculate angles for the subsequent walks. However, there are some problems with this method.

- It needs a trained physician to be present every time a trial has to be done, which is not suitable if the goal is to capture a long trial (few hours).
- Calibration step relies on the assumption that the data captured during this process is enough to get the optimal value for the calculation of the j vectors.
- It assumes that the j vectors calculated in the beginning of of calibration procedure remains valid through

Algorithm 1 Calibration: Gauss Newton Optimization Algorithm

Require: N data points from g_1 and g_2, the two Gyroscope sensors
Ensure: $N \gg 4$
  $x = (\phi_1, \theta_1, \phi_2, \theta_2)^T$
  $\hat{j_1} = (cos(\phi_1), sin(\phi_1)sin(\theta_1), sin(\phi_1)cos(\theta_1))^T$
  $\hat{j_2} = (cos(\phi_2), sin(\phi_2)sin(\theta_2), sin(\phi_2)cos(\theta_2))^T$
  ϵ the error vector $\in \mathbb{R}^{(N\times 1)}$
  while $t \leq N$ **do**
    $\epsilon(t) = \|\hat{j_1} \times g_1(t)\|_2 - \|\hat{j_2} \times g_2(t)\|_2, k = 1, ..., N$
    Calculate Jacobian $(\frac{d\epsilon}{dx})$
    Calculate Moore-Penrose-pseudoinverse $pinv((\frac{d\epsilon}{dx}))$
    Update x, $x = x - pinv(\frac{d\epsilon}{dx})$
  end while

out out the experiment which might not be true as the sensor may get displaced (slightly) during walking trials.

To address these issues we propose a solution that instead of doing a calibration in the beginning of trial, use the walking trial data for calibration. As the walking trial involves 5-6 steps it contains enough data to calculate the j vectors optimally. Apart from that, the j vectors calculated are specific to this walking trials, hence there is a less chance of error due to incorrect or old values of j vectors. From experience, we have found that if carefully implemented, the calibration process runs fast enough even with the large numbers of walking trials. One advantage of doing calibration like this is that in the long trial, which spans to several hours, this can also act as a error correcting mechanism. We can run calibration process at certain intervals to fix the j vector, which changes because of small changes in sensor positions because of walking over long period of time.

B. Angle Calculation in Sagittal Plane

[11] gives an algorithm to calculate the angles in the sagittal plane using the j vectors, j_1 and j_2, which corresponds to axes for sensors on body segments along which the maximum rotation takes place. The angles can be calculated by integrating the difference of angular velocity around the axis of rotation:

$$\text{KneeFE: } \alpha_{gyr}(t) = \int_0^t (g_1(\tau).j_1 - g_2(\tau).j_2)d\tau \quad (3)$$

Where α is the Knee Flexion Extension angle. Here the first sensor and second sensor is on the thigh and the shank of the subject respectively.

$$\text{HipFE: } \alpha_{gyr}(t) = \int_0^t (g_1(\tau).j_1 - g_2(\tau).j_2)d\tau \quad (4)$$

Where α is the Hip Flexion Extension angle. Here the first and second sensors is on the lower back(lumbar) and on the thigh of the subject respectively.

$$\text{AnkleDP: } \alpha_{gyr}(t) = \int_0^t (g_2(\tau).j_2 - g_1(\tau).j_1)d\tau \quad (5)$$

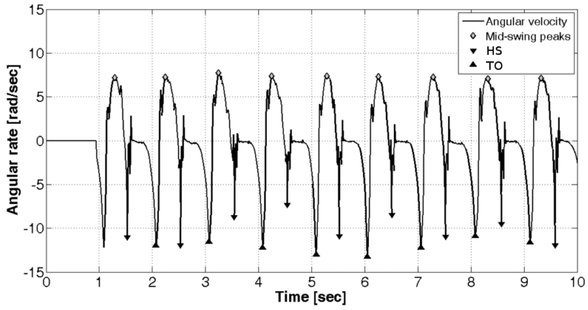


Fig. 6: Detection of HS and TO is based on finding specific patterns in the gyroscope data. Source: [4]

Where α is the Ankle Dorsi Flexion Plantar Flexion angle. Here the first sensor and second sensor is on the shank and the foot of the subject respectively. Note that the order of subtraction has to be reversed for the calculation, which is because of the way the angle is defined.

C. Heel Strike and Toe Off Detection

One of the most important phases of gait analysis is to detect the temporal parameters, Heel Strike (HT) and Toe Off (TO). They mark the beginning and the end of a gait cycle respectively. The final results of gait analysis is an average of all the gait cycles. The averaging helps in removing the artifacts which are present only in some of the gait cycles.

We use two methods [4] and [9], independent of each other, to detect the HT and TO using data from shank and foot sensors. As the accuracy in HT and TO detection is of utmost importance, having two methods helps us to cross verify the results.

The only drawback of these methods is that both of them relies on the some "specific pattern" present in the gyroscope data from the shank/foot sensor as shown in the figure 6. These conditions might hold true for a person having normal gait but may not for an abnormal gait.

IV. Experimental Setup

A. IMU Sensors

For our experiments we use 3 EXL-S3 sensors (figure 2(a)). These sensors have a tri-axial accelerometer, gyroscope and a magnetometer. It has a 32-bit MCU, Cortex-M3 processor working at 72 MHz which provides highly accurate orientation estimates using orientation estimation algorithm with Kalman filtering built into it. The accelerometer can be configured with values $\pm 2g$, $\pm 4g$, $\pm 8g$ and $\pm 16g$ and the gyroscope can be configured with values $\pm 250dps$, $\pm 500dps$, $\pm 1000dps$ and $\pm 2000dps$ (degree per second). It can transmit data at a rate of 200Hz for raw data and at 100Hz for data with orientation estimate via Bluetooth. It has a 1GB flash drive built into it. The sensor can be configured to transmit data via Bluetooth or store it locally or do the both.

We collect the data at the speed of 100Hz with the orientation estimate. The acclerometer is configure to record values in range of $\pm$2g and gyroscope in the range of $\pm$250 dps. We do not use the data from the magnetometer as it requires a uniform magnetic field and disturbance from the

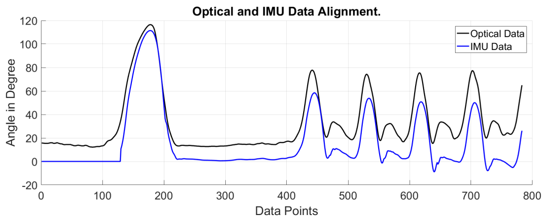


Fig. 7: Alignment of angle from optical and IMU system.

electric appliances may cause error in the data ([2], [6]). We only use gyroscope data for calculation of angles in the sagittal plane. Accelrometer data, though noisy, does not suffer from the drift and can be used to correct the drift which creeps into the result calculated using the gyroscope data as shown in the [11]. However using our methods we are not experiencing any significant drift for a walk consisting of 5 -6 steps. This can be attributed to the high quality of the sensors.

B. Sagittal Plane

We focus on the kinematic angles in the sagittal plane. This planes captures most of the movement during walking, the angles in this plane provides much more insight into the gait than other angles in the other planes. In optical system also, the angles in other planes is mostly used as a reference to whether the optical markers are correctly placed or not.

C. Comparison with Optical System

To measure the performance of IMU sensors system we place optical and IMU sensors on the subject and recorded the data at the same time. The IMU sensors were placed on thigh, shank and foot of the right leg. At the same time, the optical markers were placed on the anatomical joints as per the protocol used by the optical system. Placement of the sensors is shown in the figure 2(b).

The subject walked 5-6 steps which was captured by both IMU and Optical system. One challenge we faced is that, it is not possible to start both the systems precisely at the same time. Optical systems has its own dedicated machine to control its operations and IMU sensors broadcast data to a different machine. To find a synchronization point, subjects did a *leg raise* actions which shows up as a peak in the Knee Flexion Extension angle (as seen in the figure 7). This peak, is used to synchronize the two systems and compare the results.

V. Results

A. Offset in the Results

During the gait analysis by the optical system, anatomical measurements of the subject are taken before the walking trials. These measurements are used by the optical system to give accurate kinematic angles. After this sensors are placed on the subject and a standing trial is done. Here the subject stand in the field of the view of the cameras. This is done to capture the natural posture of the subject and the calculate the initial values of the kinematic angles.

There are no pre-measurement or standing trial in the gait analysis done using IMU sensors. It relies purely on the raw data received during the walking trial and is independent of subjects height, weight and other anatomical specifications. Because of this the angles calculated by IMU system vary by a fixed offset from the angles calculated by the optical system in the final calculations as shown in the figure 7.

B. Gait Cycle Detection, Heel Strike and Toe off

As seen in the table I, for healthy individual, HS and TO is detected with an error of few milliseconds. HS and TO marks the start and the end of gait cycle and hence it is very important to detect it accurately. The current algorithm works well for individual with healthy gait, however this cannot be generalized for abnormal gait as it relies on specific patterns in the data to find the event. Generalizing the HS and TO detection algorithm is difficult because of different type of problems associated with gait, which results into different patterns of the angles. This is a hard problem and even the optical system depends on the manual marking of HS and TO events from lab physician, using the video feed from the camera.

C. Kinematic Angles Calculation

The final report by the Gait analysis system is the average of the kinematic angles, in all the gait cycles, in all the walking trials. This removes any artifacts in the data. After the offset correction the results from the IMU sensors and the Optical system varies by a few degrees of RMSE as can be seen in the figure 9 and the table I.

VI. Portability: Android Application

The aim is to build a portable and efficient Gait analysis system, which can be carried to rural and remote places. The IMU sensors are light weight and can be easily carried around in a briefcase with its docking station and other necessary equipment such as bands to attach the sensors to body. Apart from, smart-phones nowadays are sufficiently powerful and can be used to collect the data via Bluetooth and process it locally. We built a small demo purpose Android application, which has the capability to collect data from the sensors and then process it locally. It can keep tracks of experiments performed on the device itself and sync to a remote server for backup purpose. The working of the app can be seen in the video at *https://goo.gl/Zpmdp0* and in the figure 10.

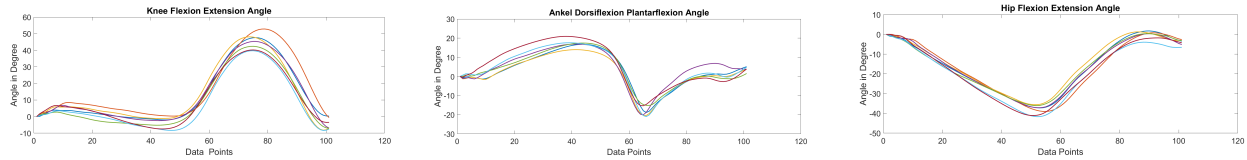
VII. Conclusion

We present a IMU based portable system for Human Gait Analysis. IMU sensors used to collect the raw data during a walk which is then broad casted to a smart phone for processing to calculate final gait parameters. We are able to calculate the angles in the sagittal plane with reasonable accuracy when compared with gold standard optical gait analysis system. The algorithms are capable of generating the results in real time and have a self error correcting feature for long term monitoring of a subject.

VIII. Future Work

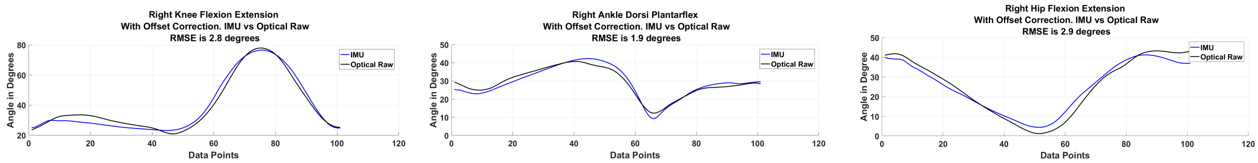
A. Angles in Frontal and Traversal Plane

The calibration procedure mentioned in the section III-A finds the axes, along which there is maximum rotation. This axis is normal to sagittal plane as most of the rotation takes place in this plane only. The major challenge that we are

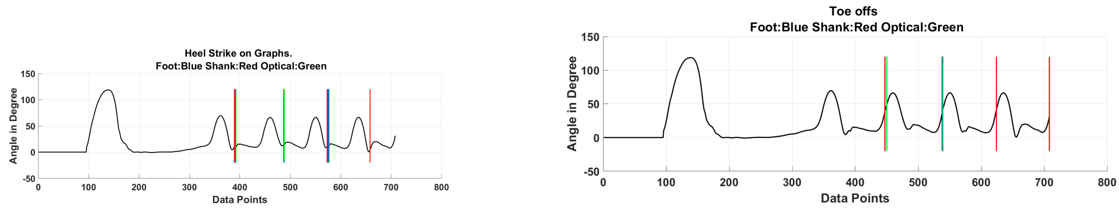


(a) Knee Flexion Extension (b) Ankle Dorsiflexion Plantarflexion (c) Hip Flexion Extension

Fig. 8: Kinematic angles in Sagittal Plane.



(a) Comparison of Knee Flexion Extension (b) Comparison of Ankle Dorsiflexion Plantarflexion (c) Comparison of Hip Flexion Extension



(d) Heel Strike Comparison (e) Toe Off Comparison

Fig. 9: The Angle calculation in the sagittal plane and the Heel Strike and Toe Off detection is comparable to the Optical system. We are also manually correcting the offset of the angles to compare the result as it is not clear how optical system comes up with the start angle for a subject.

Gait Parameter	Error	Number of Samples	Compared with
Knee Flexion Extension	$4.739° \pm 1.961°$ RMSE	17	Optical Knee Flexion Extension
Ankle Dorsi-Plantarflex	$3.7° \pm 3.02°$ RMSE	3	Optical Ankle Dorsi-Plantarflex
Hip Flexion Extension	$4.12° \pm 1.21°$ RMSE	15	Optical Hip Flexion Extension
Heel Strike Shank Sensor	23.4 ± 33.2 ms	10	Heel Strike Foot Sensor
Heel Strike Shank Sensor	34.5 ± 28.3 ms	4	Heel Strike Optical
Heel Strike Foot Sensor	27.5 ± 32.8 ms	4	Heel Strike Optical
Toe Off Shank	73.8 ± 60.2 ms	10	Toe Off Foot Sensor
Toe Off Shank	36.2 ± 36.8 ms	4	Toe Off Optical
Toe Off Foot	37.5 ± 35.9 ms	4	Toe Off Optical

TABLE I

Results table for different Gait parameters and their respective errors when compared to the Gold Standard Optical system or Results from other IMU sensor.

facing in other planes (frontal and traversal) is that during a walk, there is very little movements in these planes and because of this, the optimization method (calibration) does not give good results. This makes the calculation of angle in these planes difficult. We are looking into the ways to calculate these angle from IMU sensors raw data.

B. HS and TO Detection Algorithms

Heel strike and Toe off detection algorithms have very strong assumptions, as they rely on specific pattern present in gyroscope data. These assumptions hold in data collected for individuals with a healthy gait but may not hold for an abnormal gait. Developing an algorithm which relaxes these assumptions will be the next step. We are exploring machine learning and deep learning algorithms for this.

C. Smart-phone feature

The smart-phone application for gait analysis adds up to the portability feature of the system. A *companion feature*, along with the gait analysis can help a patient with rehabilitation process by guiding him/her through the daily exercise routines.

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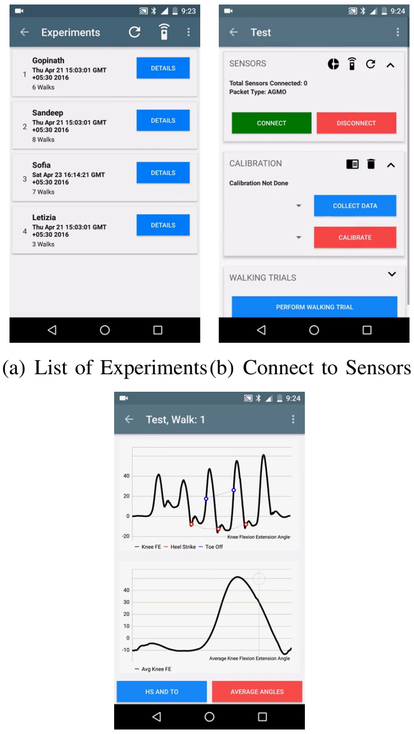

(a) List of Experiments (b) Connect to Sensors

(c) Process Results

Fig. 10: Screen shots of the android App which is capable of performing experiments on its own. It connects to the sensors using Bluetooth, collects the data and then processes it locally to get the final results.

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