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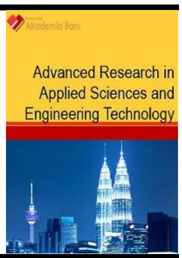

A Preliminary Study on Gait and Motion Analysis for Rehabilitation Applications

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ABSTRACT

Human gait analysis is an extensively studied research area since it provides important information for various health related and rehabilitation applications. Application of gait analysis ranges from diagnosis, monitoring, sports activities and early detection of potential hazards such as human fall. There are various types of approaches used in gait analysis including wearable, ambient and vision based devices. Among them wearable based devices is an inexpensive approach, though it requires additional resources and time for setup each time a gait analysis is required. A non-invasive approach could save lot of nursing and additional resources and indeed give more accurate useful information for gait analysis such as using Microsoft Kinect sensor since it can give depth and normal color images as well. This paper presents a preliminary study on gait analysis which can be applied to various rehabilitation application. The measurements taken includes step width, step lengths, stride lengths, arm spread, trunk sway and angles of knee with respective to hip and ankle while walking. The preliminary results showed that the approach could compute the same parameters as that of the wearable based devices with low error rates.

1. Introduction

Gait and motion analysis is a key area of research in the field of biomedical engineering and rehabilitations applications. There are basically two approaches used to gather information for gait analysis, namely using wearable sensors and non-invasive devices. Wearable sensors were the most commonly used approach and there are various studies conducted with different sensors such as accelerometers, gyroscopes, flexible angular sensors and electromagnetic tracking systems. Nevertheless, all the approaches are aimed to identify common gait parameters such as stride and kinematics information to apply into the field of rehabilitation and injury prevention. This includes identification of pathological posture and movements, pre- and post-treatment efficacy assessment, early detection of disorders and wellness and safety sports. The use of wearable or integration of

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ambient sensors are very conventional, however they are not adaptable due to the wearing difficulties, setup time, requirement of additional staffs and resources. At the same time, such approaches used to generate false measurements unlike vision based sensors [1 - 3]. This study aims to propose a completely non-invasive approach to generate the same parameters as that of the wearable sensors using Microsoft Kinect Sensor. This paper extends the methodology in [1] to perform a complete gait analysis by considering the upper body movements as well and incorporating the fall risk level identification parameters in [4].

2. Related Works

There are plenty of studies carried out with different types of sensors to obtain accurate gait information for the required application. This section will only highlight few of such works that employed non-invasive approach. Some of the studies were committed to specific disease such as the study presented by Procházka et al., uses data from Kinect sensor to recognize gait features and for the detection of disorders in movements for people with Parkinson's diseases [5]. The proposed approach uses mathematical model for motion tracking, gait feature selection and classification and for the study of Parkinson's disease. Another study by Galna et al., proposed a method for measuring the clinically relevant movements in Parkinson's disease patients using Kinect sensor. The results of the proposed method showed that the sensor employed was accurate in measuring the timing and gross spatial characteristics of clinically relevant movements, even though it couldn't achieve that accuracy in classifying minor movements like hand clasping and toe tapping [6].

Studies that is based on identification of gait parameters in real time such as the approach presented by Jiang *et al.*, [7] used length of bones and the angles of joints. This Kinect sensor based approach used two features and on this basis they made feature fusion and store feature vector into their own database to apply nearest neighbour classifier. The two features are namely as static feature (length of the bones) and dynamic feature (angles of swing legs and arms) [7]. Similarly, Gabel at el., presented a non-intrusive and accurate gait analysis system using Kinect sensor to extract gait information and measurements including standard stride information, arm kinematics and other parameters [8]. Another study conducted by Preis et al presented an approach for gait recognition based on Kinect sensor for skeleton detection and tracking in real time. This study evaluated few body features together with step length and speed, their relevance for person identification [9].

Alternatively, Bonnechere *et al.*, [10] conducted a study to evaluate the validity and reproducibility of Kinect sensor by using a marker-based stereophotogrammetry system as a reference. The results for reproducibility were statistically similar to results from stereophotogrammetry for four exercises [10]. Stone E.E. and Skubic M also conducted an evaluation of Kinect sensor for passive human fall risk assessment in home environment. They basically evaluated the use Kinect sensor for gathering measurements of temporal and spatial gait parameters with Vicon motion capture system [11].

One study also presented a robotic system using Kinect sensor monitoring human gait during normal activities of daily life. Together with this they also presented a study of the robot's accuracy in calculating the parameters required for human fall detection when compared to vicon motion capture system [12].

There were two related studies that conducted a comparison between two non-invasive sensors for its accuracy in gait analysis. The first study presented a comparison between pose estimation from Kinect and with other established motion based techniques for pose estimation. They examined the effectiveness localization of joints and estimation of pose with respect to orientation and occlusion [13]. The other study demonstrated a comparison of motion tracking performance between Kinect sensor and OptiTrack optical system. The experimental results from the study conducted showed that in terms of motion tracking, Kinect sensor was able achieve a competitive performance as of OptiTrack and also provide “pervasive” accessibility that can enable patients for rehabilitation treatment in clinic or at home [14].

3. Method

The method proposed in this study uses Kinect data stream to identify the joint position for the analysis of human movements. The algorithm uses the extracted position of joints and measurement of bone from joint to joint, since these are the parameters that constantly changes and which can distinguish human characters according to anthropometry. This paper performs a lower body analysis from leg joint movements and demonstrates an upper body analysis for movements of arm and hip only. This is because lower body analysis is more applicable in many rehabilitation applications. For this, the analysis will be conducted on, step width, step length, step time, stride lengths, stride duration, walking speed and step frequency in steps per minute. The upper body analysis will consider arm spread and trunk sway.

Gait analysis is used to identify the abnormalities in normal gait cycle which depends on various biomechanical features controlled by the nerves system [15]. They are defined as the determinants of gait which consists six variables [16] responsible for maintaining locomotion by reducing the vertical Center of mass (COM). A gait cycle is the time-period of movements when any one-foot contacts the ground to the time when the same foot contacts the ground again or simply a stride whether it is from left or right foot. A stride is the distance between two consecutive initial contacts of the same foot on the ground. A complete gait cycle consists of two phases, namely the time-period when the given foot remains in contact with the ground (stance phase) and the time-period when the same foot is not in contact with the ground (swing phase). The movements during these phases can be further separated into different parts to better understand the actions and for easy identification and classification of the complete gait cycle. For simplification of the gait analysis the proposed methodology divides the complete cycle into four main postures in a way that it will cover the major parts of the gait cycle. The following figure illustrates the chosen postures of the lower body together with the angles used to identify the postures.

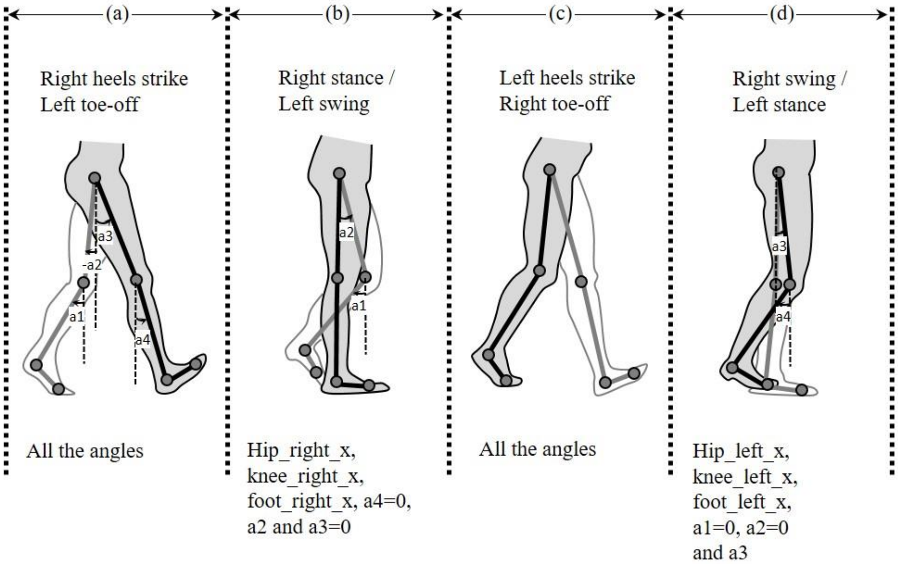

Fig. 1. Postures Representing the Complete Gait Cycle

These postures are identified by considering the position and the angles between the joints [17]. The angles and the position of the joints required to identify any posture is described just beneath it. The position of the mentioned joints is used to find which limb is at stance. It is assumed that at stance the hip and the respective knee and foot will be aligned. The angle (a1) is formed between the right knee and right ankle, assuming that the right knee is the center of rotation. The angle (a4) is the same angle formed between the left knee and the left ankle, where the center of rotation is at left knee. The angle (a2) and (a3) is the angle formed between hip center to right knee and hip center to left knee respectively, where the center of rotation is at hip center. It was assumed that the two joints (the joint representing the center of rotation and the 'other' joint) will form a right-angled triangle. The angles mentioned are supposed to change as the 'other' joint moves by keeping the joint representing the COM at stationery point. At a point, the angle will be zero and will again increase as the 'other' joint moves after crossing the center line. These angles are especially helpful to measure the amount of spread between the two limbs.

For the calculation of the angles, adjacent and the opposite of the right-angled triangle formed was used. Adjacent was calculated by subtracting the y-value of the two joints forming the triangle and opposite is the difference of the x-value of the two joints. The tangent formula for right-angled triangle was used where tangent of the angle is equal to the division of opposite and adjacent.

$$\text{a1} = \tan^{-1}\left(\frac{R\_k_X - R\_a_X}{R\_k_y - R\_a_y}\right) \quad (1)$$

$$\text{a2} = \tan^{-1}\left(\frac{H_X - R\_k_X}{H_y - R\_k_y}\right) \quad (2)$$

$$\text{a3} = \tan^{-1}\left(\frac{H_X - L\_k_X}{H_y - L\_k_y}\right) \quad (3)$$

$$\text{a4} = \tan^{-1}\left(\frac{L\_a_X - L\_k_X}{L\_a_y - L\_a_y}\right) \quad (4)$$

Here, R_k, R_a, H, L_k and L_a are right knee, right ankle, hip center, left knee and left ankle respectively. The subscripted x and y refer to x-coordinate value and y-coordinate value respectively.

Once the posture is identified, the parameters required for the fall risk assessment were computed. For the analysis of human movements, measurement from joint to joint is used, since these are the parameters that constantly changes, and which can distinguish characteristics of human activities according to anthropometry. Some of the analysis to be conducted are, step width, step length, step time, stride lengths, stride duration, walking speed and step frequency in steps per minute. These variables can also be categorized into spatial (those concerned with distance) and temporal (those concerned with time) variables.

The spatial variables are computed using the following equations if the direction of the movement is across the sensor. The x and z values in each of the equations will be interchanged if the direction of the movement is horizontal (going far or coming close) to the sensor.

$$\text{Step width} = P\_R_z - C\_L_z \quad (5)$$

$$\text{Left step length} = C\_L_X - P\_R_X \quad (6)$$

$$\text{Right step length} = C\_R_X - P\_L_X \quad (7)$$

$$\text{Left Stride length} = C\_L_X - P\_L_X \quad (8)$$

Right Stride length = $C\_R_X - P\_R_X$ (9)

Here Rz, Lz, Lx and Rx are z value of right foot, z value of left foot, x value of left foot and x value of right foot respectively. The prefix C and P means current frame value and previous frame value respectively.

In case, if the direction is vertical to the sensor then the following equations are applied.

$$\text{Step width} = \sqrt{\left(R_y - L_y\right)^2 + (R_X - L_X)^2} \quad (10)$$

$$\text{Left step length} = \sqrt{(stepwidth)^2 + \left(\sqrt{\left(C\_L_y - P\_R_y\right)^2 + (C\_L_X - P\_R_X)^2}\right)^2} \quad (11)$$

$$\text{Right step length} = \sqrt{(stepwidth)^2 + \left(\sqrt{(C\_R_X - P\_L_X)^2 + \left(C\_R_y - P\_L_y\right)^2}\right)^2} \quad (12)$$

$$\text{Left stride length} = \sqrt{(C\_L_X - P\_L_X)^2 + \left(C\_L_y - P\_L_y\right)^2} \quad (13)$$

$$\text{Right stride length} = \sqrt{(C\_R_X - P\_R_X)^2 + \left(C\_R_y - P\_R_y\right)^2} \quad (14)$$

Here Ry, Rx, Ly and Lx are the y coordinate of right foot, x coordinate of right foot, y coordinate of left foot and x coordinate of left foot respectively. The prefix C and P is meant for current frame value and previous frame value.

The angles and the identified postures are used to compute other variables such as step frequency (cadence), step time, and stride duration. Step time is the time difference between any successive instance of the feet and floor contact of the opposite feet. This is calculated from the same loop used in step frequency calculation, except here the frame difference between two immediate step hit is multiplied by two to state the step time in second. Similarly stride duration, which is the time difference between successive instance of the foot and floor contact of the same foot can also be calculated. This was calculated in a different loop since stride duration can go beyond one seconds but the concept used is the same except that the frame gap between two successive left and right foot is extracted and multiplied by two for left stride and right stride duration respectively.

Walking speed is computed by considering the movement of hip center with respective to time. More preferably, the gait speed can be easily calculated by multiplying the average step length and step time. If the subject is walking across the sensor then the x-coordinate is more practical to calculate the distance travelled and z-coordinate if the subject is going far or coming close to the sensor horizontally. In case, for vertical movements the distance travelled can be calculated using the Equation 15. Once distance travelled is calculated, the speed can be computed by dividing it over the time taken.

$$\text{Vertical movements} = \sqrt{\left(Current_{hip\_x} - Previous_{hip\_x}\right)^2 + \left(Current_{hip\_y} - Previous_{hip\_y}\right)^2} \quad (15)$$

Here hip_x and hip_y are the x coordinate and y coordinate of hip center respectively. Current and Previous is to denote current and previous frame.

Stance duration is the time when the given foot is in contact with the floor and the swing duration is the time when the foot is not in contact with the floor. These two parameters can be easily calculated by considering the postures in Figure 1, as it shows the major parts of the gait cycle, the two phases can be separated, and time duration calculated for each phase. In this way, stance duration can be simply calculated by measuring the time taken for the first three postures and the time taken for the last posture will be the swing duration. The time taken for each of the posture can be calculated by counting the number of frames passed to get the new posture over the total number of frames per second. Apart from the spatial and temporal variables, the positional information required are the height of hip, knee and position of foot. Step symmetry is also an important parameter for gait analysis as it estimates the step inequality. This parameters is computed by measuring the left and the right step lengths where the step lengths are the distance between left and right step. Step length is measured using x-axis and z-axis coordinates depending on the direction of the movements. If the direction of the movement is on x-axis then the following equation is used and if the direction of movement is on z-axis then z-values are used instead of the x-values.

$$\text{Step\_symmetry} = \left(x_{R\_foot} - x_{L\_foot}\right)_{PF} - \left(x_{R\_foot} - x_{L\_foot}\right)_{CF} \tag{16}$$

Here, R_foot is the right foot, L_foot is the left foot, x is the x-value or x-axis coordinate value, PF is the previous frame and CP is current frame.

The two parameters used for the analysis of upper body are trunk_sway and arm_spread. Trunk_sway measures how far the subject bends from side to side. It is computed from changes in the torso position with respective to the hip position. This variation can be calculated by taking x-axis values, if the direction of the movement is on z-axis as shown in the following equation 17 and using z-axis values instead of x-values if the direction of the movement is on x-axis.

$$\text{Trunk\_sway} = \frac{\left(Torso_x - \left(\frac{L\_hip_x + R\_hip_x}{2}\right)\right)_{PF} + \left(Torso_x - \left(\frac{L\_hip_x + R\_hip_x}{2}\right)\right)_{CF}}{2} \tag{17}$$

Here, L_hip is the left hip position and R_hip is the right hip position. Spread_arm is a measure of how much the two arms are spread. This parameter gives important information on physical strengthens, since during a loss of control of the body due to slip or any other fall like event, it is normal to spread the arms to balance the body, especially common among elderly and people with weaker gait. This parameter is computed by taking the difference of torso position and the two (left and right) arms. Similar to Trunk_sway, spread_arm is also calculated from x-axis if the direction of the movement is on z-axis using the formula in the equation 18 and using z-axis values instead of x-values if the direction is on the x-axis. The average of the distance of the two arms to the torso were threshold between the frames to identify any action where the subject is spreading the arms to balance the body or trying to hold something to control the body.

$$\text{Spread\_arm} = \left(\frac{\left(Torso_x - R_{arm_x}\right) + \left(Torso_x - L_{arm_x}\right)}{2}\right)_{CP} - \left(\frac{\left(Torso_x - R\_arm_x\right) + \left(Torso_x - L\_arm_x\right)}{2}\right)_{PF} \tag{18}$$

Here, *R_arm* is right elbow joint and *L_arm* is the left elbow joint.

4. Results and discussion

The preliminary testing showed promising results in computing the parameters for gait analysis. Several activities were simulated to measure the accuracy of the algorithm. Experimental data were collected on a lab environment with footsteps and measuring tape as shown in Figure 2. Footsteps and measuring tapes were used to compare the actual values of different parameters with the generated values and to find important thresholds. This also help to identify key distinguishing characteristics of different movements. Different experimental environments were also used to assess the ability of the proposed system to handle obstacles blocking the view of the subject.

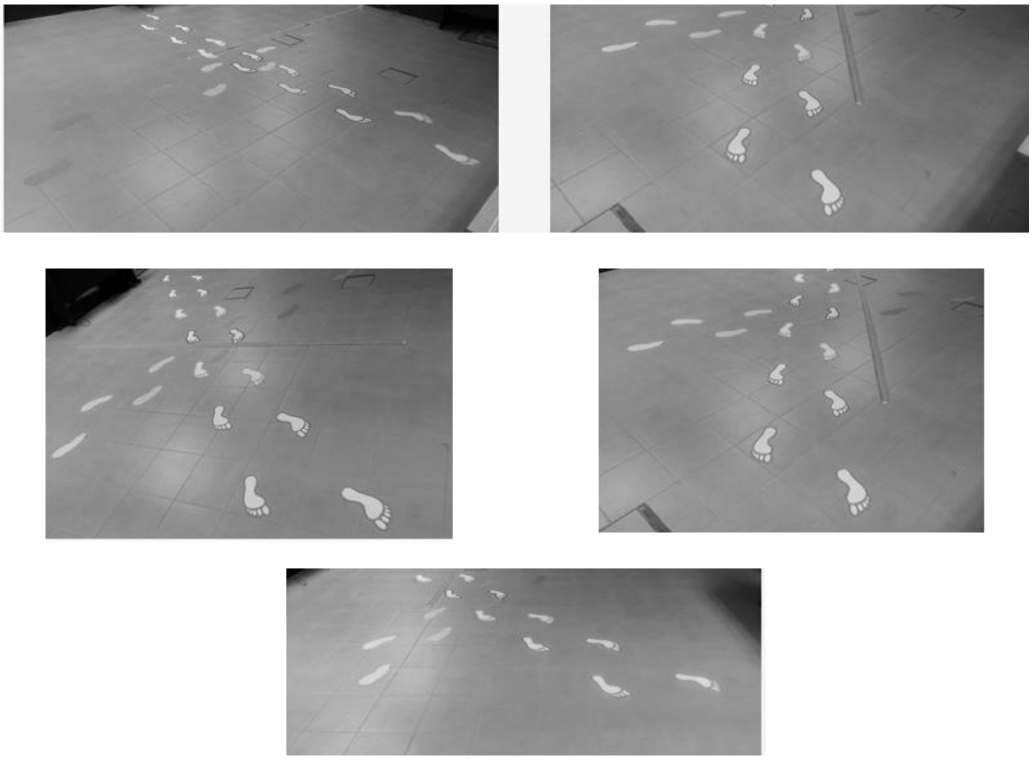

Fig. 2. Experimental setup

Walking in different direction were simulated to validate the proposed algorithm as most of the gait parameters were extracted from walking. The table 1 shows the actual and predicted number of steps together with accurately detected number of steps for walking into two directions for three meter. The first column shows the actual number (average of three simulation) of footsteps placed during the experimental walking on each of the directions (across the sensor and vertical to the sensor). The predicted number of steps for each walking experimental is shown in the second column of the Table 1. They are measured by dividing the distance travelled for each of the experiment over the average step length computed (generated by the system from that experiment). The last column shows the number of steps detected by the system for each of the experiments. For walking across the sensor, the system accurately detected all the right and left steps when round-off to a whole number. For experiments on walking vertical to the sensor, the system detected all right steps and failed to classify all left steps. In-terms of the predicted number of steps, the average error for walking across and vertical is 13.63 percentage and 15.18 percentage respectively.

Table 1
Actual and predicted number of steps with accurately detected steps

	Actual no of steps		Predicted no of steps		Accurately detected steps	
	Left	Right	Left	Right	Left	Right
Across	5	6	5.67	6.83	5	6
Vertical	5	6	6	6.67	6	6

The step length and the time taken for the steps also gives important information for the classification of fall risk levels. It was observed that the time taken for the right steps are more than the left steps. This is because the subject is more confident when the weight is loaded on the right leg, since subject is right handed. The time taken to place the first step was also higher and it was then maintained at an equal amount between the two sides. The following figure shows the step lengths for the two legs, stride length and the respective step size for a sample of simulated walking. The first part of the figure shows the left and right stride length together with the average step size for each stride (two step lengths). The average error for all the identified step lengths are also plotted in the same figure. The second part of the figure shows the average step lengths for the respective stride length together with the respective average stride length (left and right stride length).

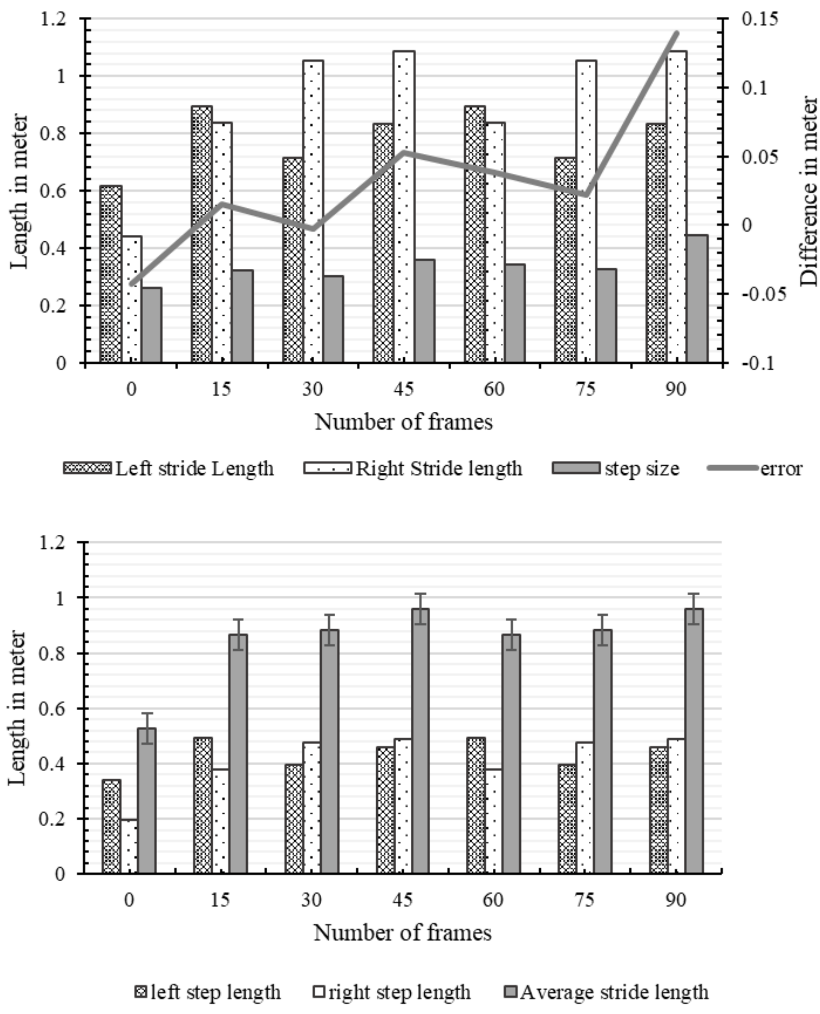

Fig. 3. Step and stride measurements with the step size from a single sample

5. Conclusion

This paper demonstrated the use of Kinect sensor for gait analysis towards rehabilitation applications. The methodologies employed used the common parameters as that of the other approaches and validated the accuracy of the proposed approach in performing the same gait analysis non-invasively. The results showed promising performance as similar to other conventional approaches and thus eliminating hassles involved for the setup of the analysis and reduce the requirement human resources. Since this is just a preliminary study and there are significant improvements and enhancements needed for an accurate gait analysis so that it can be applied in any of biomechanical application reliably.

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