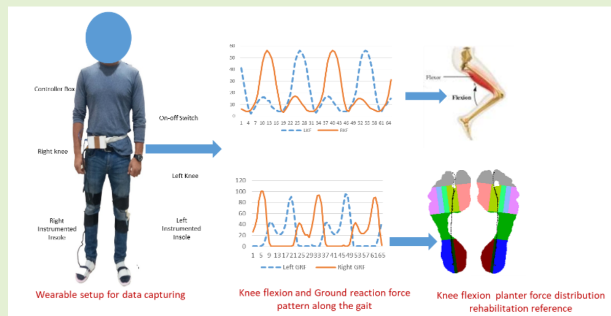
Gait Abnormality Detection in Unilateral Trans-Tibial Amputee in Real-Time Gait Using Wearable Setup

Radheshyam Rathore, Amit Kumar Singh, Himanshu Chaudhary, and Karthikeyan Kandan

***Abstract*—The presented study proposes a novel approach to detect gait abnormalities in unilateral trans-tibial (TT) amputees using a wearable setup. The system uses force-sensitive resistors and potentiometers to collect data on the user's gait patterns. A machine-learning algorithm based on Extreme Learning Machines is utilized to classify the gait patterns as normal or abnormal. The system is evaluated on a dataset of healthy and unilateral TT amputees, and the results reveal that the ELM-based classification technique achieved high accuracy, sensitivity, specificity, and *F*1 score. The proposed wearable gait setup is tested by conducting a standard 6-m walk test, and the collected data is segmented into stance and swing phases. The study also compares various gait parameters of healthy and amputated subjects, and the results show significant asymmetry in the amputated subjects. The proposed setup also detects asymmetry in force distribution under each foot. The study's findings reveal that the proposed wearable gait setup is a reliable and effective tool for gait analysis in unilateral TT amputees, and the results are comparable with those obtained using a Vicon gait measurement system.**



***Index Terms*—Data processing, gait analysis, knee flexion, potentiometer, pressure insole, pressure sensors, transtibial (TT) amputation.**

I. Introduction

EXTENSIVE research has been done on multisensor-based biomechanical gait analysis using vision and wearable sensors [1], functional demands on the intact limb during walking for active trans-femoral and trans-tibial (TT) amputees [2], [3], osteoarthritis and elderly amputee gait [4], compensatory mechanisms in below-knee amputee gait in response to increasing steady-state walking speeds [5], and the biomechanics of below-knee amputee gait [6]. Other studies have focused on evaluating specific prosthetic components, such as prosthetic foot kinematics [7], dynamic elastic response prosthetic feet [8], and the effects of different socket types on prosthetic fitting and rehabilitation [9]. Additionally, studies have explored the effects of gel liner thickness on gait biomechanics and pressure distribution within the TT socket [10], [11]. With the promise that its full contact reduces pistoning when walking, the total surface bearing (TSB) socket was presented as a revolutionary design [12], [13]. The effect of prosthetic liner thickness on the gait of TT amputees was also studied, and it was shown that liner thickness may change some aspects of gait [14], [15]. Stride segmentation of inertial sensor data using statistical methods for different walking activities [16] provides stability analysis of joint trajectories [17] toward developing a computational model for bipedal push recovery [18], and design of vector field for different subphases of gait and regeneration of the gait pattern [19]. Various studies on data-driven computational model for bipedal walking and

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Malaviya National Institute of Technology (MNIT), Jaipur, Ethics Committee.

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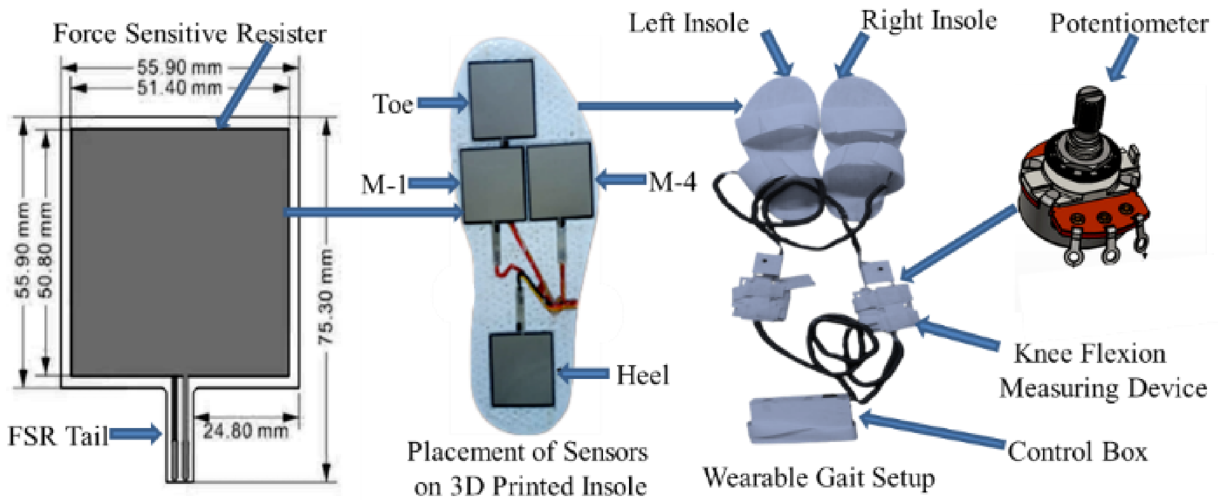


Fig. 1. Description of wearable gait setup and sensors placement location.

push recovery applications [20], in clinical human gait classification using extreme machine-learning approach [21]. An optimized hybrid deep-learning model using ensemble learning approach for human walking activities recognition was used in past research [22]. Fusion of multisensor-based biomechanical gait analysis using vision and wearable sensors [23], in bidirectional association of joint angle trajectories for humanoid locomotion using the Boltzmann machine approach [24], speed-, cloth-, and pose-invariant gait recognition-based person identification [25], occluded gait reconstruction in multiperson gait environment using different numerical methods [26], for the development of universal polynomial equation for all the subphases of human gait [27], and modeling bipedal locomotion trajectories using hybrid automata [28]. Method such as pattern identification of different human joints for different human walking styles using inertial measurement unit (IMU) sensors [29], and biometric gait identification based on a multilayer perceptron [30] were reported in few researches. Most studies on movement asymmetry in lower limb amputation have concentrated on local gait characteristics such as weight transfer during stance, generation of ground reaction forces, step time, and step length. The effects of asymmetries in amputees have typically been studied during linear walking.

II. Methods

Plantar force distribution was measured using four lexi-force sensors. Based on biomechanical considerations, these sensors were placed on the first metatarsal head (Meta1), fourth metatarsal head (Meta4), hallux, and heel.

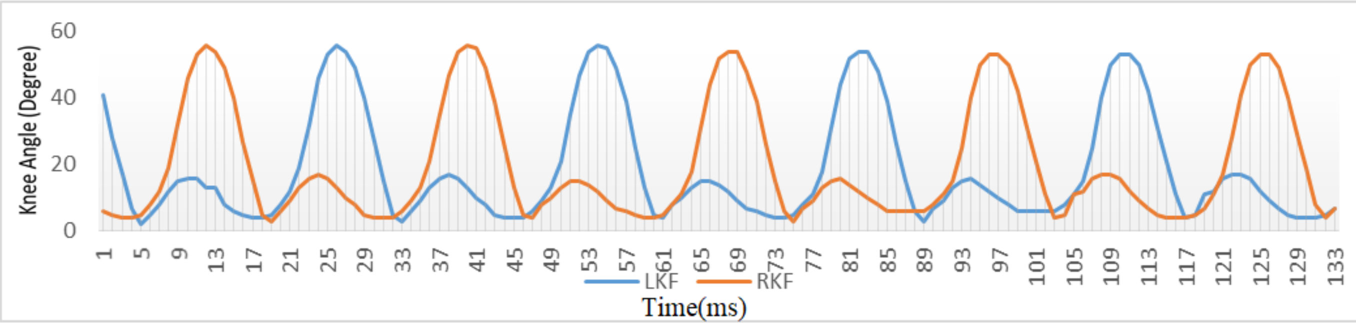
A. Participants

The study involved 66 participants, including 40 healthy individuals (34 males and six females) and 26 unilateral TT amputees (18 males and eight females). All participants provided voluntary informed consent, and amputated subjects met the following criteria: wearing a prosthesis for at least two years and using it for at least 6 h per day, being moderately active community ambulators, not using upper extremity aids, having no history of falls within the previous 12 months, and being free from neuromuscular disorders that could affect gait characteristics (as self-reported). The participants had a mean age of 35 ± 12 years, a mean height of 1.65 ± 0.08 m, and a mean mass of 75 ± 11 kg. All amputee participants used total contact patellar tendon bearing sockets and rigid pylons. Prosthetists provided expert opinions to determine the optimal prosthetic foot and ankle prescription for each participant based on their functional requirements, to maintain clinical relevance.

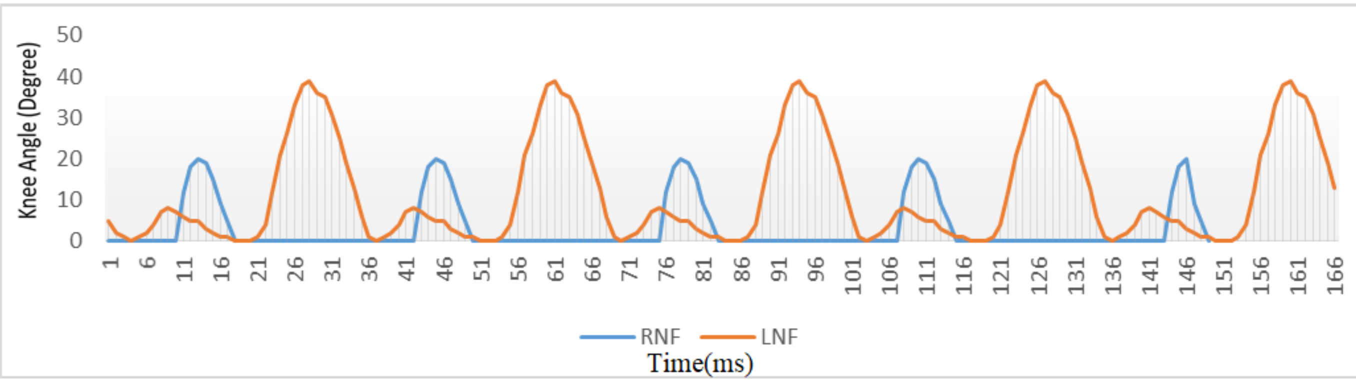
Fig. 2. Unilateral TT amputee wearing gait analysis setup.

B. 6 m Walk Test

The 6-m walk test was conducted using a method adapted from a previous study [31]. A straight walkway of 10 m was



(a)



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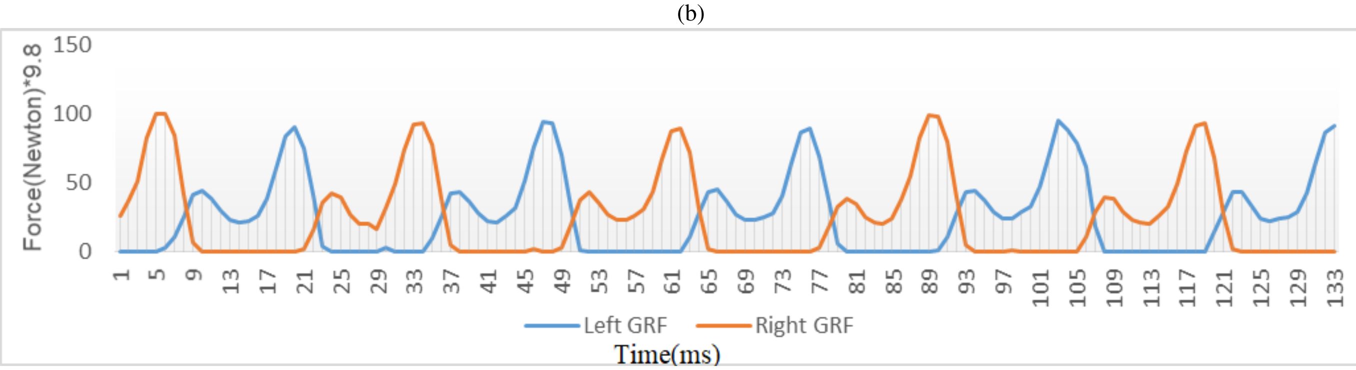
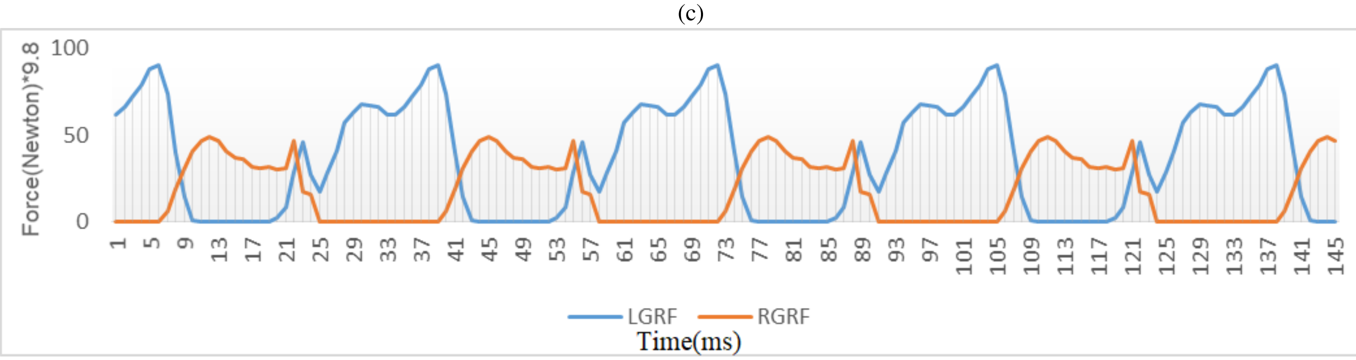


(c)



(d)

Fig. 3. Real-time gait analysis output for left and right leg knee flexion and planter force for healthy and amputated subjects. (a) Real-time gait analysis output for left and right leg knee flexion of a healthy subject. (b) Real-time gait analysis output for left and right leg knee flexion of a unilateral trans-femoral amputee. (c) Real-time gait analysis output for left and right leg total ground reaction force of a healthy subject. (d) Real-time gait analysis output for left and right leg total ground reaction force of a unilateral trans-femoral amputee.

marked and divided into four sections: 0–2 m, 2–8 m, 8–10 m, and beyond. Subjects were given the first 2 m to accelerate to their normal walking speed, and the last 2 m to decelerate, while the 6-m distance was used for data collection. The timer started when the heel of the subject's reference leg touched the 2-m mark and stopped at the 8-m mark. Two cones were placed at the ends of the walkway, and lime powder was used to mark the sides of the walkway to guide the subject's path. Participants were instructed to walk at their normal speed and to rest if they experienced any discomfort during the trial.

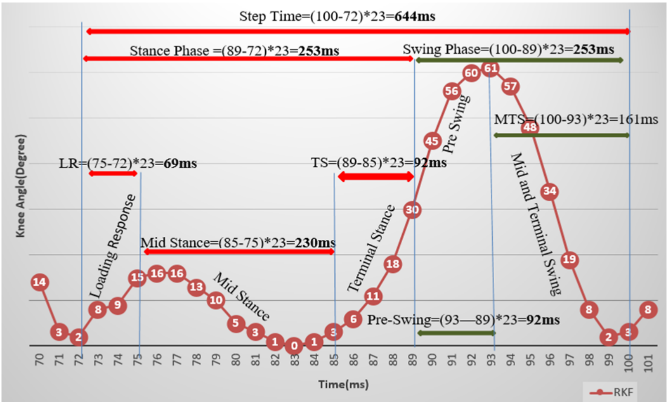


Fig. 4. Gait data segmentation into various gait phases.

10 min of practice time was given before the start of the six trials. Gait parameters were measured for each trial, and the average of these parameters was used to establish normative gait parameters for healthy subjects.

C. Wearable Gait Analysis Setup and Data Acquisition

The footbed was fit with force-sensitive resistors, with dimensions of 55.90 × 55.90 mm^2, a tail length of 10 mm, a tail width of 11 mm, and a measuring range of 0–100 kg. To ensure accurate temporal information and angle displacement, it was important to position the sensors precisely beside the joints. A specialized method was developed for this purpose. Two Burster potentiometers were used to measure the knee and hip angles and were integrated into the setup shown in Fig. 1. The length of the setup could be adjusted to accommodate variations in thigh and shank length. The hardware system, including electronics and a backpack, had a total weight of 1.3 kg. Fig. 2 shows a unilateral TT amputee wearing prostheses and gait analysis setup.

D. Data Smoothing

The algorithm first creates an array that can store ten readings from the analog sensor. As each new reading comes in, it is added to the array, replacing the oldest reading. Then, the algorithm generates the sum of all the numbers in the array and divides it by ten to produce an average value. This value is used to smooth out any outlying data. Unlike other methods that wait for a certain number of readings to accumulate before calculating the average, this algorithm calculates the running average with each new value added to the array, which means there is no lag time.

E. Gait Parameter Calculation

The measurement system used to monitor the gait cycle provided valuable information. Fig. 3 illustrates the experimental data obtained from the plantar force distribution during the stance phase of the gait cycle. Initially, when the movement begins, the heel bone strikes the ground, resulting in the weight being concentrated on the heel. This causes the sensors on the heel to exhibit the highest force values. As the loading response occurs and the foot becomes flat, the entire body weight is transferred to the reference foot, which results in more force being exerted on it. The pressure on the forefoot sensors increases while the heel maintains high pressure. The midstance event occurs when the reference foot is in complete contact with the ground, which means all sensors are exposed to force. When the heel lifts off, all body weight is based on the toes, with the maximum force being exerted on the big toe. This phase occurs in 30–50.

TABLE I
PERFORMANCE INDEX

Performance Metric	Value
Accuracy	92.3%
Sensitivity	93.2%
Specificity	91.4%
F1 Score	92.4%

F. Graphs for Sagittal Knee Flexion and Total Ground Reaction Force for Healthy Subject

A group of 12 individuals between the ages of 25 and 30, who were both physically and mentally healthy, were selected from a pool of students and colleagues. Each subject's comfortable walking speed was reported, and they were then asked to walk on a 10 m straight path. However, due to poor signal-to-noise ratios (SNRs) in the raw data, the amplitudes of the Flexi-force sensors were decreased after being processed with an inverse Chebshev filter. Additionally, all signals were time-shifted. The filter enhanced the SNRs of the force sensors from an average of 6.95–10.15 dB. Despite the time shift and amplitude reduction, the data's temporal correlations remained unaltered, thus the gait analysis results were not impacted. The initial contact (Icontact) and toe off (Toff) detection, which is the first step in gait analysis, was carried out as described in Fig. 4. Fig. 3(a) and (b) demonstrates a sample of the knee flexion, with the right knee flexion signal shown as a red solid line and the left knee flexion signal displayed as a blue line. On the other hand, Fig. 3(c) and (d) shows a sample of the outcomes, with the right foot GRF signal shown as a red solid line and the left foot GRF signal represented by a blue line.

G. Joint Angle Calculation

The proposed setup captures knee joint flexion by measuring the sensor voltage output and changing the sensor value into flexion angles of the knee joint. The Rotary potentiometer sensor is used. The sensor is a passive device that changes its resistance due to the rotation of the shaft; the sensor produces a voltage output correlated with the rotation angle—the higher the rotation angle, the higher the voltage value. The sensor was connected to Arduino, one of the ends is given +5VDC supply and another is grounded. This is a connection that provides a simple way to convert a change in resistance into a dc voltage level. The output voltage V_{out} is the voltage drop across R_2. By applying Ohm's law to the series combination of R_1 and R_2, the commonly used equation for the voltage output of a voltage divider is shown in (1) and (2) shows knee flexion angle calculation from the voltage output

$$V_{out} = (R_2/(R_1 + R_2))V_{in} \tag{1}$$
$$V_{out} = (0.0225\theta + 2.3445). \tag{2}$$

TABLE II

DETECTED DISTRIBUTION OF GROUND REACTION FORCE, SPEED, CADENCE, AND KNEE FLEXION FOR NORMAL SUBJECTS AND AMPUTEE

Gait parameters	Side	Mean values for healthy subjects	Asymmetry	Peak value for amputated subjects	Asymmetry
Peak ground reaction force	Left	65.08	0	79	60.7
	Right	65.08		48	
Peak ground reaction force at toe	Left	30	0	75	59.2
	Right	30		16	
Peak ground reaction force at heel	Left	24.5	0.25	48	31.3
	Right	24.75		35	
Peak ground reaction force at Meta1	Left	13.92	0	40	46.5
	Right	13.92		25	
Peak ground reaction force at Meta4	Left	9.99	0.01	22	83.3
	Right	10		12	
Speed, cm/s	Left	246.33	0	220.72	0
	Right	246.33		220.72	
Cadence, step/min	Left	127.75	0	110.23	0
	Right	127.75		110.23	
Peak knee flexion	Left	47.42	0.09	42	70.9
	Right	47.33		20	

H. Asymmetry Calculation

Assuming that $X_R < X_L$, where X_R and X_L are the values of the specified parameter for the right and left limbs, the factors were calculated using the following equation:

$$\text{Asymmetry Index} = |X_L - X_R|/0.5(X_L + X_R) * 100. \quad (3)$$

1) Asymmetry Index: A way of calculating the percentage difference between the kinematic and kinetic characteristics for both lower limbs when walking is the SI factor. SI = 0 denotes complete symmetry, whereas SI > 0 denotes its asymmetry [32]. The gait symmetry technique that is most often used and mentioned is the SI index. The symmetry index was calculated for stride length, step length, speed, peak knee flexion, cadence, peak ground reaction forces at the toe, peak ground reaction forces at meta1, peak ground reaction forces at meta4, and peak ground reaction forces at the heel for the amputee's normal and abnormal limb. If the symmetry index was found more than zero, then the gait obtained for amputated subjects is not symmetrical chance but they have gait abnormality.

I. Performance Index

The performance of the ELM-based classification technique was evaluated using several performance metrics, including accuracy, sensitivity, specificity, and $F1$ score. The results of the evaluation are presented in the following Table I.

Table I shows that the ELM-based classification technique performed well in detecting gait abnormalities in unilateral TT amputees. The accuracy, sensitivity, specificity, and $F1$ score were all above 90%, indicating that the technique is reliable and accurate. The high sensitivity and specificity suggest that the technique is capable of detecting both true positive and true negative cases with high accuracy, which is essential for effective gait analysis. Overall, the use of the ELM-based classification technique in this study provided a valuable tool for the real-time detection of gait abnormalities in unilateral TT amputees.

III. RESULTS

Trials were carried out on 34 healthy and 24 TT amputees with their written consent. Table II shows plantar force distribution of both left and right legs at the plantar surface at four sensors locations, that is, toe, heel, Meta1, and Meta4. This table shows peak values during one complete gait cycle for all subjects. The trial shows that the average peak of total ground reaction force is 65.08 ± 3.40, the peak ground reaction force at the toe is 30.00 ± 0.3.72, the peak ground reaction force at the heel is 24.75 ± 6.01, the peak ground reaction force at Meta1 is 13.92 ± 0.09, the peak ground reaction force at Meta4 is 9.92 ± 1.00, speed is 246.33 ± 6.88 cm/s, cadence is 127.75 ± 0.09 step/min, and the average peak knee flexion is 47.42 ± 1.31. The distribution of plantar force at the knee joint during flexion in the sagittal plane was analyzed using the two methods. Plotting the trajectories of time versus plantar force is the last step in measuring stability, which demonstrates that the walk was stable. The knee joint moves least during toe-off and heel strike and more during the stance phase.

IV. DISCUSSIONS

Compared to healthy people, TT amputees walk differently. The undamaged limb is thought to experience more loading as a consequence. Amputees use a variety of strategies to make up for their loss, including slower walking, stronger knee and hip joints, and larger ankle range of motion on the healthy limb [33], [34]. According to the research, the asymmetry in an amputee's gait shortens their time in stance as well as their ground response forces when compared to a healthy limb [35], [36], [37]. A healthy person's gait velocity ranges from 1.2 to 1.5 m/s [38], [39]. In addition, other investigations [40], [41], [42], [43] showed that TT amputees walked more quickly than we did.

V. CONCLUSION

In this study, the individual who had a unilateral TT amputation showed a pattern of unevenly distributed plantar pressure and GRF. Plantar force distribution, space–time foot roll-over, and GRFs were different in the individual with TT amputation's amputated limb than they were in the subjects who were in good physical condition. In comparison to the healthy limb and able-bodied groups, the severed limb shows a larger participation of the lateral rear foot and medial and lateral mid-foot region and a lower participation of the medial and lateral forefoot, according to the plantar pressure study. Along with heel strike and toe-off events for all trials, the average step length is 0.60 ± 0.04 m, the average stride length is 1.20 ± 0.05 m, and the average speed is 0.67 ± 0.03 m/s. The average of the peak of total ground reaction force is 65.08 ± 3.40, the peak ground reaction force at the toe is 30.00 ± 0.3.72, the peak ground reaction force at the heel is 24.75 ± 6.01, the peak ground reaction force at Meta1 is 13.92 ± 0.09, the peak ground reaction force at Meta4 is 9.92 ± 1.00, speed is 246.33 ± 6.88 cm/s, Cadence 127.75 ± 0.09 step/min, and the verage peak knee flexion is 47.42 ± 1.31. According to the GRFs, the stress on the healthy limb has greatly risen. The suggested method appears to help people with unilateral TT amputations tell between their lower limbs. The wearable setup seems to be a useful and sensitive piece of equipment for analyzing gait in people who have had limbs amputated.

A. Future Directions

The outcome of this work can be utilized for developing a real-time wearable device for automatic activity and health monitoring devices. It will also help in developing new shoe designs for rehabilitation. The plan of developing the product for automatic real-time gait recognition for analysis of various gait abnormalities such as stroke multiple sclerosis Parkinson's disease, and their surveillance. The study on Gait Abnormality Detection in Unilateral TT Amputee in Real-Time Gait using Wearable Setup opens up various possibilities for future research. One potential avenue for future work could be to investigate the effectiveness of the wearable setup in detecting gait abnormalities in individuals with other types of amputations or disabilities. Additionally, the study could be expanded to investigate the effects of varying speeds, inclines, or terrains on gait abnormality detection. Further research could also explore the potential use of machine-learning algorithms to improve the accuracy of gait abnormality detection. Another possible direction for future studies is to investigate the effect of different prosthetic devices on gait abnormality detection. Furthermore, the study could be extended to larger population size, including individuals with different demographics and gait characteristics. Finally, the application of the wearable setup in real-life scenarios and its impact on the quality of life of amputees could also be explored. Overall, there are many avenues for future research in the field of gait abnormality detection using wearable setups, which could lead to significant advancements in the detection and treatment of gait abnormalities in amputees and individuals with other mobility impairments.

Conflict of Interest

There is no conflict of interest to declare by the authors. The content of the manuscript has been seen and agreed upon by all the coauthors. We certify that the work of this manuscript is original and has not been submitted to any other publication.

Ethics Committee Review

An ethical committee was formulated for the verification of all ethical practices. Based on the ethics committee report it is found that all the ethical practice is followed. No Human and animal are harmed during the gait data-capturing process of the stated project work.

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