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Development of Foot Insole system for measurement of Ground Reaction Forces

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Abstract—

A Foot Insole system is designed and developed, for real time monitoring of ground reaction forces and gait parameters while performing various activities. In this paper, the various activities includes walking, stair ascend and stair descend. Force Sensing Resistors are integrated in the foot insole to capture the required set of data and post-processed. Accelerometer sensors readings are also collected at each step, to analyze the reaction forces at the knee and the ankle joint. The data was captured with 5 healthy subjects, performing the aforementioned activities. The average peak reactive force at the foot and the joints are compared. The reactive forces are higher during stair descend when compared with the reactive forces generated during stair ascend and walking. The paper also highlights the possible application of the developed device in medical and sports related fields.

Keywords— Force Sensing Resistors, Centre of Pressure, Ground Reaction Forces, Gait analysis.

I. INTRODUCTION

Foot biomechanics is the study of relationship between biology of foot and lower leg in relation with physics, i.e., kinetics and kinematics of forces which balances and propels the body weight. The force between the ground and human foot is known as the ground reaction force. It is an important parameter for analyses of abnormalities in walking cycle or gait cycle. Gait analysis is the process by which quantitative information is collected to aid in understanding the gait abnormalities and variations of musculoskeletal activities.

Alongside this the dynamic shift in centre of pressure (COP) is often been used for quantitative assessment of postural control [1]. Previously, the COP was measured by Force platforms [2] due to high accuracy. But the force platforms are not easily portable as they are confined to laboratories and critical maintenance is necessary to use them effectively. This causes restrained access to the force platforms. The sophistication of the system in clinical or sports trials is also very high, making the entire system costly. Moreover, not everyone might have access to these laboratories which makes portable and dynamics response measuring devices a suitable alternative. Recently the insole measurement took off its pace in order to improve the dynamic response of the measuring It can be used for force measurement and can also perform gait analysis. Some examples where the gait analysis is important in the medical and sports field are explained in [3]-[5]. The proposed system in this paper utilises force measuring resistors to measure ground reaction force. In this paper, a method for depicting the trajectory of COP [6] is proposed to estimate the COP data and related physical parameters such as pronation of foot. The ground reaction force measurement is important for treatment of symptoms to diseases. Study already indicates that the ground reaction forces of patients suffering from lower-limb deformities or diseases experience a noticeable deviation in gait pattern and ground reaction forces [7]. The challenges involved in this area includes both mechanical design of devices and the strategies to analyse data. The currently available systems in market or research laboratories are highly complex, costly and vary hugely to meet their independent applications. The developed insole is based on Force sensing resistors (FSRs) integrated to a computer with help of Arduino microcontroller and MATLAB software.

The proposed device, is embedded with five sensors to measure the vertical ground reaction forces, placed over the plantar and metatarsal region of foot. The data is collected during various activities like walking, stair ascend and stair descend. Using CoP trajectory, the horizontal ground reaction forces are calculated. Along the FSRs, the data from accelerometers are collected. The data is post processed, and using the concept of inverse dynamics, the reaction forces at the knee and the ankle joint is calculated. This study could provide a portable and dynamic solution for assessment of gait and other applications.

II INSOLE PROTOTYPE DEVELOPMENT

A. Force Sensing Resistor Calibration

A Force Sensor is defined as a transducer that converts an input mechanical force into an electrical output signal. The Force Sensing Resistor (FSR) is one type of force sensor, which is resistance-based. In these sensors, the electrical resistance varies under tension or compression of the sensor. Force Sensing Resistors are used due to their higher flexibility, smaller size and thickness and low cost compared to the other force measuring sensors. The challenge with the FSR is the calibration, as their response is non-linear. The sensors used in this study are 12.7mm in diameter, 92.25mm in length, and a measuring range of 0-20kg. The sensors circuitry is as shown in Fig. The voltage divider is used to divide the input voltage based on the resistance of each component. The value of force needs to be calibrated to the output voltage. The value of resistance used in this study is 10KΩ.

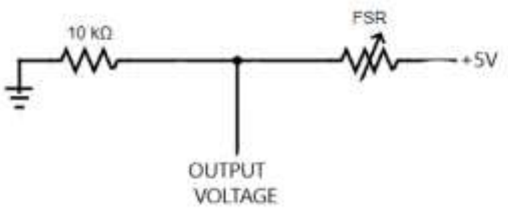

Fig.1 Voltage divider circuit

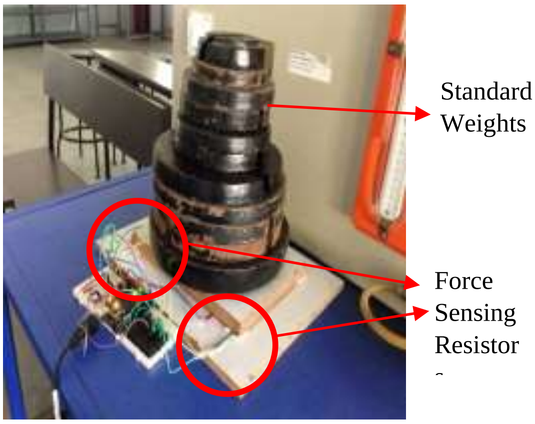

Fig.2. Sensor calibration using standard weights.

The sensors are calibrated using the standard weights from 0 to 20 kg as shown in Fig.2. The corresponding voltage readings for all the weights ranging from 0-20kg in steps of 5kgs is recorded. The force applied (in Newtons) versus the voltage graph is plotted in Fig.3. Since the curve is non-linear, curve fitting can be done to find the equation of the curve that best fits the curve. The equation is used to represent the relationship between the force applied and the voltage in the form V = function (F), where V is the voltage and 'F' is the Force applied in newtons.

Equations with various degree of polynomial are tested, and then the equation with an error percentage of less than 5% is selected. Fig.4. showcase the curve fitting performed on the force vs voltage plot for a FSR sensor. In a similar manner, the curve fitting is performed for all FSR used in the prototype.

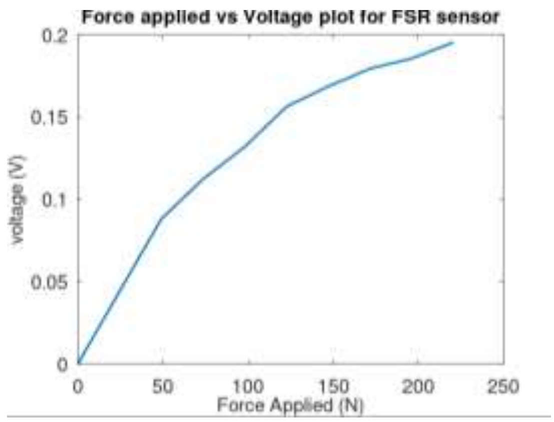

Fig.3. Force applied (in N) versus voltage plots for a FSR sensors during calibration.

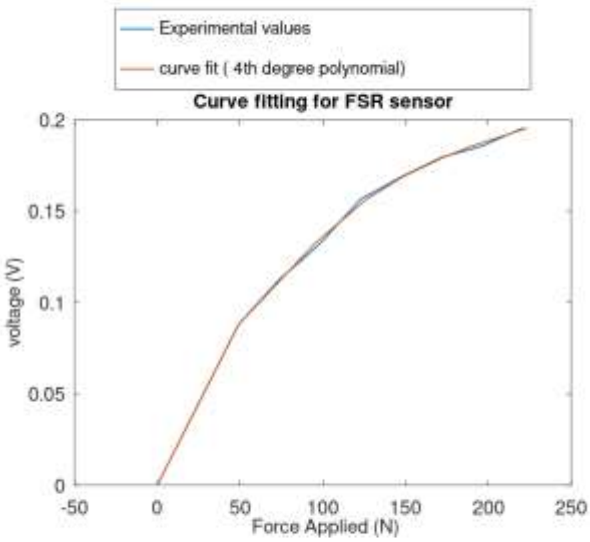

Fig.4. Curve fitting for FSR sensor calibration.

B. Sensor Placement

The sensors were pasted on the insole. The insole consists of a rubber-like fabric and foam which forms the base, conductive thin sheet for pasting the sensors and then covered over with a foam layer. The primary aim in sensor placement, is to design the prototype with minimum number of sensors which are placed at appropriate locations, but at the same time also meet the requirements of the various applications the insole is used for. The anatomy of the foot is studied and the sensors are placed in strategic locations under the foot which comes in contact for longer period of time and also carries most of the load. Small pucks are placed on top of the sensor areas in order to concentrate the force on the sensing areas. Accordingly two sensors were placed in the region of the metatarsal bones, two more sensors at calcaneus region, and one at big toe phalange region.

C. Setup

The setup consists of five force sensing resistors pasted on to the foot insole and two ADXL335 accelerometers located at the centre of mass point of the foot and the shank. These sensors are connected to the Arduino board and the data from the Arduino board is transferred to MATLAB and further post-processing is done to calculate various parameters required in the study.

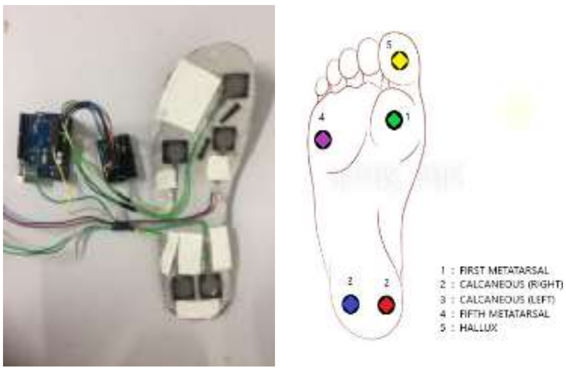

Fig.5. Sensor placement on the foot insole.

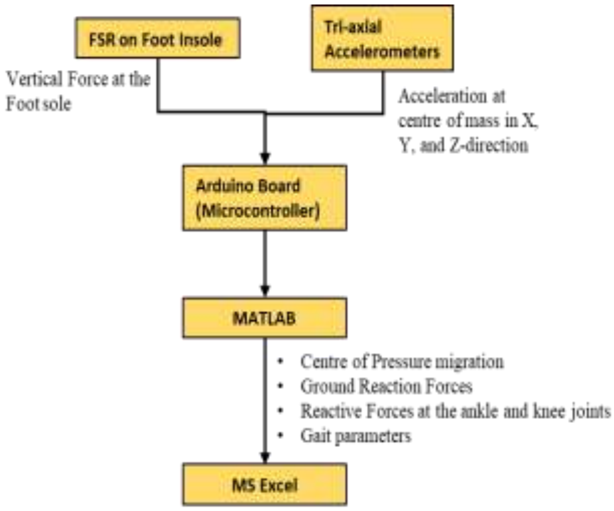

Fig.6. Data flow

Fig.7 Prototype developed

The data is further stored in a MS-Excel file. The data flow is as indicated in Fig.6. This setup is used to perform gait analysis, analyse the percentage distribution of normal forces at the foot sole and also calculate the reactive forces at the knee and ankle joints. The insole is fixed onto a footwear and the accelerometers are accordingly positioned at the centre of mass point of the foot and the shank, as shown in Fig.7.

III. METHODOLOGY

A. Ground Reaction Forces

The ground reaction forces is defined as the forces applied by the ground on the body at the point of contact between the body and the ground. It includes the reaction forces in all the three directions. The foot insole developed can measure the vertical forces applied on it. The horizontal forces are calculated by observing the Centre Of Pressure (COP) migration. The centre of pressure reveals a greater understanding about the dynamics of different joints. The study of COP shift and related mechanics of stance is called as dynamic posturography. The COP is the point of application of the resultant vertical force acting on the body. The shift in COP indicates how we adjust muscles in order to keep the body in balance. The centre of pressure shift in X-axis and Y-axis is mathematically derived based on the insole dimensions and the placement of the sensors. The second derivative of the COP gives the acceleration along the respective horizontal directions. Further multiplying with the mass at every instant, the horizontal forces along the X and Y-axis are thus calculated.

$$F_x = M * \frac{d^2(COP_x)}{dt^2} \quad (1)$$

$$F_y = M * \frac{d^2(COP_y)}{dt^2} \quad (2)$$

The equation (1) is used to calculate the horizontal force along the X-direction, while the equation (2) is used to horizontal forces along the Y-direction. 'M' is the mass acting on the entire insole at very instant of time. COP_x and COP_y are the centre of pressure coordinates in the X-axis and Y-axis respectively.

B. Measurement Of Ankle And Knee Reactive Forces

Along with the ground reaction forces, if the centre of mass of the foot and the leg shank is known, then the reactive forces at the ankle and the knee joints can be calculated. The free-body diagram for this set of calculation is shown in Fig.8. The values of the segment mass and the centre of mass point are taken from [8].

A large number of studies have attempted to estimate forces around the knee during various activities. In this study, the inverse dynamics approach is used to calculate the knee and ankle joint reactive forces. From the accelerometers , the acceleration is measured at various instances like at heel strike, at midstance and finally at the toe push-off. The vertical forces are obtained from the FSR. The horizontal forces are computed by measuring the COP shifting and the vertical forces. These ground reaction forces are then transferred to the ankle and knee joints by using the free-body diagrams.

The Assumptions in the inverse dynamics model include:

- The joints are frictionless pin-joints
- The segments are rigid with the mass concentrated at the centre of mass point.

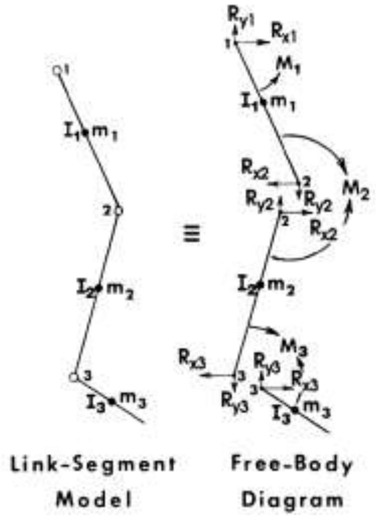

Fig.8. Free-body diagram of the human leg.

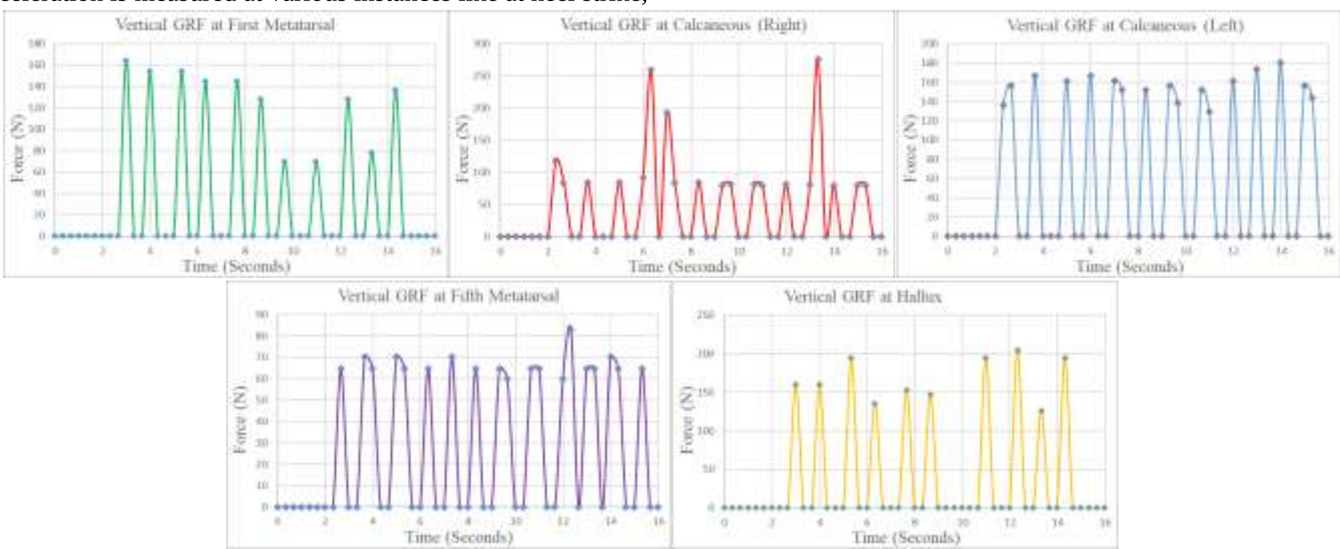

Fig.9a. The vertical ground reaction forces (GRF)generated at individual sensors during ground level walking.

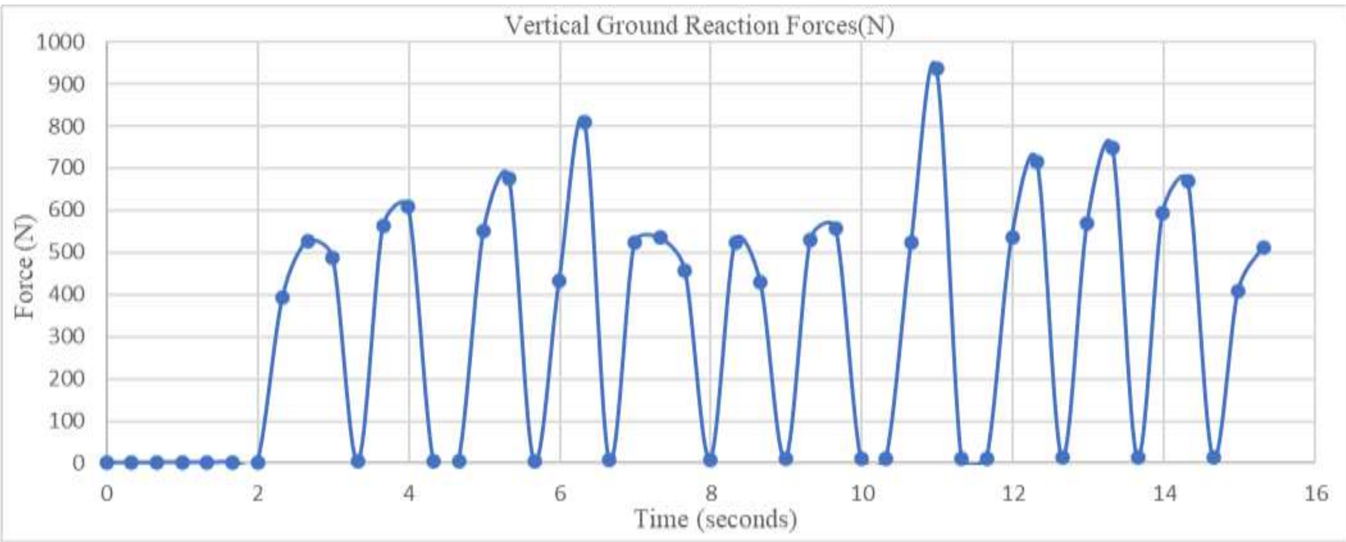

Fig.9b. The total vertical force generated during ground level walking.

IV. Analysis and Results

A. Ground Reaction Force Measurement And Gait Analysis

The experiments are performed during walking on-level ground, up-stair climbing and down-stair climbing. The vertical forces from the individual sensors are recorded in real time and are plotted. The total force is the summation of the forces on the five sensors. The sensors are programmed to measure three readings per second. This experiment was performed on five subjects. The entire setup is fixed on the dominant foot of the individual. The subject walked around 12 steps covering around 10 meters. The vertical ground reaction forces at individual sensors are calculated as shown in Fig.9a. The summation of the individual forces gives the total vertical force, which is displayed in Fig.9b. The COP migration along X and Y-axis is measured depending on the positioning of the sensors and insole dimensions. The horizontal forces are calculated from the vertical force and COP position as indicated in (1) and (2). The basic gait parameters like stance time, swing time, stride length, gait velocity and cadence can be interpreted and measured from these plots.

The gait parameters are calculated and tabulated in Table 1. The stance time represents the time when the foot is on the ground, in other words, when the sensors measure a force, it means the foot is on the ground. During a step, the amount of time for which the force readings are above zero is measured and this time corresponds to the stance time. During the swing time, the foot is not on the ground, and therefore the force readings from the sensors is zero. The amount of time for which the force is zero is measured and that corresponds to the swing time. The total length across which the subject performed the activity of walking is 10m. The number of steps taken by the subject is 12 as shown in the Fig.9b, from this the stride length is calculated. Gait velocity is the defined as the ratio between stride length and total stride time. Cadence is another gait parameter which is determines the number of steps an individual takes per minute. The other gait parameters like step angle and step width are not calculated in this study. These parameters can be measured and over long periods of time, the deviation in an individual's gait pattern can be monitored.

TABLE 1: GAIT PARAMETERS OF SUBJECT-1 DURING GROUND-LEVEL WALKING

Gait parameters	**Values**
Stance time	0.867 seconds
Swing time	0.67 seconds
Stride time	1.527 seconds
Stride length	0.833 m
Cadence	55 steps/minute
Gait velocity	0.769 m/s

TABLE 2: COMPARISON OF VERTICAL REACTION FORCES DURING VARIOUS ACTIVITIES

Subject No.	**Average Peak Vertical Reaction force(N)**		
	Walking	***Stair ascend***	***Stair descend***
1	441.45	506.85	539.55
2	434.25	470.88	519.93
3	404.18	496.97	608.20
4	418.56	470.88	495.41
5	430	506.85	521.9

The average peak ground reaction forces during various activities is measured and compared during various activities. The foot insole was fixed on the dominant foot during the entire experiment for all the subjects The average peak ground reaction forces are tabulated in Table-2. It can be noticed that the vertical ground reaction forces are least during walking. The vertical ground reaction forces increases during stair ascend, and is the highest in stair descend. This trend can be noticed across all subjects.

B. Ankle And Knee Joint Forces Calculations

The ground reaction forces and the acceleration from the accelerometers are measured. The joint reaction forces are calculated.

Sum of forces = mass*acceleration.

Consider the foot segment first and calculate the reaction forces at the ankle joint. Based on Fig.10 , we can formulate the following formulas :

$$R_{xp1} + R_{xd1} = m_1 * a_x \quad (3)$$

$$R_{yp1} + R_{yd1} = m_1 * a_y + m * g \quad (4)$$

Here, the point 'p' refers to the proximal joint and the point 'd' refers to the distant joint. The proximal point for the foot is the point of contact with the ground, and the distant point is the ankle joint. 'm' refers to the mass of the segment. a_y and a_x are the acceleration values and 'g' is the acceleration due to gravity. The same set of formulas as in equation (3) and (4) are applied to the shank segment to calculate the reactive forces at the knee joint. The free-body- diagram is as shown below. Subscript '1' was used to represent the foot segment, and in Fig.11 the subscript '2' is used to represent the shank segment of the leg.

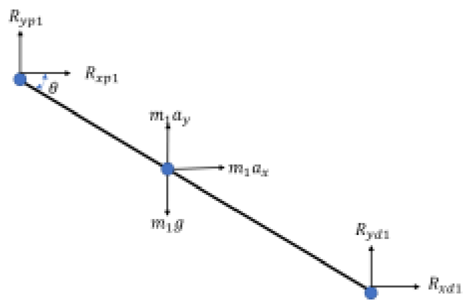

Fig.10.The Free-body diagram of the foot segment

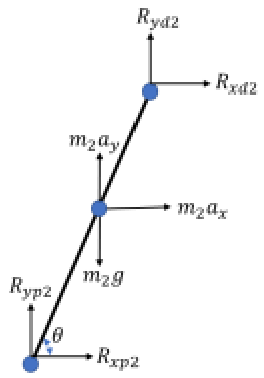

Fig. 11. Free-body diagram of the shank segment.

The knee joint forces where calculated during walking, stair climb and descend for 10 subjects. Table 3 is the results of the peak reactive forces at the knee joint during staircase ascend and descend. It can be also observed based on the experiment that the knee joint reactive forces are slightly higher during the stair case descending activity compared to the activity of staircase climbing. Even in this set of experiment the foot insole was fixed on the dominant foot for all the subjects. It can be inferred from the results that the reactive force at the knee joint during stair descend is higher than during stair descend.

TABLE 3. THE MAGNITUDE OF REACTIVE FORCES AT THE KNEE-JOINT DURING STAIR ASCEND AND DESCEND ACTIVITY.

Subject No	**Magnitude of Resultant knee joint force during stair ascend (N)**	**Magnitude of Resultant knee joint force during stair descend (N)**
1	461.16	494.37
2	314.46	357.25
3	434.27	480.43
4	378.32	451.71
5	440.67	498.06
6	443.90	485.39
7	361.93	439.31
8	379.61	440.51
9	458.32	513.42
10	465.29	516.260

V. AREAS OF APPLICATION FOR FUTURE WORK

The prototype developed can be used to perform the basic gait analysis in real-time. In addition to that the insole was also measures the ground reaction forces at the sole, the reactive forces at the knee joint and also monitors the dynamic migration of the centre of pressure during various activities.

A. Gait Pattern Analysis

Gait analysis is the study of human walking. A single sequence of functions performed by one limb is called as a gait cycle. Each gait cycle is divided into two periods- the stance phase and the swing phase. The swing phase applies to the time duration during which the foot is lifted from the ground, and the stance phase applies to the time duration during which the foot is on the ground. The duration of a complete gait cycle is called as the cycle time. The stance phase can be further divided into heel strike, mid-stance and toe-off while the swing phase can be divided into initial swing, mid swing, and terminal swing.

The foot insole measures the various gait parameters. The gait analysis is extensively important in the medical and sports field. When a person gait pattern is altered or is abnormal, they usually experience pain initially. If left undiagnosed it can lead to bigger health issues. Identifying these earlier can allow the individual to take necessary precautions. On the other hand, the gait pattern helps in performing the pronation analysis and can determine whether the pattern is a normal pronation. Over-pronation or under-pronation. This can be found, by analysis which sensors record higher force. If the sensors on the inner side of the foot record higher forces, it might be an indication of over-pronation whereas if the sensors on the outside part of the foot record higher forces, it might indicate under-pronation or supination. Depending on the type of pronation, different set of shoes can be used to prevent injuries, especially athletes.

B. Detection Of Possibility Of Foot Ulcers In Diabetic Patients

The studies [9]-[10] have shown that the ulcers occur at the location of the highest horizontal forces and highest vertical forces. The abnormally high loading on the foot to ulcerations, which on the longer run can also lead to lower extremity amputations. The foot insole can be used to monitor the pressure or force map regularly, an increase in the forces can be identified earlier and necessary steps can be taken to avoid ulcerations.

VI. CONCLUSION

The current project deals with the development of an instrumented foot insole used to perform gait analysis in real-time. In addition the insole was also used to measure the ground reaction forces and dynamic migration of centre of pressure during various activities. Gait analysis was performed for various activities like normal ground level walking, upstair climbing and downstair walking along with the measurement of ground reactive forces and the forces at the ankle and knee joints. Various analysis using wearable sensors can be widely performed in daily environments, various clinical occasions, and other possible applications.

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