STRIDALYZER INSIGHT SMART INSOLES: A CLINICAL GRADE GAIT ANALYSIS SYSTEM

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***Abstract*— Gait analysis is crucial in the medical sphere, sports and research. It can facilitate prevention of diseases having gait-related symptoms, alleviation of pain with posture correction and performance improvement. It is being simplified and made more accessible with the development of sensor insoles combined with intelligent analytics. Stridalyzer INSIGHT is a smart insole system which offers ubiquitous clinical-grade gait analysis. In this paper, we present an overview of the device and the embedded sensor network, and evaluation of the data results. Weight distribution, vertical ground reaction force (GRF) and ground contact time (GCT) data has been evaluated using statistical metrics, with the pressure plate as the gold standard. The percentage difference in weight distribution data between the insoles and pressure plate were found to be 7.75(0.78) and -3.85(5.87) for left and right respectively. The correlation between the insoles and pressure plate vertical GRF data for dynamic gait (walking) was found to be 0.65(0.07) and 0.9 for left and right respectively. The percentage difference in GCT data between the insoles and pressure plate were found to be 0 and 12.4(1.8) for left and right respectively. The accuracy of the data can be improved by reducing the capacitance of the sensors and the circuit, compensating for the temporal and magnitudinal effects of capacitance while processing data and increasing the sensor area. Stridalyzer INSIGHT smart insoles can provide out-of-clinic gait analysis to complement the clinical systems, but the data needs to be validated for more varied anthropometric measurements.**

Keywords*— *Sensor insoles, Gait analysis system, Ground reaction force, Ground contact time

I. INTRODUCTION

Lower-body biomechanical analysis is crucial for diagnosing and rehabilitating certain injuries and ailments. Conventionally, this has been achieved using motion capture, electromyography (EMG) and platform-based systems such as force plates. However, these systems are limited in usability to in-clinic only, and are cumbersome to set up and drive. The in-shoe system, namely insoles, is portable and convenient to use. Nevertheless, conventional in-shoe system offers lower precision than other methods, as it has limited sensor density limiting the accuracy. But, with the advent of flexible, ultra-thin and low-cost piezoresistive sensors, multiple sensors are being incorporated in the insoles. Thus, all the main pressure zones of the foot are being sensed to capture the pressure distribution and variation. This is elevating the accuracy of the data, which is comparable to those obtained through conventional methods. In this paper, we present the statistical analysis of body weight distribution (static gait) for three subjects and impact forces (dynamic gait) for two subjects. The data is obtained from distinct methods, namely theoretically derived vertical ground reaction force (GRF) graphs, pressure plate (gold standard) and Stridalyzer INSIGHT. Stridalyzer INSIGHT is a gait analysis system consisting of sensor-embedded insoles, mobile application with real-time and context-aware analytics and a cloud-based software backend (Fig. 1). It is used in medical and sports applications, as well as research. The sensors are placed at the important pressure zones on the soles, ensuring that the most critical data is captured for accurate analysis.

Fig. 1. Stridalyzer INSIGHT system: Mobile application, cloud-based software with analytics and sensor-embedded insoles

The paper provides an overview of the device operation and the embedded sensor network. The experimental procedure and data results for static and dynamic gait have been discussed. Finally, the statistical analysis and inferences have been presented.

II. DEVICE OPERATION AND EMBEDDED SENSOR NETWORK

The insoles contain piezoresistive force sensors and the central circuit with the microcontroller. The sensors are placed at six most important location for posture and locomotion analysis: hallux, metatarsal 1 and 2, centre of arch, centre of mid-foot and centre of heel (Fig. 2). The central circuit contains 6-axis motion sensor module, which combines accelerometer and gyroscope. They measure the linear and rotational motion of the foot to analyze gait parameters like ground contact time (GCT), peak load, body balance, impact forces and pronation type. The mobile application receives real-time data from the insoles over BLE network. Real-time context-aware analytics is used to analyze the data and compute various gait parameters. The mobile application running simultaneously during the gait activity show the real-time gait parameters. Force Sensing Resistor (FSR) based sensors are used for pressure sensing.

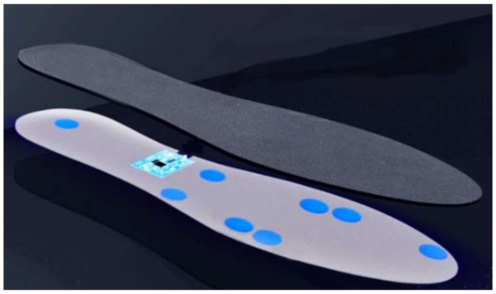

Fig. 2. Sensor locations on the insole

FSR is a polymer thick film (PTF) exhibiting decrease in resistance with an increase in the force applied to the active surface. In general, FSR response approximately follows an inverse power-law characteristic (roughly 1/R) (Fig. 3). The actual measured pressure range of operation of the FSR is 0 to 1206.58 kPa (0 to 22 lbs applied over 0.125 in2). The saturation pressure of a typical FSR is on the order of 689.476 kPa to 1378.95 kPa. The pressure sensors used in the insoles have circular active areas, measuring 14mm in diameter. The sensors are built by affixing the FSR film on the active area containing printed circuit pattern acting as electrodes (Fig. 4). Gold electrodes are used in the sensors to ensure inertness under varied temperature and humidity conditions in which the device is used. A circular lining of adhesive material is used to affix and separate the film from the electrodes at the active area. Gold electrodes sense the resistance changes of the FSR with varying pressure applied on the sensor. The sensors are used in parallel potential divider circuits working with 3.3V reference voltage.

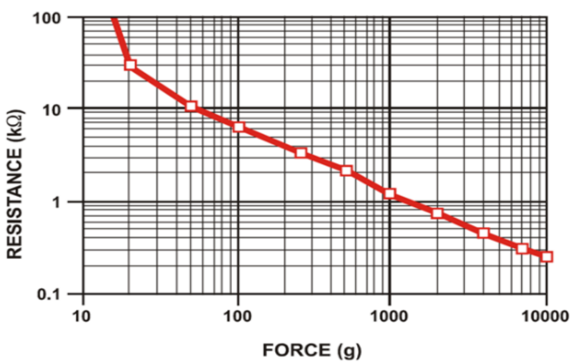

Fig. 3. FSR Response Graph (Force vs Resistance)

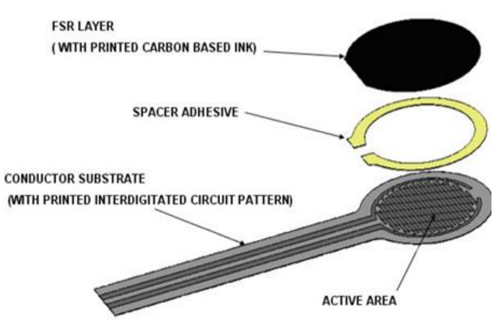

Fig. 4. FSR Structure and Integration

III. Testing and Data Collection

A. Objective

The objective of the experiment was to analyze the data results of the insoles obtained for body weight distribution and impact forces. For this, the pressure plate was used as the gold standard as these could provide the actual variations and overall trend for each subject. Theoretical vertical GRF graphs for walking, which were scaled according to the gait cycle time of each subject, were used to provide the typical GRF trend, usually observed.

B. Procedure

The anthropometric characteristics of the subjects is as summarized in Table I. The subjects were selected with fairly good variations in their anthropometric characteristics. None of the subjects had a history of injuries or medical conditions or had any physical deformities. The first part of the experiment involved gait analysis of the subjects with the insoles. The insoles were inserted into the footwear of the subjects. Insoles of suitable sizes and footwear that ensured a proper placement of the insole and a firm grip while walking were selected. The insoles were calibrated for 30s with the subject's weight. For calibration, the subject's weight was entered as input to the mobile application, and thereafter the subjects stood with the insoles mounted such that their body weight was spread over both soles entirely, then only on the metatarsals and toes and later only on the heels, each for 10s. In the experiment, data sampling frequency and unit of data were selected as 25 Hz and pressure respectively. The type of activity was selected as static (standing) or dynamic (walking). Then, the subject's anthropometric characteristics were entered as shown in Table I. In the static activity, the insoles were mounted such that the sensor positions were located at the centre of each targeted pressure zone. This was done by marking each sensor location on the insole and marking the centre of the hallux, metatarsals, midfoot and heel. These marks were aligned while mounting the insoles. Consequently, the subjects were asked to stand in their normal standing style and the activity was started. The experiment used stand activities spanning 30 s for each subject. The weight distribution data over the entire activity was collected. In the dynamic activity, the subjects walked on plain ground with comfortable self-selected speeds. The selected speeds were in the range of 1.0 m/s to 1.6 m/s. After 30 s of walking with the insoles mounted for familiarity, walk activities spanning 60 s were carried out.

TABLE I. Anthropometric Characteristics of the Subject Sample

Physical Parameters	Subject 1	Subject 2	Subject 3
Gender	Female	Male	Male
Age	23	26	21
Weight (kg)	65.1	89.9	59.2
Height (cm)	155	170	171
Foot Size (cm)	23.8	26	26
Arch Height	Normal	Flat	High

Eight steps were selected from the entire activity for analysis. The collected gait data was exported from the mobile application to cloud. In the second part, the subjects repeated the experiment with the pressure plate. A VCP1600 pressure plate from Voxelcare online CAD/CAM systems, shown in Fig. 5, was used in the experiment. The pressure plate has 1600 resistive sensors each of size 10 mm x 10 mm. The maximum measurable pressure is 100 N/cm2. The pressure plate was calibrated using the factors given in the table. In the static case, the body-weight distribution data for 30 seconds of standing activity was collected for each subject (Fig. 6). The pressure plate markings separating the left and right soles and the front and rear parts of each sole were used to align the feet placements to ensure accurate analysis. In the dynamic case, the pressure plate was placed on the path marked for the walk activity and the subjects walked end-to-end on the path (Fig. 7). The foot placements were aligned using the same method as in static mode. After the activity stabilized, the data for eight foot-strikes each of the left and right foot on the pressure plate were collected. The pressure plate and insoles were not used simultaneously during the activity as it could produced alterations in the pressure measurements provided by the pressure plates. This was due to the interference caused by the insoles acting as a layer between foot and pressure plate toning down and neutralising pressure variations and patterns. The pressure plates were recommended to be used barefoot for accurate pressure sensing and measurements.

IV. Results and Discussion

The performance metrics of the INSIGHT system that were analysed for static gait were the body weight distribution between the left and right foot, the weight distribution on different areas of each foot sole and the typical maximum pressure point on either soles.

Fig. 5. Pressure plate VCP1600 used in the experiment

Fig. 6. Procedure for static gait analysis on pressure plate

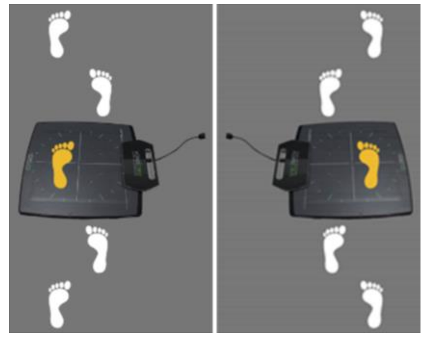

Fig. 7. Procedure for dynamic gait analysis on pressure plate

In the dynamic gait scenario, the stance phase of the gait cycle was analysed for various performance metrics. The performance metrics for dynamic gait were the average ground contact time and the vertical GRFs throughout the stance cycle as a percentage of the peak GRF in the entire cycle. However, the peak GRF measured by the INSIGHT system could not be validated, as GRFs were measured by the pressure plate as percentages of peak value and not as absolute values.

A. *Static Mode*

Each stand activity lasted for a period of 30 s, with the frequency of data collection set at 25 Hz. This duration was selected in order to obtain sufficient data samples that offset the effects of momentary deviations in the posture to obtain the characteristic pressure distribution on the soles for each subject. The summary of the experimental data obtained for the three subjects in the static mode is as given in Table II. The overall deviation of insole measurements from pressure plate in the examined performance metrics was 9.7%. This is higher than the accepted value of 5% for scientific measurements as given by scientific literature. This could be attributed to various factors. The most important factor is the instantaneous deviation in the standing posture shifting the body weight. The areas having maximum pressure distribution over the entire activity are: at the centre of the right heel for Subject 1, below the centre of the right heel for Subject 2, and on the right side of the lower portion of the left heel for Subject 3, as detected using the pressure plate. Using the insoles, the maximum pressure was detected at the sensor on the right heel for Subject 1 and the sensor on the left heel for Subject 3. However, the maximum pressure distribution was detected at the sensor corresponding to metatarsal 1 on the left insole for Subject 2.

B. *Dynamic Mode*

The pressure plate markings separating the front and rear parts of the sole were used to align the feet placements accordingly to ensure accurate analysis. In the next part of the experiment, the insoles were mounted ensuring proper alignment using the same procedure as the static mode. The frequency of data collection was set at 25 Hz. The steps are considered independent of each other and the average of the eight steps obtained from the pressure plate was used as the gold standard. The average vertical GRF over the gait cycle and the vertical GRF graphs for the subjects are as shown in Table III and Fig. 8 and 9 respectively. The average of the correlations between the results obtained from theoretical and pressure plate (gold standard) methods in each case is equal to or above 0.7.

TABLE II. SUMMARY OF EXPERIMENTAL DATA IN THE STATIC MODE FOR THE SUBJECT SAMPLE

		Sample Size	Left			Right			Total Mean(SD)
			Front Mean(SD)	*Back Mean(SD)*	*Total Mean(SD)*	*Front Mean(SD)*	*Back Mean(SD)*	*Total Mean(SD)*	
Pressure Plate	Weight (kg)	3	13(6.2)	22.8(8.9)	35.9(7.4)	14.6(7.9)	20.9(8.5)	35.5(9.1)	71.4(16.3)
	% of Total		37.3(20)	62.7(20)	100	41(22.5)	59(22.5)	100	
Insole	Weight (kg)	3	20.8(11.4)	20(6)	40.9(5.4)	14.7(10.1)	21.6(5.2)	36.3(5.9)	77.2(11)
	% of Total		49.2(19.8)	50.7(19.8)	100	38.2(24.1)	61.7(24)	100	
% Diff			74.4(73.1)	4.9(69.4)	15.3(13.1)	-9.3(28.8)	13.6(40)	4.1(14.3)	9.7(13.6)

TABLE III. AVERAGE VERTICAL GRF OVER THE GAIT CYCLE IN THE DYNAMIC MODE FOR SUBJECT SAMPLE

Time (ms)	Subject 1						Subject 2					
	Left			Right			Left			Right		
	Pressure Plate (% of Peak)	*Theoretical (% of Peak)*	*Insole (% of Peak)*	*Pressure Plate (% of Peak)*	*Theoretical (% of Peak)*	*Insole (% of Peak)*	*Pressure plate (% of Peak)*	*Theoretical (% of Peak)*	*Insole (% of Peak)*	*Pressure plate (% of Peak)*	*Theoretical (% of Peak)*	*Insole (% of Peak)*
0	5.1	7	0	1	0.3	6.6	0.5	1	0.6	0.6	1.7	6.6
40	23.1	33	11.74	19.2	22.5	44.5	12.9	14	13.2	13.5	6.5	37.5
80	38.3	54	21.4	34.5	59.9	73.9	27.6	29	28.3	30.8	19.8	63.5
120	65.5	93	31	56.1	80	90.5	47.3	50	48.5	47.4	33.2	81.1
160	86.3	122	50.8	74.4	93.8	100	58.4	61	59.9	59.1	47.9	93.2
200	99	140	60.1	87.7	100	95.7	68.7	72	70.5	71.8	70.8	100
240	93.4	132	64.7	84.9	88.2	86.4	75.9	80	77.8	77.8	74.9	98.1
280	76.4	108	65	72	67.4	73.5	86.1	91	88.3	80.2	77.5	90.4
320	72.6	103	63.5	64.1	56.4	68.2	94.2	99	96.6	76.7	76	80.7
360	77.4	109	63.1	64.3	56.6	66.2	99.2	104	101.7	75.7	71.3	71.6
400	79.9	113	66.2	70.2	60.1	68.9	94.6	99	97	73.7	66.7	68.2
440	82.4	117	70.4	77.3	63.9	73.5	86.9	91	89.1	76.4	65.7	66.2
480	85.9	121	78.2	88.2	67	81.8	83.4	88	85.5	79.7	67.9	67.2
520	90.6	128	88.7	94.2	70.7	92.2	88.2	93	90.4	83.8	73.8	69.8
560	93.4	132	100	92.4	72.6	99.2	92.2	97	94.5	89.1	82.3	75.3
600	89.7	127	91.8	79.7	67.5	95.4	95.1	100	97.5	91.6	91.9	81.8
640	66.4	94	73.8	29.1	42.7	75.2	97.7	103	100.2	94	98.6	91.2
680	17.8	25	64	0.6	13.9	41.7	99.2	104	101.7	97.6	100	97.5
720	1.6	2	60.8	0.1	2	12.9	100	105	102.5	98.7	89.1	99.2
760	1.2	2	50.3	--	0.4	1	98.3	103	100.8	86.5	68.4	94
800	0.8	1	24.3	--	--	0	81.3	85	83.3	46.9	40.4	75.2
840	0.4	1	4.5	--	--	--	29	30	29.7	6.5	11.2	48.4
880	0	0	0	--	--	--	3.1	3	3.2	0.5	2.1	21.5
920	--	--	--	--	--	--	--	--	--	--	1.6	5.7
960	--	--	--	--	--	--	--	--	--	--	--	0.2
1000	--	--	--	--	--	--	--	--	--	--	--	0

TABLE IV. COVARIANCE AND CORRELATION BETWEEN PRESSURE PLATE, INSOLE AND THEORETICAL GRF IN THE DYNAMIC MODE

	Sample Size	LEFT		RIGHT	
		Covariance Mean(SD)	*Correlation Mean(SD)*	*Covariance Mean(SD)*	*Correlation Mean(SD)*
Pressure plate and Theoretical	2	783(273.4)	0.7(0.2)	1006.1(6.7)	0.8
Insole and Pressure plate	2	802(6.2)	0.7(0.1)	1097.3(138.1)	0.9
Theoretical and Insole	2	917.9(267.9)	0.8(0.1)	953.5(24.3)	0.9(0.1)

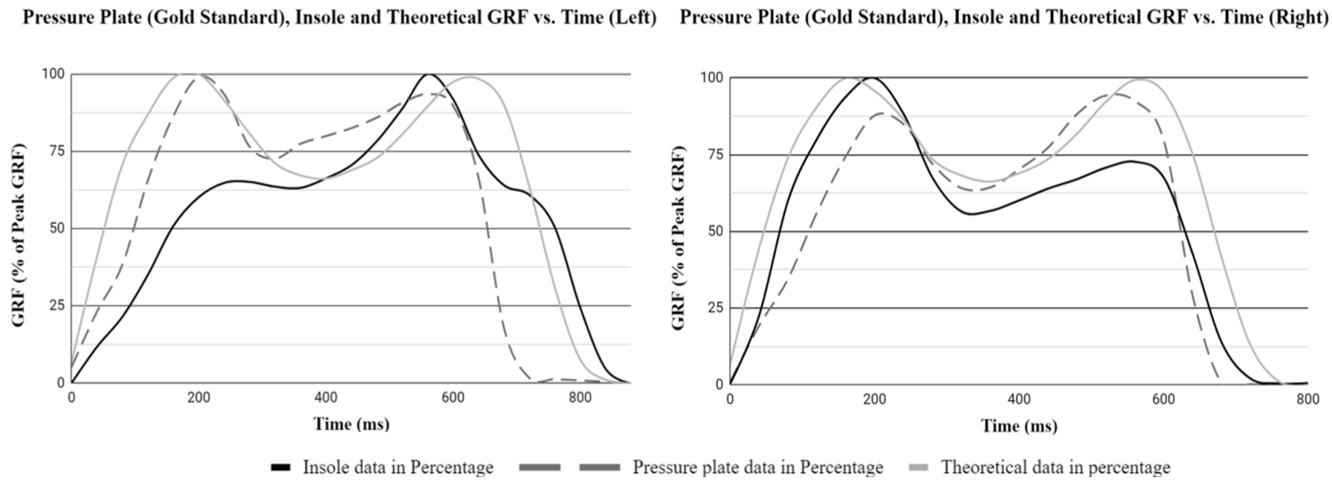

Fig. 8. Average vertical GRF as percentage of the peak GRF over the entire gait cycle: Subject 1

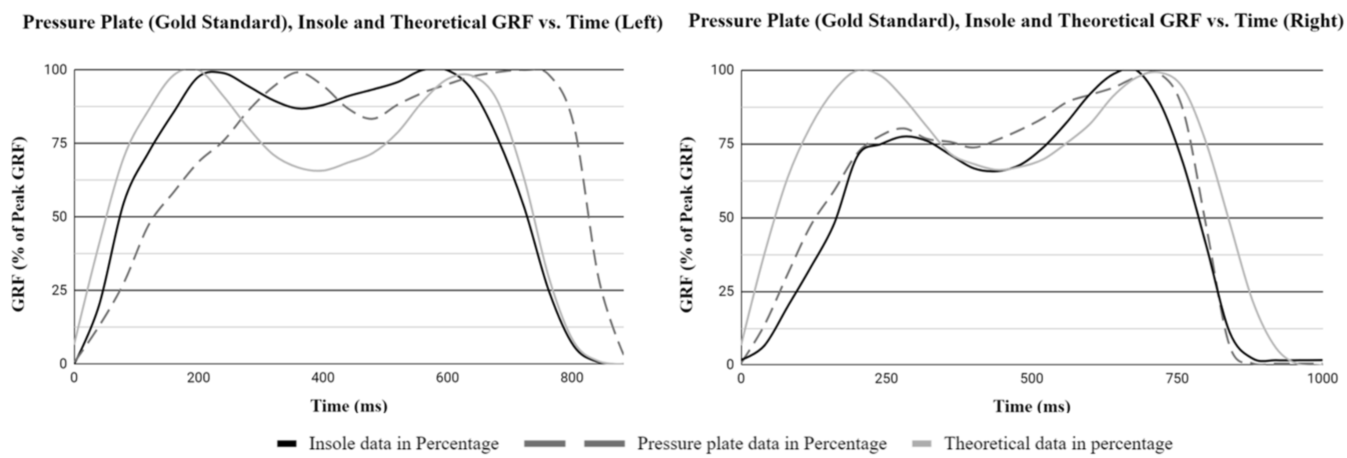

Fig. 9. Average vertical GRF as percentage of the peak GRF over the entire gait cycle: Subject 2

This shows that the two methods are in good agreement and these methods were used for validation of the Stridalyzer INSIGHT performance. Table IV shows the correlation and covariance between the data obtained through all methods for the subject sample. The average correlations between the insoles and the pressure plate lie within the range of 0.6 to 0.9. Whereas, the insoles seem to be in greater agreement with the theoretical values with average correlations within a relatively narrower range of 0.7 to 0.9. The ground contact time is measured from the instant the vertical GRF come into play in the gait cycle (initial contact) to the instant they disappear (toe-off). The percentage difference in the ground contact time was found to be zero for left foot and within the range of 11.1% to 13.6% for right foot (Table V). It has been observed that the insoles capture the overall trend of the vertical GRF over different stages of the gait cycle with accuracy comparable to accepted standards. The insole data conforms to the typical GRF trend given by scientific literature as can be inferred from its correlation with the theoretical data. However, the insole fails to capture certain variations in the GRF, especially when the variations occur over relatively shorter time periods. This could be due to three main reasons. Firstly, capacitance of the sensors and circuit components being used which can cause time lag in the alteration of the FSR resistance with varying pressure.

TABLE V. Ground Contact Time as detected by the Pressure Plate and Insole

	Sample Size	Left Mean(SD)	Right Mean(SD)
Pressure Plate	2	880	800(113.1)
Insole	2	880	900(141.4)
% Diff	2	0	12.4(1.8)

Another reason could be the occurrence of pressure variations at a rate that is faster than the sampling frequency. This may cause failure in capturing finer variations. Finally, there is always scope for differences between gait activities carried out separately, as human movement cannot be exactly replicated each time. The effects of capacitance and sampling frequency on the data accuracy can be reduced reasonably with sensors having lower capacitance and adjusting the device sampling frequency to obtain accurate data. Compensations can also be made to counter the time-lag effects while data processing through analytics. However, the deviations caused due to variations in the posture and movement is inevitable. The trials need to be carried out in more varied subject samples in order to determine the extent of deviation in the data from the gold standard due to posture and movement variations and other factors. With the current accuracy level, the system can assist the clinical methods with gait analysis in the outdoor scenarios. The data can be validated using standard methods.

V. Conclusion

The experimental results and the analysis illustrate that the Stridalyzer INSIGHT system provides reasonable accuracy in determining the key aspects of static and dynamic gait analysis. The usage of discrete sensors only at certain pressure areas of the soles does not provide a holistic perception of the pressure distribution. This is because certain other important pressure areas and deviations can be missed as gait characteristics varies in each person and does not always follow a certain trend. However, an approximate overall understanding of standing and walking can be acquired. Hence, the system can complement traditionally used methods, namely treadmill-based gait analysis systems and pressure plates, for dynamic and static gait analysis. These systems, being confined to clinical use under stringent conditions, don’t offer portability. Stridalyzer INSIGHT is a non-intrusive mobile system, which does not alter the movement or posture of the wearer.

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