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A wireless gait analysis system by digital textile sensors

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***Abstract*—This paper studies the feasibility of spatio-temporal gait analysis based upon digital textile sensors. Digitized legs and feet patterns of healthy subjects and their relations with spatio-temporal gait parameters were analyzed. In the first experiment, spatio-temporal gait parameters were determined during over ground walking. In the second experiment, predicted running, backward walking, walking up stairs and walking down stairs parameters were determined. From the results of the experiments, it is concluded that, for healthy subjects, the duration of subsequent stride cycles and left/right steps, the estimations of step length, cadence, walking speed, central of pressure and central of mass trajectory, can be obtained by analyzing the digital signals from the textile sensors on pants and socks. These parameters are easily displayed in several different graphs allowing the user to view the parameters during gait. Finally, the digital data are easily to analyze the feature of activity recognition..**

I. INTRODUCTION

GAIT analysis is commonly used to help athletes and injured people. At the present time, it is primarily carried out in laboratory, or in physician's office with visual observations. The clinicians rely extensively on gait analysis for diagnosis and treatment options, but have been confronted by numerous complexities [1]. Preferably, the gait analysis system and procedures should be real time monitoring, inexpensive, easy-to-use, and easily available. However, the conventional devices are usually either to use a specific field test, or to have a full-fledged gait analysis in a laboratory. The gait analyses do not reflect motor function under real-life conditions [2]. There is a need for a low cost device that can provide quantitative and repeatable results, and a need for monitoring gait over long periods of time; in particular, gait analysis of patients with Parkinson's disease would be greatly enhanced by studies looking at gait outside of the motion lab [3].

Gait analysis is suggested from any condition and does not require the subject to be aware of or cooperate with its use, making it particularly valuable in surveillance, or other applications where non-contact operation is required [4]. In a recent walking study [5], it was demonstrated that an assessment of essential spatio-temporal gait parameters and analysis of movements within subsequent stride cycles is possible based on measurements of lower trunk accelerations. This result needs complex algorithms for analyzing the acceleration patterns.

Another study, the Gait Shoe is capable of enabling the analysis of gait in untraditional ways, such as over long time periods and in the home environment [6]. But the system uses multiple sensors and all data are analogical signals. So it needs complex analyzing system to solve the gait parameters.

To solve the problems shown above, in this paper a gait analysis system is presented with the following features:

1. wearable and comfortable as ordinary pants and socks, to reflect the real-life and long-term conditions;
2. wireless transmitting, not to interfere the subject under test;
3. washable, durable, reliable, low cost, to be easily applied to user outside labs and office;
4. digital output and Bluetooth interface, so that the measured data can be easily analyzed by popular digital devices, such as PDA or notebook computer.

We have presented digital textile sensors for monitoring posture [7]. To apply the digital textile sensors in this study, we should define what gait parameters are necessary in our system first of all.

It is well known that consider that postural control in humans relies on information from receptors in the proprioceptive, visual, and vestibular systems of the body. It means foot contact detection is important for the determination of essential spatio-temporal gait characteristics. Especial plantar proprioceptive inputs are the dominant sensory information for balance when the body is standing still on a fixed firm surface or moving through the environment [8]. Therefore, dome shape force sensors are installed on socks to evaluate the plantar sensation.

Owing that a vision-based system for human motion analysis poses a significant challenge for accurate joint localization [9], clip type force sensors are knitted on pants to evaluate the knee localization.

Additionally, a clip type sensor is also installed between the trouser legs to detect the step length and walking speed. As a result we can analyze the spatio-temporal gait parameters from any condition for a long period of time.

II. SYSTEM DESCRIPTION

The wireless gait analysis system, shown in Fig.1, is comprised of dome shape sensors on socks and clip type sensors on pants, connected to the microcontroller (MSP430, Texas Instruments). Digital data from each sensor are

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sampled at the rate of 100 Hz, and then transmitted through Bluetooth interface to PC or PDA, as shown in fig. 2.

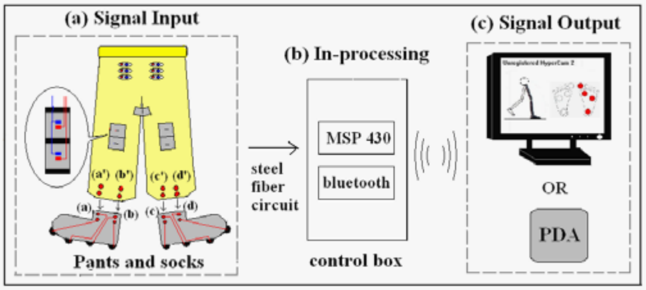


Fig.1. The system block diagram of the wireless gait analysis system.

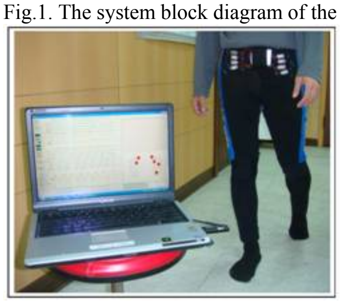


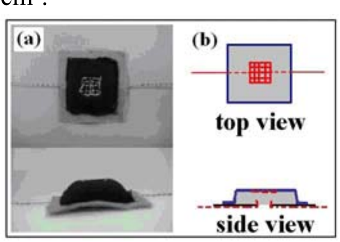
Fig.2. The photo of the initial prototype.

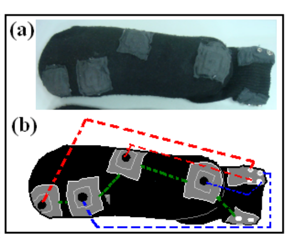
III. MATERIAL AND METHOD

In this study, we design pants, socks, and sensors based on the size of ordinary adults. Five male and five female subjects are recruited, with heights from 150 to 174 cm and weights from 45 to 69 kg. After try-and-error for one year, the sizes and forces shown below were determined and verified by all subjects without malfunction. The pants and socks installed with sensors were washed by wash machine one time per every working day and showed no significant difference.

A. Dome Shape Sensor

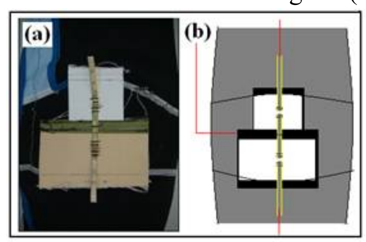
The dome shape sensor is shown in Fig.3. The base layer of this sensor is knitted on sock, then a dome-shape SBR (Styrene Butadiene Rubber) set on the base to elevate the the contact layer. Each side of contact layer is knitted with a electrical conductive fiber, with diameter of 0.2 mm. Two conductive fibers are also knitted on the base layer. When pressed by force greater than 80 grams, the conductive fiber on the contact layer will contact the both conductive fibers on the base layer, such that the sensor will switch from "off" to "on" state. The size of the dome shape sensor is 1.5*1.5*0.4 cm^3.

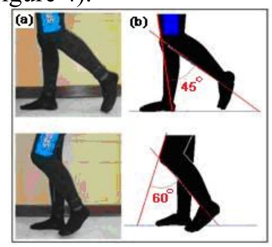




Left Fig.3. The dome shape sensor.
(a) Real sample and (b) the analogue structure where the marked red line is the part of the conductive fiber.
Right Fig.4. The right sock. (a) the real sample and (b) analogue structure.

The adult spatio-temporal plantar pressure pattern results in a specific course of the center of pressure (COP) characteristic for adult gait. At first contact, the COP is found under the heel. During roll-off it moves laterally and to the front and when the forefoot is reached it quickly shifts medially again [11]. The central of pressure is along the middle of the foot to the metatarsal heads, where it moves medially, ending at the hallux. Therefore, the sock is equipped with 4 dome shape sensors for plantar pressure sensing. The first is set on the heel part, the second is set on the middle lateral side, the third is set on the metatarsal area, and the last is set on the big toe (Figure 4).





Left: Fig.5. The two-stage clip type sensor.
(a) Shows the real sample of the clip shape type. (b) The structure of clip type sensors which conductive fiber marked by the red line and blue line.
Right: Fig.6. The result of the two-stage clip type sensor. (a) the photo of real situation (b) the analogue situation.

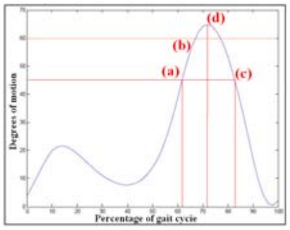
B. Clip Type Sensors

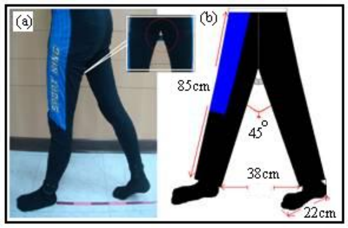
The structure of the clip type sensor is shown in Fig.5. There is a clip (0.5 cm) within the rubber band which contains rubber thread, and on the both sides of the clip is knitted by conductive fibers. The first rubber band for this design is made of 66% nylon and 34% rubber thread and the size is 5.5*5 cm^2. The second rubber band is made of 50% cotton and 50% rubber yarns and the size is 5.5*10 cm^2. The real sample is shown in Fig. 5(a) and the analogue structures are shown in Fig. 5(b). The two-stage clip type sensors were knitted on the knee parts of the pants for sensing sagittal angle. One is to detect 45 degree flexion, and the other is to detect 60 degree flexion (Fig.6), because the angle of knee is about 45 degree during pre-swing or terminal swing. And, the angle of knee is about 60 degree during mid swing period. [9] [12] (Fig.7).100 grams force is needed to switch the clip type sensor from "on " to "off" state for 45 degree flexion on the first rubber band, and 400 grams for 60 degree flexion on the second rubber band.

A former study has shown that body movements about join require specific amounts of skin extension [10]. Lengthwise across the knee for example, the skin stretches anywhere from 35–45% during normal joint movement. When a particular joint moves, fabric around the joint will either expand or contract accordingly, assuming the fabric is fitting to the skin, and has the necessary elastic properties.

Another clip type 45 degree sensor knitted between the trouser legs was used to estimate step length and walking speed, shown in Fig.8. When the clip type sensor triggered, the distance between both trouser legs is about 38 cm.

Considering the length of a foot is about 22 cm, one step length can be estimated as 60 cm.





Left: Fig.7. Knee motion during a gait cycle. (References: [9])
Right: Fig.8. The result of clip type sensor between the trouser legs
(a) The photo of real situation. (b) The analogue situation.

The experimental procedure is:

1. Straight Line forward Walking
   For each subject and each trial, mean walking speed was calculated from the time it took for the subject to cross the 10M distance along the trajectory. Per trial, digital signals measured between the 10M distance were used for further analysis.
   To this purpose, simple algorithm was used. To evaluate the algorithm, estimated walking speed was compared to the calculated mean walking speed.
2. Running on a treadmill (6 km/hour)
3. Backward Walking
4. Walking up stairs
5. Walking down stairs
6. Analyzing features for recognition

IV. RESULT AND DISCUSSION

1. Walking forward on a straight line:

The result of wireless gait analysis system is shown in Fig.9.

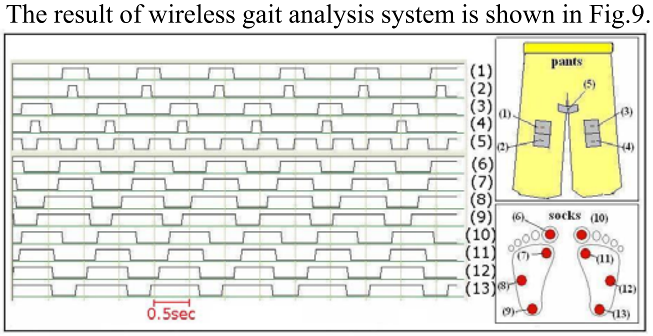


Fig.9. The results of wireless gait analysis by digital textile sensors. (1) L't knee(45°), (2)L't knee(60°), (3)R't knee(45°), (4)R't nee(60°), (5)Crotch, (6)L't toe, (7)L't middle part, (8)L't etatarsal, (9)L't heel, (10)R't toe, (11)R't middle part, (12)R't metatarsal, (13)R't heel

To simplify the analyzing procedure, only the results of right heel, right toe, left heel and left toe are analyzed. (Fig.10)

A. Phase of gait:

1). Initial Contact

Right heel contact the ground is defined as point (a) (Fig.10)

2). Loading Response

The loading response phase constitutes the period of initial double-limb support and ends as the point (b) (Fig.10) where left toe off. The period is 0.09 seconds.

3). Mid-stance

It begins when the contralateral foot leaves the ground and ends when right heel rises as the point (c) (Fig.10).The period is 0.23 seconds

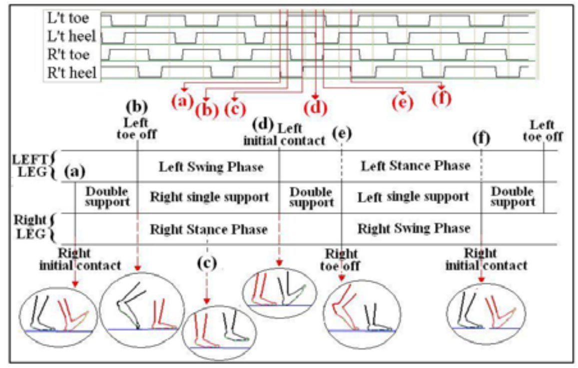


Fig.10. Phase of gait. The red color represents right foot and black color represents left foot.

4). Terminal Stance

Terminal stance constitutes the second half of single-limb support. It begins with heel rise and ends when the contralateral foot contacts the ground as the point (d) (Fig.11).The period is 0.2 seconds.

The period between point (a) and point (e) is the stance phase, of which the period is 0.62 second.

5). Pre-swing

Pre-swing is the terminal double-limb support period. It begins when the contralateral foot contacts the ground and ends with ipsilateral toe off as the point (e) (Fig.10), the period is 0.1 seconds.

The next initial contact is right heel contact the ground again as the point f in Fig.11. The period between the point (e) and (f) is the swing phase. The period of the swing phase is 0.42 second. So, we can calculate the stand phase take approximately 59.6% of the gait cycle, and the swing phase takes the remaining 40.3%. The period between point (a) and point (b) is double support. The period between point (d) and point (e) is another double support. During walking, the period of double support occupies about 8.6%. Finally, the stride period is 1.04 second.

6). Initial Swing

Fig.11 shows only the results of right and left knees, toes and heels for analyzing the swing phase. It begins the moment the right foot leaves the ground and continues until maximum knee flexion occurs, as point (h).When the right knee flexes 45 degree, it is the point (g). We can see the point (g) is very near the point (e) which means the end of pre-swing phase. And when the knee flexes 60 degree, it is the point h. It is very near the point h' which means the maximum knee flexion occurs.

7). Mid-swing

Maximum knee flexion and end are when the tibia is in a vertical position. We use the knee flexed 45 degree again as tibia is in a vertical position as the point i.

8). Terminal Swing

The period is between point i and point f' and is 0.06 sec.

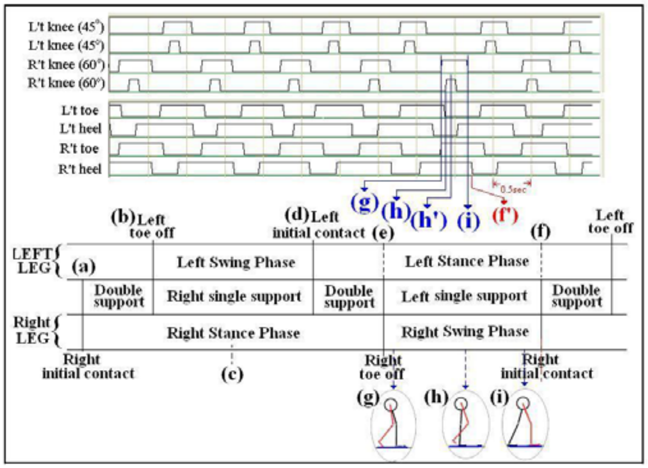


Fig.11. Phase of gait. The red color represents the right leg and foot; the black color represents the left leg and foot.

B. Temporal Parameters

Stride length, cadence and walking speed are three important interrelated temporal parameters. We used the clip type sensor between the trousers legs and right heel dome sensor to detect them.

To evaluate its performance, a male subject of 156cm height walked 10 meters for measuring. He took 8.29 seconds and 15 steps, i.e., his walking speed, cadence, and stride length are 1.2 m/sec, 108 times /min., and 0.6 m.

Viewing the data by sensors (Fig.12), the period of 5 stride lengths is 5.27 second. The cadence is then calculated to be 113 times/min. The clip type sensor between the trouser legs was triggered ten times between the 5 stride lengths. Accordingly, the calculated walking speed is 1.13 m/sec, about 6% error from the actual speed.

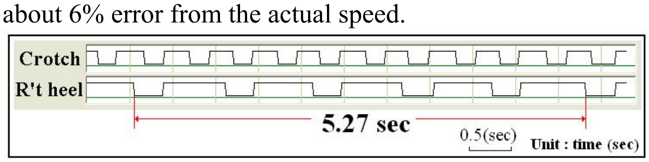


Fig. 12. The results of right heel (dome sensor) and (clip type sensor).

C. Central of pressure (COP):

The result data from right sock was shown Fig.13.

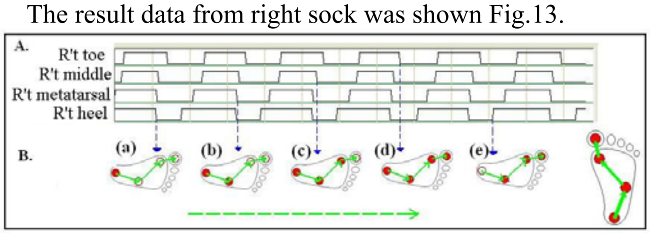


Fig.13. The central of pressure movement from right foot.

We can use the 4 dome sensors on the bottom of the sock to trace the COP movement. It is found regularly that, first of all the dome shape sensor on the heel was pressed, then the sensor on lateral side, then the sensor on the metatarsal area, finally the sensor on the toe. Then, the dome shape sensor on the heel part was high, which meant the COP was shifted to the contralateral foot. The result data from two socks was shown in Fig.14, the COP movement between two socks.

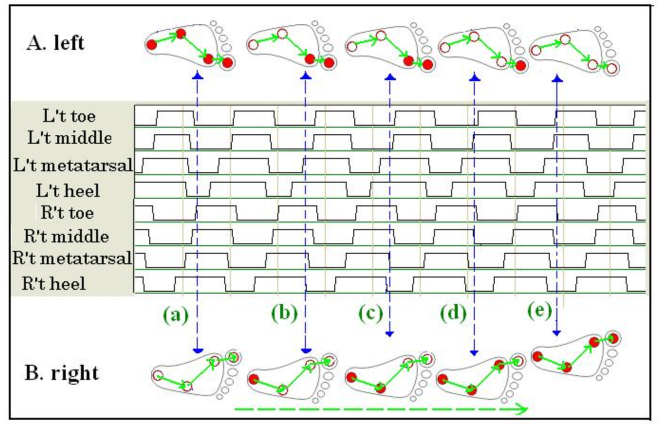


Fig.14. The COP movement between two socks.

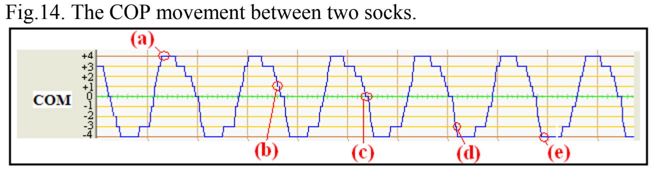


Fig.15. The central of mass trajectory during walking.

We found when left foot full contacted the ground (point a) (Fig.15), the right foot was swing. The left heel raised and right heel contacted the ground (point b on point c) , then only the left toe was on the ground and only the right did not contact the ground (point d). Finally, the left foot swung and the right foot fully contacted the ground (point e). We found the gait data is characterized by smooth, regular and repeating movements. So, we could count "4". When the left foot was fully contacted the ground; when the right foot was fully contacted the ground, we could counted "-4". Then, the sum of left and right feet's data was assumed the central of mass com trajectory during walking.

2. Running on a treadmill

The data of running was shown in Fig.16. We can find that duration of stance phase period A decrease but that of swing phase B increase. Stride frequency tends to increase. The double support period is almost absent (point C).The period of stance phase is 0.23 sec and swing phase is 0.43 sec.

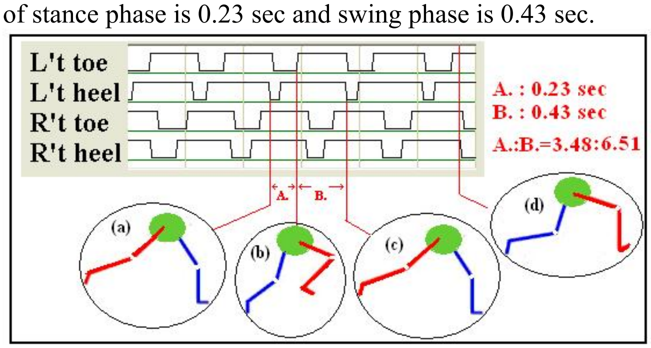


Fig. 16 The result of running. The red color represents the right leg and foot; the blue color represents the left leg and foot.

3. Backward walking:

The data of backward walking was shown in Fig.17. We found the phase of feet motion is inverse with forward walking.

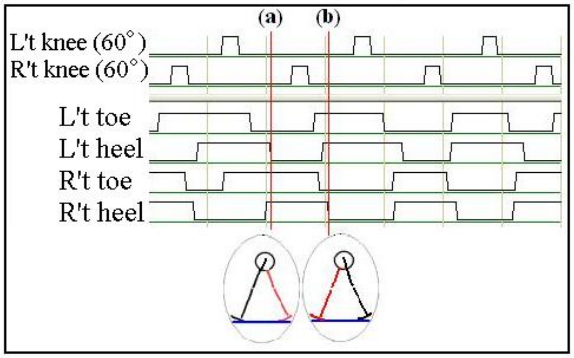


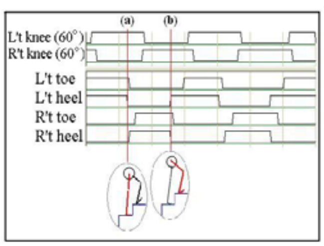
Fig.17. The result of backward walking. The red color represents the right leg and foot; the black color represents the left leg and foot.

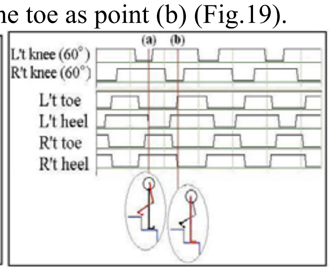
4. Walking up stairs:

The data of walking up stairs was shown in Fig.20. We found there is significantly difference. For example, when the left foot just began on the stance phase, the knee was flexed over 45 degree as point (a), and the first sensor on the right foot that contacted the next stair was the heel as point (b) (Fig.18).

5. Walking down stairs:

The data of walking down stairs was shown in Fig.19. There were different results too. For example, when the left foot was during the stance phase, the knee was flexed over 45 degree as point (a), and the first sensor on the right foot that contacted the next stair was the toe as point (b) (Fig.19).





Right: Fig.18. The result of walking up stairs. The red color represents the right leg and foot; the black color represents the left leg and foot.
Left: Fig.19. The result of walking down the stairs. The red color represents the right leg and foot; the black color represents the left leg and foot.

6. Analyzing features for recognition

Finally, the results can be easily displayed in several different graphs allowing the clinicians to know the subject's walking state and movement changed (Fig.20).

	Walking		Backward walking		Walking up stairs		Walking down stairs	
	A	B	A	B	A	B	A	B
L't knee (60°)	0	0	0	0	1	0	0	1
L't toe	1	0	0	1	1	0	0	1
L't heel	0	1	0	1	0	1	0	1
R't knee (60°)	0	0	0	0	0	1	1	0
R't toe	0	1	1	0	0	1	1	0
R't heel	1	0	1	0	0	0	1	0

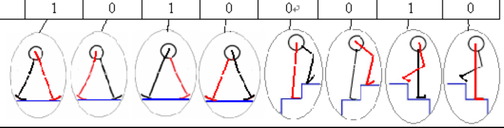


Fig.20. The database and graphs for analyzing user's walking state and movement changed.The red color represents the right leg and foot; the black color represents the left leg and foot.

VI. Conclusion

A wireless gait analysis system using digital textile sensors is proposed. The sensors are small and compatible to clothes so that they do not affect the wearer's activity. In the experiments, walking speed, cadence, stride length, and single- limb and double-limb support, swing, and stance times were computed from the sensor readings. In particular, the system can detect the central of pressure movement and central of mass movement. These parameters are easily displayed in several different graphs allowing the user to view the timing parameters. It is able to analyze features for walking forward, walking backward, walking up stairs, and walking down stairs. Models for gait under different conditions, and analysis on gait variability, by the proposed system will be studied as a continuing research topic. Fuzzy logic will be applied such that the system can still work as well under the complicated condition outside laboratory.

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