ICIC Express Letters
Part B: Applications
Volume **8**, Number **1**, January **2017**

pp. **79–84**

THE STUDY OF AN EXOSKELETON GAIT DETECTION SYSTEM APPLIED TO LOWER LIMB PARALYSIS

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Received June 2016; accepted September 2016

Abstract. *Gait analysis plays an important role in research related to sports biomechanics, or human motion. Based on pressure sensors on the bottom of the foot, a gait detection system was designed for exoskeleton actuation. The kernel of the control board was based on an Arduino Mega2560 server intended to receive dynamic pressure data from the walking gait. The use of a projection curve for the plane of position made it possible for eight main events in the human gait cycle to provide a closed curve on a 3-D plot. In the gait cycle experiments, which were conducted six times, the coefficient of variation of the right foot (R1) was between 1.2% and 12.6%. The center of the eight main events was calculated using center law. The system may be used to drive a robotic exoskeleton in cases of low limb paralysis.*
Keywords: Gait evaluation, Plantar pressure, Zero moment point, Exoskeleton

1. **Introduction.** Foot pressure measurement in gait analysis is an important issue in many fields related to rehabilitation, sport biomechanics and shoe-making, among other applications. Normal gait data are essential for diagnosing and treatment of abnormal gait patterns. The three-dimensional nature of human gait has often been discussed, but in the sagittal plane may be the most important one [1]. Abnormal plantar pressure may also reflect different pathological clinical signs and may even lead to adverse consequences. For example, neuropathy due to diabetes may cause a risk of festering that can be evaluated using plantar pressure [2]. The plantar side pressure distribution of Charcot Marie Tooth (CMT) patients has been shown to reveal symptoms of excessive pressure [3]. The spine is responsible for supporting the body's vital organs. The spinal ganglia within the brain are an important medium of communication for all motor neurons. If the medullary ganglia have been damaged, the brain will not be able to pass motion signals to the tissues [4]. Although spinal cord injury recovery is possible, the time course for recovery using today's medical technology is still unpredictable. It can only be viewed through overall health, rehabilitation and proper medical care. If the care and rehabilitation is not good, especially in cases of lower limb motor nerve damage, it may result in muscle atrophy, which in severe cases can turn into paralysis, causing difficulties or a lifetime of being bedridden. There is currently no effective cure for these injuries. Medical technology can only delay further deterioration of the spinal cord neuropathy via surgery. The development of lower limb exoskeleton robots can help paralyzed patients to stand and walk again, which has great significance for these patients in terms of quality of life.

In 1969, Vukobratovic et al. proposed the concept of the Zero Moment Point (ZMP) walking robot in their dynamic equilibrium theory [5]. This theory is still widely used in robot dynamic stability control. ZMP is a very important concept in the legged locomotion of biped robots. It specifies the point with respect to which dynamic reaction force at the contact point of the foot with the ground does not produce any moment in the horizontal direction. This is the point where the total horizontal inertia and gravity forces equal zero. If the ZMP falls inside the range of the contact area, stable motion is possible. Honda's ASIMO humanoid robot is an example of the use of the theory of ZMP to achieve balance and walking in a biped robot [6]. In addition, the research and development related to the Hybrid Assistive Limb (HAL) exoskeleton robot gives patients the hope of regeneration [7]. Although the HAL robot makes use of a pressure measuring device to provide position feedback to the motor, its main control is still based on electromyography signals. EMG measurement depends on muscle size, previous axonal damage, and other factors. When the muscle is fully contracted, there should appear a disorderly group of action potentials of varying rates and amplitudes. The recent progress in pressure sensors brings us a hope of measuring the body's foot pressure. Because resistive pressure sensors have poor precision and are larger in size than capacitive pressure sensors, plantar pressure measurements are based on capacitive sensors. Plantar pressure measurement and analysis can be used as an index for health status assessment. In recent years, the development of thin film pressure sensor, with a measurement range from 10N up to 100N, has enhanced applications for feet walking measurements. In this study, a gait detection system is developed using a plantar pressure measurement for lower limb paralysis. The position of the ZMP is calculated through a plantar pressure measurement. The normal human gait model is applied on the patient's paralyzed lower limb, and the patient's own plantar pressure is measured to compensate for controlling a motor-driven exoskeleton used to walk. A control model of human walking can be established by the ZMP distribution in each gait event analysis.

2. Materials and Method.

2.1. System architecture.

System architecture. Figure 1 presents the plantar pressure detection system. The signals from the pressure sensor array (GD25-100N) and gyroscope (Gyro L3G4200) are captured in a processor (Mega 2560) and then retrieved into a computer for the purpose of ZMP calculation.

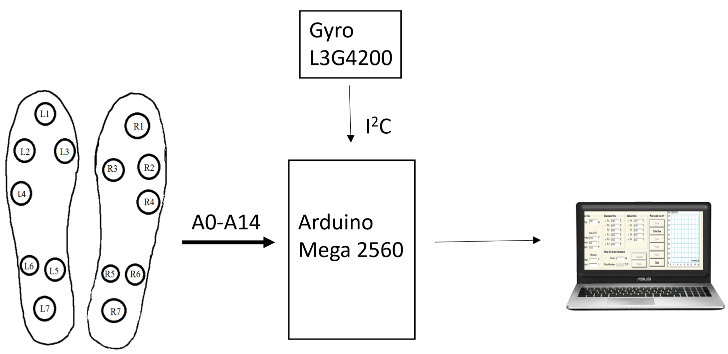


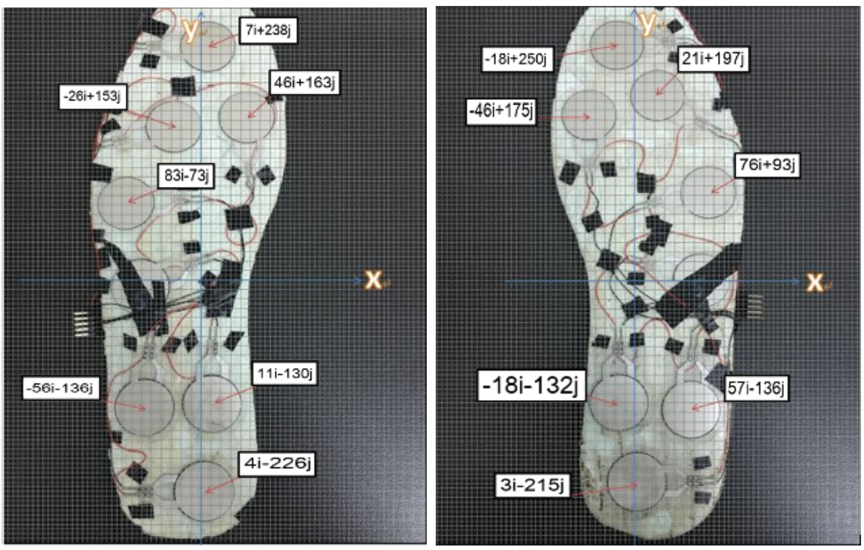
FIGURE 1. A plantar pressure detection system architecture

A gyroscope module uses an I^2C interface for transmission. It uses only two bidirectional open-drain lines, a Serial Data Line (SDA) and a Serial Clock Line (SCL), with pulling-up resistors for noise fluctuation error prevention. The acceleration for X, Y, and Z movement and the rate of rotation in space are measured using gyroscopes as a reference value that serves as a criterion for posture determination. During the experiments, a camera is set up, and reflective stickers affixed on the subject's hip, knee, and ankle joints as sampling point references.

2.2. **Pressure sensor and position vector.** Film pressure sensors (GD-25 100N, UneoTM) made of piezoresistive polymer composites are used. The sensor technology employs the latest advances in piezoresistive polymer composite processing and printing-based micromachining technology to enable simple and high-quality linear output in the form of variable conductance that is proportional to the input force. The pressure sensor is connected to the Arduino Mega 2560 with a sequence. In 1999, Vaughan et al. proposed the percentage share of a gait cycle and distinguished gait into eight phase points (0%, 10%, 30%, 50%, 60%, 70%, 85%, and 100%) [1]. These phase points can be accurately taken out of the pressure data and reference images can be used for comparison. After walking foot pressure data normalization software (MATLAB) is used to display the data as a parula colormap with 64 colors. The colormap is displayed in order to distinguish the relationship between the eight phase points and their respective pressure levels, and the center of gravity is calculated using the gravity method. The moving trajectory of the eight phase points derived from the gait analysis can be used to control the motor used to drive the exoskeleton robot. This process helps to build the walking model for the lower limb exoskeleton robot.

2.3. **Position of the center of gravity.** The pressure values measured through the plantar sensors can be used to observe the gait cycle, and they also serve as a reference indicator for dynamic equilibrium. When the center of gravity is within the range of the area of the foot, the user will be able to maintain balance; conversely, if falling outside the range, this may be a fall indicator. This data can be fed back to the exoskeleton robot controller. The formula in the Center of Pressure (COP) calculation is presented in Equation (1). Position vector $\left(\overrightarrow{COP}\right)$ can be calculated using position coordinates (x, y) and the measured value of the pressure force (F), as shown in Figures 2(a) and 2(b). The gravity parameters of plantar pressure in the human gait can be used to assess the situation when the foot is in a state of either dynamic or static balance. On the other hand, physicians can diagnose whether or not a subject's walking habits are correct and can also assess surgical recovery.

$$\overrightarrow{COP} : (x_{cop}, y_{cop}) = \frac{\Sigma(x_s, y_s) * F_s}{\Sigma F_s} \tag{1}$$

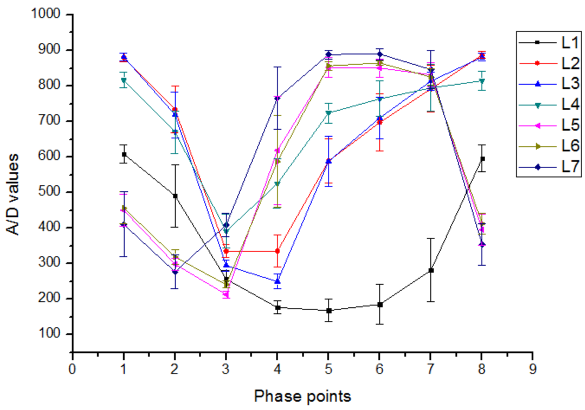


(a) (b)

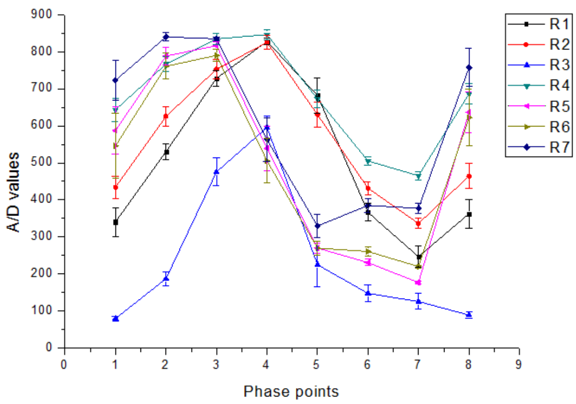
FIGURE 2. The position coordinates of both (a) left and (b) right feet

Table 1. Images of eight phases of a gait cycle

Initial contact	Loading response	Mid. stance	Terminal stance
			
Preswing	Initial swing	Midswing	Terminal swing
			



(a)



(b)

Figure 3. The relationship of eight phase points to a gait cycle for feet: (a) left, and (b) right feet

2.4. **Gait analysis.** In order to accurately obtain the eight phase points in our experiment, a movie was recorded during the gait period, and then the movie duration was increased 8 times. The actual movie was converted into slow motion (i.e., $\times 0.125$) in order to facilitate the capture of photographs of all eight phase points, as shown in Table 1. A gait cycle was between 1.35 and 1.6 seconds in the experiments.

3. **Results and Discussion.** In this study, a plantar pressure sensing device with a sampling time of 0.07 seconds was used. Each phase point in this period was calculated through the average of three gait cycles of the pressure data from toe (R1 or L1) to heel (R7 or L7) performance. The relationship of the eight phase points to a gait cycle for feet is shown in Figure 3. The gait cycle experiments were run six times, and the coefficient of variation of the right foot (R1) was between 1.2% and 12.6%. Due to the use of a micro controller clock, if the percentage of the selected point was not completely consistent with the definitions, then the previous point was used for the calculation since the errors would be only a few milliseconds when computing the eight phase points. Finally, the parula colormap was plotted to illustrate the data. The difference in value between the max. and min. was about 700 values. In order to calculate each phase point in a gait cycle by all of the data for the seven plantar pressure sensors, the rectifiable center of gravity

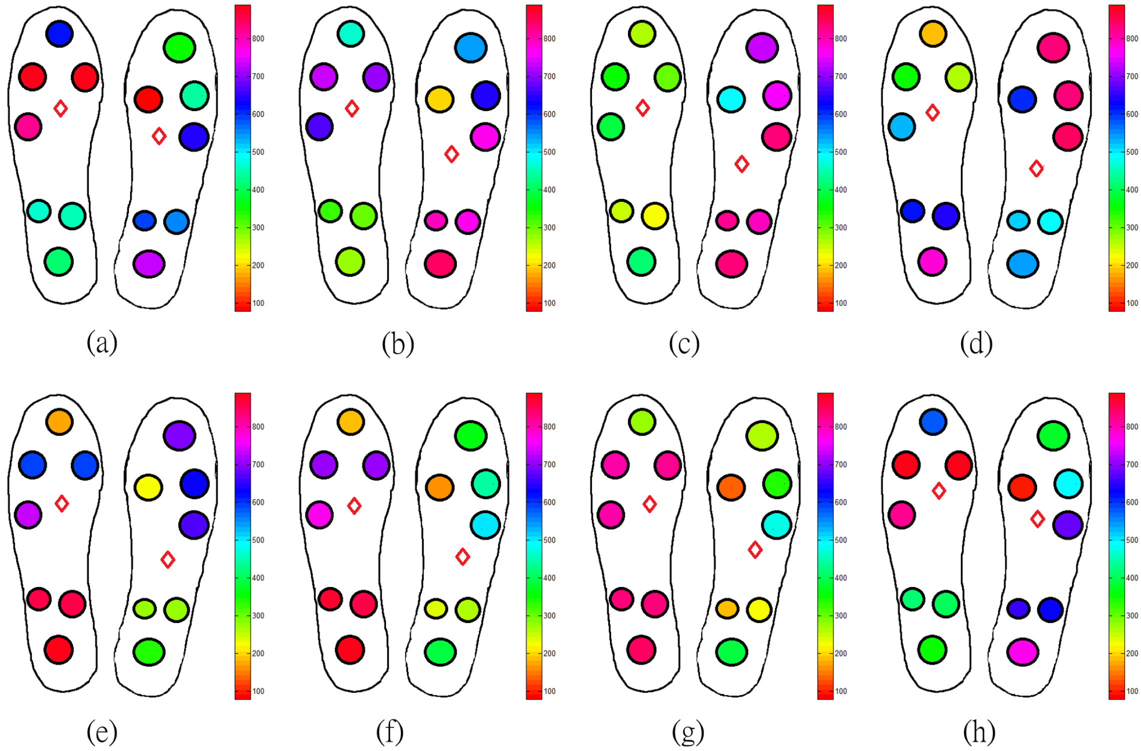


Figure 4. Pressure values are represented by the graph of HSV color gradation, where the diamond represents the center of gravity

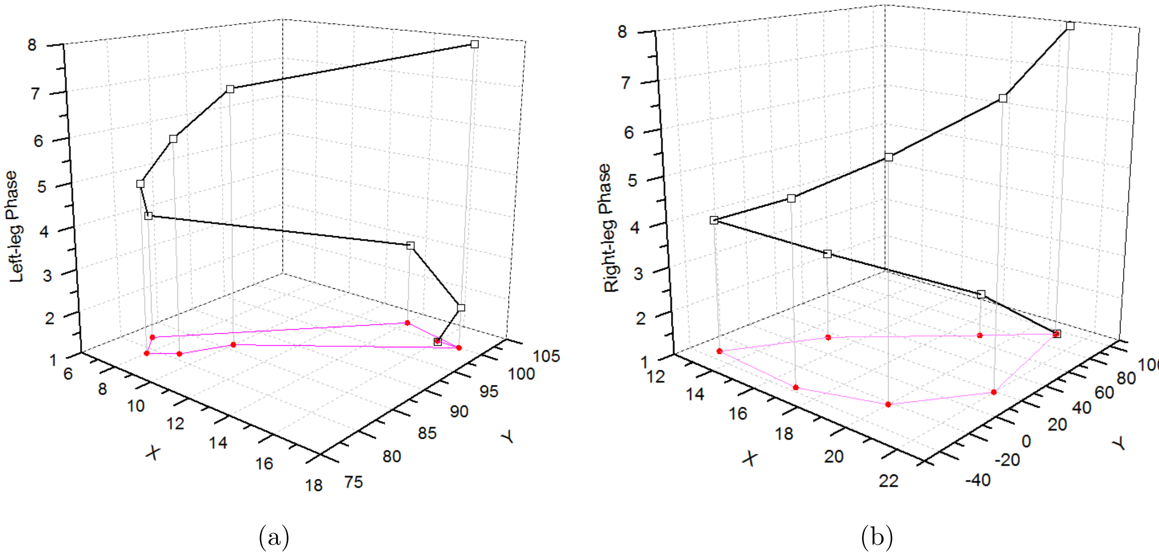


Figure 5. The trajectory of the center of gravity presents a closed curve in the gait cycle (a) left, and (b) right feet

position was obtained. The HSV color gradation is divided into 64 levels, as shown in Figure 4. Pressure values are represented by the graph, where the diamond represents the center of gravity. The amount of change and shift was obtained through the 3-D plot. In terms of the Z-axis for the phase points, the X and Y axes are the center of gravity of the plane coordinates using the Z-axis projection in the X-Y plane. The trajectory of the center of gravity presents a closed curve in the gait cycle, as shown in Figure 5. The position of the center of gravity will also return to the initial starting point in a complete gait cycle. The track of the center of gravity in a walking cycle will be in a limited range.

If it exceeds this range, it can be inferred that gait instability may result in a state in which the subject falls over.

4. **Conclusions.** This study proposes a gait detection system for low limb paralysis based on plantar pressure sensors. The gait detection system includes 14 pressure sensors, a data recording system and a post-analysis procedure. Regardless of the length of the gait cycle, the correct gait phase point can be obtained by using the definition of the eight phase points. The use of dynamic positioning images in experiments confirmed the state of the motion gait phase points to match a percentage definition of the cyclic nature of human gait. In order to obtain a phase point, the gait cycle must be calculated first. From the results, a normal gait will present a regular cycle. When a person walks in the gait cycle without conforming to this law, this may be diagnosed as gait instability or as someone with an abnormal foot. Lower limb paralysis or certain diseases can cause an abnormal gait. The proposed gait detection system provides feedback to the control system that can guide the patient toward a normal gait. This indicator may give the medical team a reference for health rehabilitation, and it also makes proper use of medical resources. The pressure data is obtained through normalization and a colormap display, where the pressure distribution in a normal walking gait and a center of gravity trajectory are presented. Both are used to calculate shifts of a patient with lower limb paralysis during walking and correction of the controller drivers will help stabilize the patient's gait.

Acknowledgment. This work is partially supported by the Ministry of Science and Technology, Taiwan, under the research grants 104-2815-C-269-018-E.

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