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Research paper

Low Cost Monitoring System of Ground Reaction Force during Normal Gait Cycle for Motion Control and Analysis of Active Ankle Foot Orthosis

Mohd Nor Azmi Ab Patar [1]*, Hokyoo Lee [2], Azim Patar [3], Muhammad Azmi Ayub [4], Aminuddin Hamid [5]

[1,5,6]Faculty of Mechanical Engineering, Universiti Teknologi MARA, Shah Alam, Selangor Malaysia
[3]Department of Neurosciences, School of Medical Sciences, Universiti Sains Malaysia, 16150 Kota Bharu Kelantan
[2]Department of Mechanical and Control Engineering, Niigata Institute of Technology, Japan
**Corresponding author E-mail: azmipatar@salam.uitm.edu.my*

Abstract

Human gaits are complicated motion where it involves synergy of muscle coordination, timing, and balance. Many people are unable to walk with normal gait pattern due to neuromuscular disorder. In order to support the weakness muscle, Active Ankle Foot Orthosis (AAFO) device is developed to provide permanent assistance and control the motion of the foot from being dragged during walking. One of the challenges that researchers has to face with the development of AAFO is providing an efficient transmission and producing continuous and smooth gait cycle. This paper proposes a real time gait phase detection system to control AAFO for rehabilitation and assist ankle motion. Real-time gait phase is obtained by measuring ground reaction force (GRF). The proposed system consists of AAFO equipped with ball screw actuator that provides direct assistance to control ankle joint during dorsiflexion and plantarflexion motion. Three force sensors were embedded insole and an encoder was attached at the ankle joint. The developed control algorithm shows that the real-time GRF measurement has the ability to enhance the AAFO functional performance and improve patient's gait.

Keywords: *Ankle Foot Orthosis, Ground Reaction Force, Real Time Measurement, Gait Phase Detection, Rehabilitation*

1. Introduction

Human movement generates a sequence of pattern or human gaits. Sometimes the human gaits are the same during walking, running or jumping. Sequence of normal human walking has a repeated gait due to multitude of joints in the human body; hence it creates a redundant degree of freedom at the foot [1]. Spinal cord injury is one of the neurological disorders which may have been caused by stroke and trauma. Normally it may be disturbed the ability to walk. Human gait can be analyzed by measuring the ground reaction force (GRF) [2] by placing force sensors at the bottom of foot. The GRF can be used to control the motion of Ankle foot Orthosis (AFO). Ankle Foot Orthosis (AFO) is a generic tools which improves gait in patients with neuromuscular diseases by optimizing specific muscles to restore its strength [3] during stability and strength exercises. Thus, it would enable more functional training programs to be implemented, which may result in a more effective transfer of these skills to actual daily life activities. It facilitates and assists the user to do repeated motion of lower limb. In conventional approach, this fatigue work is conducted by a physical therapist, who assists the targeted patients to make repetitive movements in parallel bar. In the precision expertise today, this job is nowadays handled by mechatronics actuator system for instance, servo motor, pneumatic air cylinder or hydraulic motor known as active ankle foot orthosis (AAFO) [4].

AAFO is an equipment with a microcontroller which optimize and controls critical angle of ankle motion during a passive exercise for ankle dorsiflexion and plantarflexion movements. These movements involve control algorithm to ensure that such motions imitate normal walking cycles. The control algorithm is categorized into three method which are passive, pre-programming and real-time method [5]. Passive method activates based on input information such as flexion angle, time taken and velocity which are automatically processed by the microcontroller. Once the device is triggered (ON), the user strides based on AFO movements until the device is turned OFF. Later, passive approach is more appropriate if the user's foot is off to the ground. Pre-programming method is useful and more practical to make AFO for striding on surface and it will also make dorsiflexion or plantarflexion based on pre-set velocity and angle of the ankle. Nevertheless, the motions do not imitate normal walking cycles perfectly and may affect the rate of walking recovery [6].

To overwhelm the limitation, real-time method is presented to Active Ankle Foot Orthosis (AAFO) microcontroller. In this research works, we focus on the integration of flexible force sensors [7] to regulate the servo motor rotations. Three force sensors are mounted properly underneath of AAFO's foot plate surface to sense ground reaction force data as the input to the microcontroller, therefore suitable motions can be accomplished based on suitable timings and user's ankle position during gait motions [8].

2. Ground Reaction Force Measurement

To create a smooth trajectory profile of the active ankle foot orthosis (AAFO), it is important to understand the types of force which is generated from foot during the walking motion of human body. The force exerted from foot is identified as ground reaction force (GRF) where it is acts under the surface of the foot during different human movement. It consists of vertical component and shear component acting along the contact area as shown in Figure 1. The shear component is a horizontal force exerted between the floor and foot to avoid human from slipping when walking and this force is small compared to vertical GRF. In AAFO, only vertical GRF is measured, the shear components are not measured. In other words, the GRF can be associated with acceleration of the centre of the mass as shown in equation (1), (2) and (3) where *m* is the body mass, *a* is acceleration of the centre mass and *R* is force at ankle joint [9].

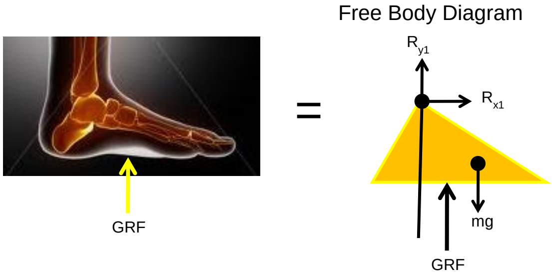


Fig. 1: Free Body diagram of force at ankle joint

$$\sum F_y = ma_y \quad (1)$$

$$R_{y1} + GRF - mg = ma_y \quad (2)$$

$$GRF = ma_y + mg - R_{y1} \quad (3)$$

3. Methodology

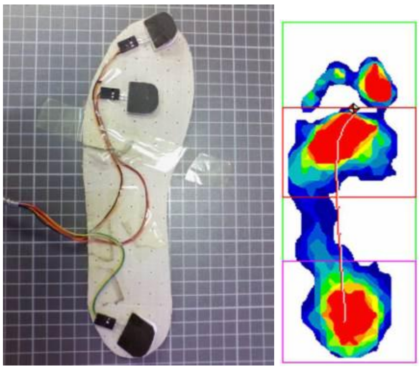
In order to achieve an accurate and real-time measurement of GRF, several aspects of the hardware and software of the system must be considered. These include sensor selection, placement of sensors, data acquisition and motion control. The details of these very important aspects can be summarized as follows.

3.1. Selection of Force Sensors

The selection of suitable sensors is significant to generate a smooth trajectory profile of human walking movements which resemble normal walking pattern. The selection of force sensor considers the following criteria; force range, frequency response and its bandwidth, repeatability, sensitivity, accuracy, environment condition and cost. Flexi force sensor [10], a force sensing resistor, meets these criteria well and this sensor technology is based on resistance. Force Sensing Resistors (FSR) are a polymer thick film (PTF) device which exhibits a decrease in resistance with an increase in the force applied to the active surface. Once force is applied to the active detecting region, it correlates to the variation of resistance detecting area relative to the vertical force applied [11].

3.2. Placement of sensors

Placement of force sensors is to ensure the best location to position the flexi force sensors in a proper manner to obtain a prominent pressure region acts between the foot and the support surface during daily life activities. An in-shoe based foot plantar pressure sensor F-scan system is a technology from Tekscan, displays pressure distribution on the foot. G.C. Trachtenberg [12] already done proof of concept trials using F-scan system and mapping the pressure region on the foot plantar while walking as illustrated in Figure 2.



(a) sensor placement on the in soles,, (b) Pressure distribution on foot [6]

Fig. 2: Force sensor placement and pressure distribution on foot

This portable device, with a custom-made sensor, consists of 960 sensing elements which are high sensitivity pressure sensor. It can measure pressure ranging from 345 kPa up to 862 kPa. Other benefits of F-scan are portable and compact to be implemented at different location and the force sensor can be customized to suit different users [13]. However, this F-scan sensor is slow and unsuitable for real-time motion control of the AAFO. From the walking cycles of a person at swing region and stance region, the force distribution is more intense at the minor region of the fore foot, at the heel and at the thumb. It can be concluded that force sensor must be place at the minor region of fore foot, thumb region and heel region where intensity of pressure distribution is found [14]. Therefore, three flexible force sensors are placed at those intensity of force areas.

3.3. Data acquisition and motion analysis system

The AAFO consists of three force sensors and one incremental encoder which feed into real time signals for processing in the microcontroller that controls the rotational motion of dc motor as shown in Figure 3 and Figure 4. The sensors installed on foot surface in contact with the footplate, receive analogue vertical force input from the body weight distributed on the sole of the foot during walking and standing phase. In analogue-to-digital converter (ADC) accepts an analogue input-a voltage or a current-and converts it to a digital value that can be read by a microprocessor. At that moment, it will be transferred into National Instrument Universal Motion Interface (NI UMI 7764) and then transmitted to microcontroller for the data to be in-depth processed and analysed. The processed data flow will be demonstrated by LabVIEW programming block in the term of LabVIEW block diagram G code. A microcontroller which is mounted with PCI-7740 interfaced card obtains angular displacement signals from the rotary sensor and transmits the data to the output in order to rotate the servo motor. The signals will also be analysed to obtain information on the ankle position control, velocity control, acceleration control and torque feedback control. The detected force data also output feedback to incremental encoder to detect motion at a specific angle and phase of gait cycle [15].
Several limitations and assumptions are made during measuring and detecting real-time gait cycle. There are only three parameters that vary; forces, time and the angle of joint. All other parameters such as the flatness of the treadmill surface, the momentum of the foot and the orientation of the foot and leg in the interaction between the floor or treadmill and the sensor are assumed to be constant. The motion involves only one degree of freedoms in dorsiflexion and plantar flexion directions [16]. There is no sliding motion between the foot and the sole. Only ankle joint is considered (i.e. excluding the knee and hip joint).

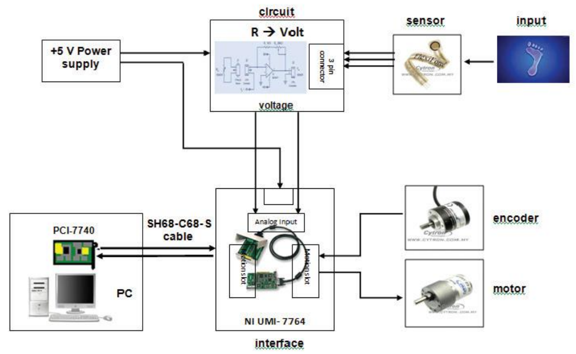


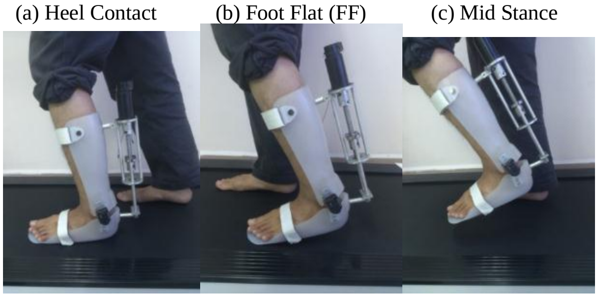
Fig. 3: Schematic diagram AAFO interfacing system [17]

(a) System overview of AAFO includes sensors and DC motor, rotary encoder and lead screw mechanism placement
(b) Calibration of pressure distribution under insole area
(c) Functional test of pressure distribution under insole area
Fig. 4: The system integration of AAFO mechanism with actuator and sensors [18]

3.4. System evaluation

To evaluate the effectiveness of AAFO system, experiments had been done using treadmill as machine to simulate walking on horizontal plane surface. The treadmill was moving in horizontal plane in which the speed could be tuned manually. The speed of the treadmill was set close to the average normal human walking speed which is at 3.0 m/s. For fast and slow walking speed, the treadmill was set at 3.5 m/s and at 1.4m/s, respectively. Pictures in Figure 5 shows a healthy subject wearing the AAFO on the left foot and walking on the treadmill. The subject walked at constant speed and then 3 gait cycles were captured. The experiment was repeated for 10 times and the subject was given 5 minutes rest time in between the experiments to avoid from being exhausted.

(a) Heel Contact (b) Foot Flat (FF) (c) Mid Stance

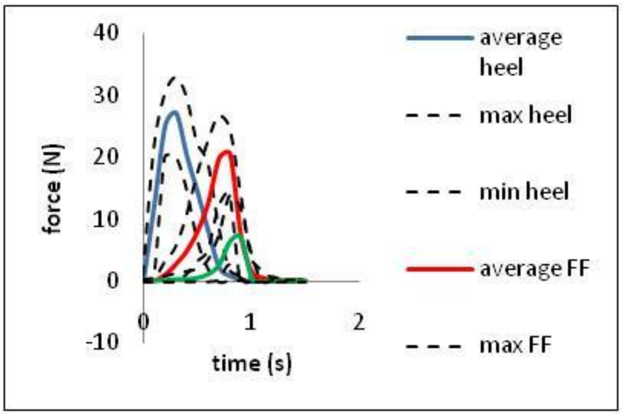


(c) Heel Off (d) Toe Off (e) Swing Phase
Fig. 5: The AAFO functional motion control was tested on healthy volunteer

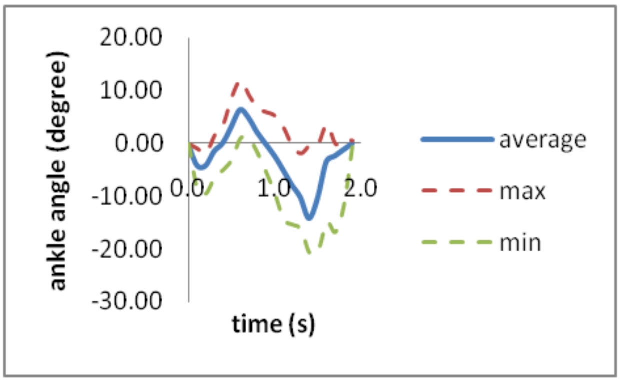
4. Results and Discussions

The device had been tested on a healthy person using a control algorithm that was developed previously. During normal walking condition, three parameters data of ankle joint angle, force distribution on foot and gait phase were collected. The range of GRF results based on three forces sensors at the heel, the fore foot and the end foot were plotted as shown in Figure 6. Based on the feedback from these sensors shown in Figure 7, the dc motor was controlled in real-time and Figure 8 shows the rotational motion of the DC motor. The gait cycles were repeated ten times and the range of the results is shown in Figure 6. Measurements of GRF were successful where the DC motor rotated and followed the range of gait cycle motion as shown in Figure 7.

The experimental results show that the force sensors functioned well and the signals can be used to control the DC motor. The DC motor can be rotated to provide dorsiflexion and plantarflexion motion based on control algorithm that has been created.



(a) The range of GRF results based on three forces sensors at the heel, the fore foot and the end foot



(b) The range of ankle angle of rotation results based on rotary encoder at the ankle joint
Fig. 6: Range of GRF and ankle angle of rotation results for normal gait cycle

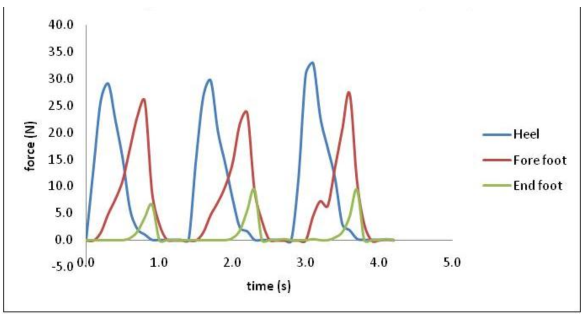


Fig. 7: Example result of GRF for normal gait cycle

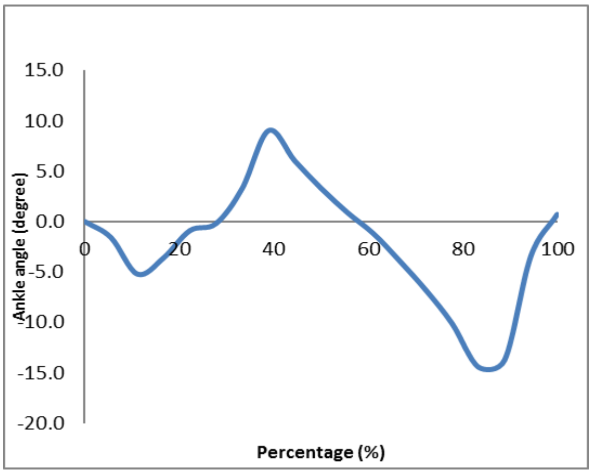


Fig. 8: Example result of ankle angle rotation motion for normal gait cycle

5. Conclusion

The AAFO system proposed three force sensors embedded insole shoe to determine the phase of gait cycle. The performance of the force sensing unit was verified by healthy subject [19] wearing the AAFO embedded with sensor and walking on treadmill [20]. The output of the proposed method is successful to detect every gait phase and produces continuous and smooth motion phase of gait cycle during walking.

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