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The Development of Control System for Orthofes

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ABSTRACT

This paper presents the development of control system to control the walking sequence of OrthoFES for paraplegic walking. A new methodology for paraplegic gait, based on exploiting natural dynamics of human gait, is introduced. The work is a first effort towards restoring natural like swing phase in paraplegic gait through a new hybrid orthosis, referred to as Orthosis-Functional Electrical Stimulation (OrthoFES). This mechanism simplifies the control task and results in smooth motion and more-natural like trajectory produced by the flexion reflex for gait in spinal cord injured subjects. Results show that the OrthoFES can be control according to the walking sequence by controlling the brakes and FES.

Keywords: OrthoFES, paraplegic, control system

1. INTRODUCTION

Paraplegia is impairment in motor and/or sensory function of the lower extremities. It is usually the result of spinal cord injury (SCI) which affects the neural elements of the spinal canal. Sisto et al. [1] reported that more than 200,000 people in the United States (US) suffer from SCI and each year 10,000 new cases occur. Brown-Triolo et al. [2] in their study found that 51% of SCI subjects defined mobility in terms of life impact and autonomy, and gait was found to be perceived as the first choice in possible technology applications. Their subjects also indicated willingness to endure time intensive training and undergo surgery operation if mobility is guaranteed. Therefore, solutions to mobility loss were seen as an exciting prospect to these patients.

Restoring gait in SCI is a research challenge. Researchers have investigated various electrical, mechanical and combined techniques also called hybrid orthosis to restore functional movement in the lower limbs [3-10]. Among the gait phases, the swing phase is important in advancing the leg in order to contribute to movement of the body in the direction of gait progress. Hip flexion is an essential part of pick-up in the swing phase of reciprocal gait, whilst passive hip extension is important during the trunk glide in stance. Researchers have attempted to provide hip flexion to improve walking by a method called functional electrical stimulation (FES). FES was first introduced in 1967. It is a technique that uses low level of electrical current to stimulate the physical or bodily functions lost through nervous system impairment, caused by paralysis resulting from SCI, head injury, stroke or other neurological disorders, restoring function in people with disabilities [11]. Currently, applications of FES include standing, walking, cycling, rowing, ambulation, grasping, male sexual assistance, bowel-and-bladder function control and respiratory control. Moreover, paraplegic walking with only FES has significant drawbacks in function restoration. Firstly, due to stimulated muscle contractions, muscle fatigue will quickly occur because of the reversed recruitment order of the artificially stimulated motoneurons. As a result, there are limitations in standing time and walking distance. Another disadvantage is erratic stepping trajectories because of poor control of joint torque due to withdrawal reflex [12].

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Hybrid systems can overcome these limitations by combining FES with the use of a lower limb orthotic brace and might allow paraplegics to ambulate in more natural, efficient manner than they might with traditional passive orthoses. Orthoses can guide the limb and reduce the number of degrees of freedom in order to simplify the control problem. The use of active muscle can also be reduced by locking orthosis joints [13]. Moreover, the approach is useful to support body weight, protect the joint and ligament [14]. Furthermore, its rigidity improves walking efficiency and reduces overall energy cost [15]. Several hybrid systems have been developed. The first hybrid orthosis system combining powered orthosis with FES called hybrid assistive system (HAS) was introduced by Tomovic in 1972 [16]. The work in HAS was continue by Popovic and Schwirtlich [17-19]. HAS has subsequently been changed to powered orthosis because of use of DC motor in the orthosis. Powered orthosis consists of a small direct current (DC) electric motor installed at one or more joints with or without electrical stimulation support. A functional movement closely mimics the swing phase of gait than the flexion reflex [8, 18-19]. However, this type of hybrid system is not used in practice because of the size and weight of motor and batteries.

The most widely tested orthosis is named reciprocating gait orthosis (RGO) [4,7,9]. This mechanism moves the contralateral limb forward by using surface stimulation of hip extension. Then, by alternating stimulation of the hip extensors, walking can be achieved with less energy consumption. However, during the leg-swing phase the body requires to be lifted by the arm with the help of crutches, making it difficult to produce foot clearance. Consequently, muscle fatigue will quickly occur [9]. Goldfarb et al. [13] used controlled-brake orthosis, which is able to address the constraint of FES-aided gait by combining FES with a controllable passive orthosis. This hybrid system includes computer-regulated friction brake at the hip and the knee. Muscle fatigue is reduced by locking the brakes during stance phase and turning off stimulation to the quadriceps muscle. Moreover, leg movement repeats smoothly during the swing phase.

Durfee and Rivard [20] introduced energy storage orthosis (ESO) which can be driven through a complete gait cycle. This mechanism uses stimulated muscle power to move the limb and also to drive the orthosis structure, storing energy in the process. Gas springs crossing the hip and knee joints are flexed equilibrium energy-storage elements. The energy store and transfer systems comprise a pneumatic fluid power system connected between knee and hip joints. This can capture the excess energy during the quadriceps stimulation in order to transfer to the hip and release at appropriate instant to achieve hip extension.

Kobetic et al. [21] introduced their hybrid orthosis called hybrid neuroprosthesis (HNP). The system uses 16 channels of FES stimulation delivered via chronically indwelling intramuscular electrodes to activate 8 different muscles for the knee, hip and ankle flexion and extension. Electrodes are connected to an external control unit (ECU) temporarily or permanently to an implanted generator powered and controlled via radio frequency by ECU. The variable constraint hip mechanism (VCHM) consisting of hydraulic system with double acting cylinders linked to each hip joint and controlled by energizing specific solenoid valves is designed to maintain hip posture. The result obtained from the clinical test with one paraplegic subject is promising. However, the system size and weight undermine its advantages for the user.

In this paper, a hybrid OrthoFES gait system which combines mechanical braces (with coordinated joint locking mechanism) with an energy storage element mounted on it and FES to generate the swing phase of paraplegic gait is presented. This approach also substantially simplifies and reduces the problem of control tasks in a hybrid orthosis while offering more benefits on quality of a swinging leg.

2. METHODOLOGY

This section will explain in details methodology that has been carried out in developing OrthoFES system. It will be separated into 2 main parts. The first part will discuss the development of OrthoFESorthosis. In this section, the selection of brakes and materials used for this development will be discussed. The second

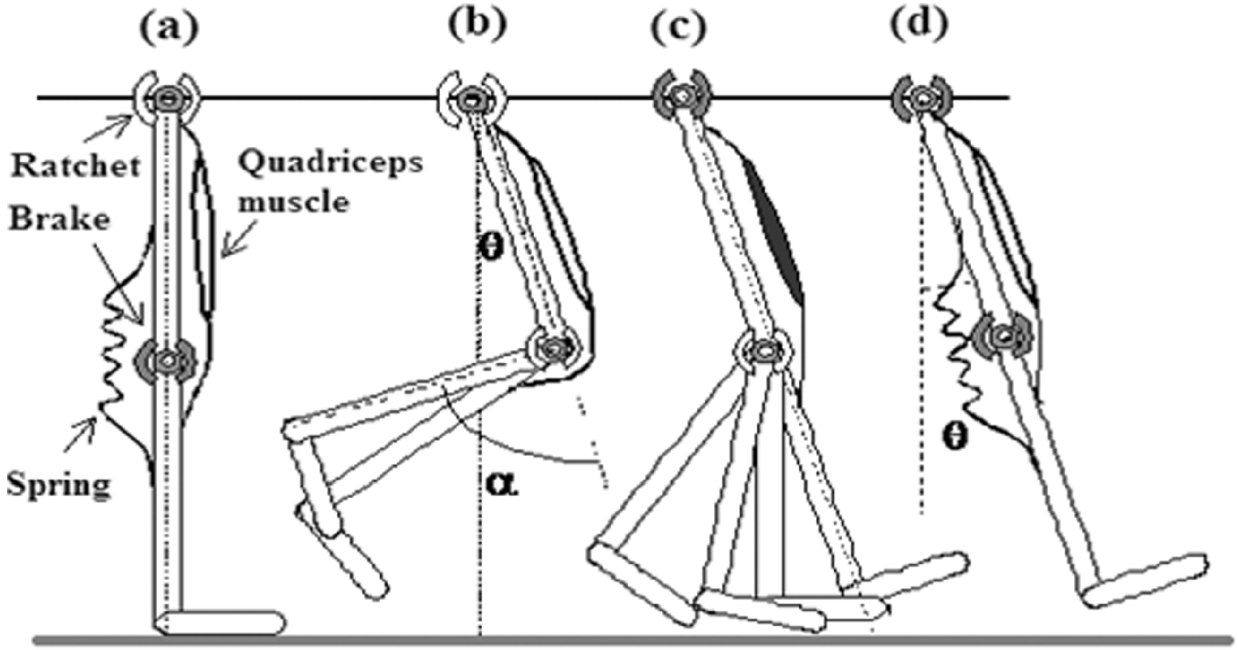


Figure 1: OrthoFES swing phase synthesis.

part will discuss the control system develop to control the brakes and FES circuit to control the movement of paraplegic with OrthoFES.

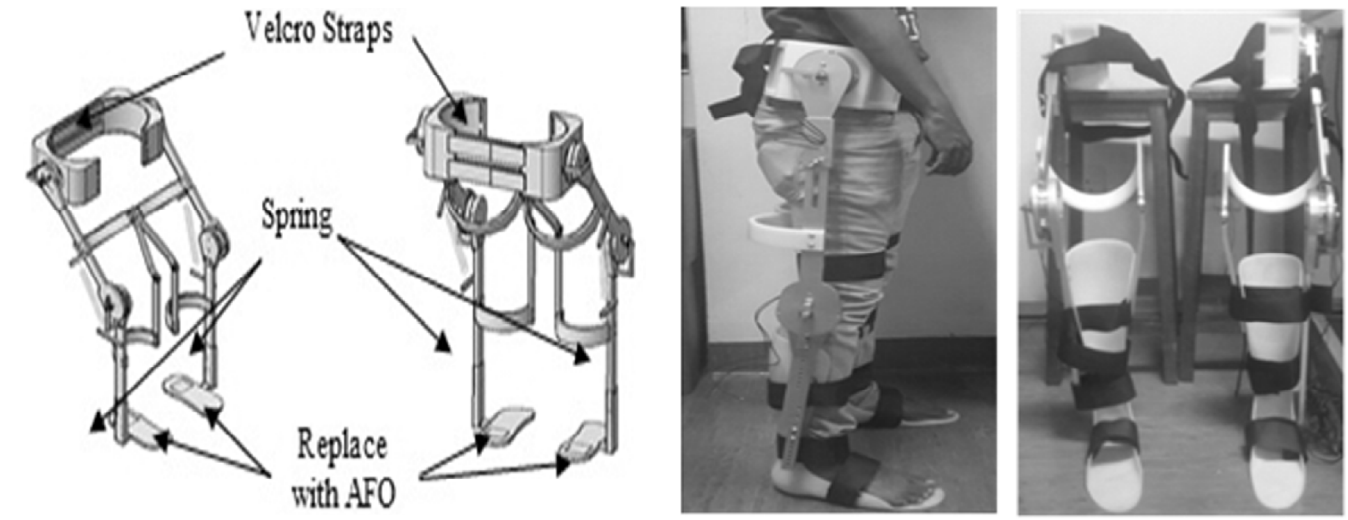
Before all main parts can be discussed in details, the walking phase using OrthoFES will be explained. Figure 1 demonstrates the swinging leg in the OrthoFES. To synthesize the swing phase of gait using the OrthoFES, the following procedure is required. Once the brake at the knee is released, and the spring causes the knee to begin to flex. This will then cause FES to take part where, quadriceps muscle is stimulated to extend the knee against the spring torque. Next, when the knee is fully extended the brake at the knee is applied and quadriceps stimulation is turned off. The user will move forward and complete the walking cycle and this cycle will repeat. The synthesis of the process is shown in Figure 1. It can be seen that it is possible to obtain knee flexion, knee extension and hip flexion using only a single channel of stimulation per leg.

2.1. OrthoFES Development

In this study, a potentiometer is used as a sensing element to measure hip and knee angles. In the orthosis development, two potentiometers are used for each leg. It is mounted at outer side of knee and hip of the leg frame.

A controlled magnetic brake is the main part in those types of hybrid orthosis which use the brake as a dissipative element. Considerations for selecting a brake technology include peak resistive torque, control bandwidth, size, weight and residual friction. One parameter in selecting a brake is low free rotation friction and low inertia. This is a simple switchable brake with a spring elastic element with well-defined properties provides the necessary function and trajectory. The specifications of the brake are as follows; the model is 111-08-12G-24V and the manufacturer by Miki Pulley. The magnetic brake is using 24 V and maximum torque is 50N-m.

The construction of the leg orthosis has been designed using AutoCAD before the fabrication process is carried out. Figure 2(a) shows the final design for this project. The main material used for the frame is alloy. The alloy is very light in weight and suitable to use at external bracing for leg orthosis. The ankle-foot part is replaced with AFO which is Ankle Foot Orthosis which is made of plastic.



(a) OrthoFES using AutoCAD (b) Actual OrthoFES.

Figure 2: OrthoFES

Figure 2(b) shows the actual OrthoFES after fabrication process takes placed. The OrthoFES is fabricated according to the specifications needed. The design is applicable and flexible depending on the patients. The size of the OrthoFES can be adjusted according to the patient's size.

2.2. OrthoFES Control System

This section will discuss the development control system to be applied for OrthoFES device. The development of OrthoFES control system includes two parts, which are software and hardware construction. The first stage is to design the programming part. The control sequences will follow the walking sequence in Figure 1. There are two brakes and FES need to be controlled for each leg. Then the hardware control part will be developed. It consists of relay, potentiometer (attached to the frame) and Arduino.

In this part, the Arduino controller is used to regulated the condition of FES and electromagnetic brake at leg orthosis whether on and off state according the analog input obtained from the potentiometer that acts as an angle sensor of OrthoFES. A relay module is an electrically operated switch that allows the user to turn on or off a circuit using voltage and/or current much higher than the Arduino could handle. There is no connection between the low voltage circuit operated by Arduino and the high power circuit. Besides, the relay module protects each circuit from each other. The use of relay module will enable the OrthoFES can be controlled remotely by external devices.

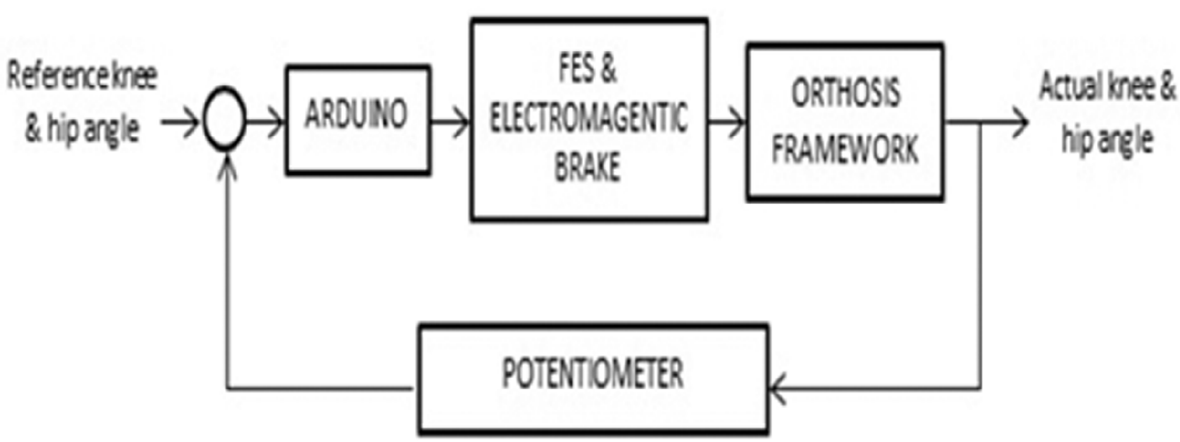


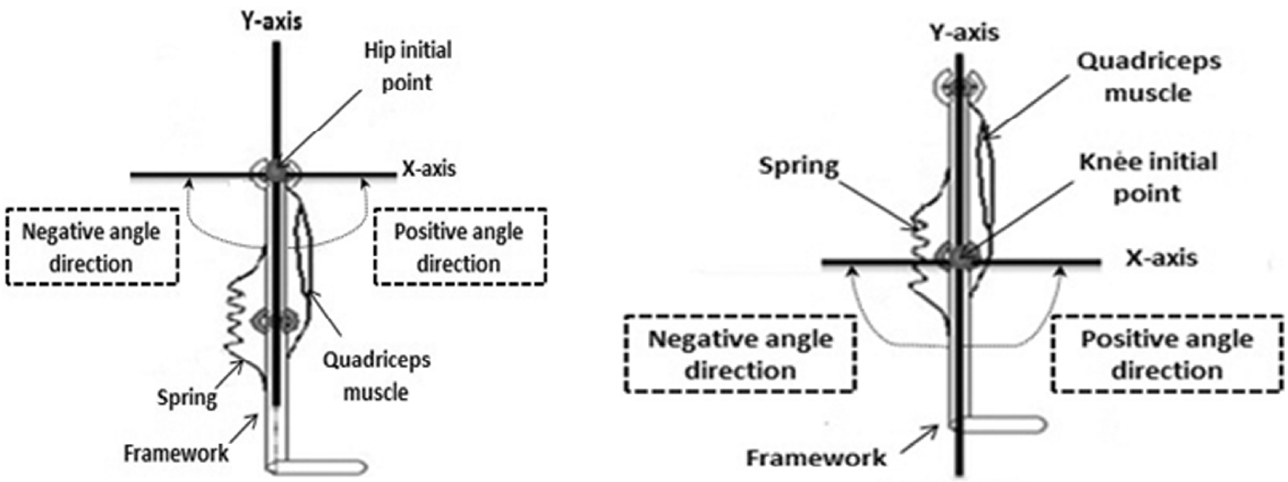
Figure 3: Control block diagram

Figure 3 shows the close loop control block diagram that represent the performance of the system controlling functional electric stimulation (FES) and magnetic brakes of OrthoFES. The comparison of the output ADC value has been converted from angle rotation of potentiometer with the desired set value of ADC then will generate a signal to the Arduino controller. The set of instruction that has been programmed according the step sequence of walking gait has been stored in Arduino controller.

4. RESULTS

In this part, the OrthoFES control system has been tested on a healthy subject to ensure the control system is running according the sequence in Figure 1 and suitable for paraplegic patient's condition. The hip and knee angles produced from walking with and without OrthosFES have been obtained and comparison will be made.

Figure 4(a) shows the angle reading from the hip's sensor during hip movement. When the framework is moving forward (hip extension), the sensor will read as positive value while the sensor will read as negative value when the framework is moving backward (hip flexion). Figure 4(b) shows the angle reading from the



(a) Hip angle direction **(b) Knee angle direction**

Figure 4: Reference for hip & knee angles

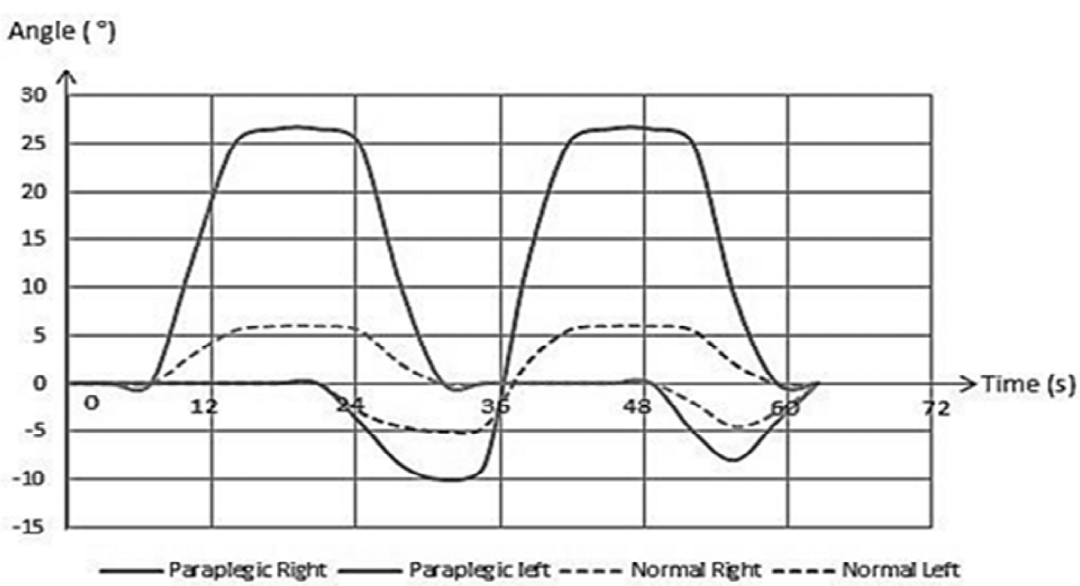


Figure 5: Hip angles for one gait cycle of paraplegic & normal subjects

knee's sensor during knee movement. When the framework at knee part is extended, the sensor will read as positive input while the sensor will read as negative input when the framework at knee part is flexed.

Figure 5 shows the hip angle for one gait cycle obtained from paraplegic and normal subjects. It is show that the maximum angle recorded at hip sensor for paraplegic subject is more than the maximum angle for normal subject. The different maximum hip angles obtained for both walking condition is about 20° at maximum extension while -5° is the maximum angle the hip can move in the opposite direction. It is because the normal walking is done by a voluntary movement while the paraplegic walking is done according to the waling sequences controlled movement with help from OrthoFES. It is important for paraplegic walking to has the larger hip extension than hip flexion because a subject needs a sufficient foot ground clearance while a subject has normal walking can control their toes and have a sufficient foot ground clearance.

Figure 6 shows the one gait cycle obtained at knee sensor from paraplegic and normal subjects. Knee flexion recorded from paraplegic subject is more than the knee flexion recorded from normal subject. It is because the normal subject does not needs to provide the large angle of knee flexion before knee extension while the paraplegic walking needs to provide the larger angle of knee flexion before knee extension. This is to make sure the step is long enough to balance the body weight and to lower down the point of body centre for the subject with lower limb disability.

5. CONCLUSION

The development of OrthoFES is to eliminate reliance on the withdrawal reflex and the associated problems of habituation and poor controllability in paraplegic walking. Instead, a simple switchable brake with a spring elastic element with well-defined properties provides the necessary function and trajectory. This paper presents a simple control system using arduino to control all 4 brakes (2 at the hip and 2 at the knee for both sides) and 2 channels of FES (for each leg). From the results, it can be concluded that all brakes and FES can be controlled according to the sequence set for the OrthoFES. There is a smooth walking gait with higher angles produced by paraplegic with OrthoFES compared with normal subject. This occurred to overcome all the problems associated with the orthosis discussed in the introduction section.

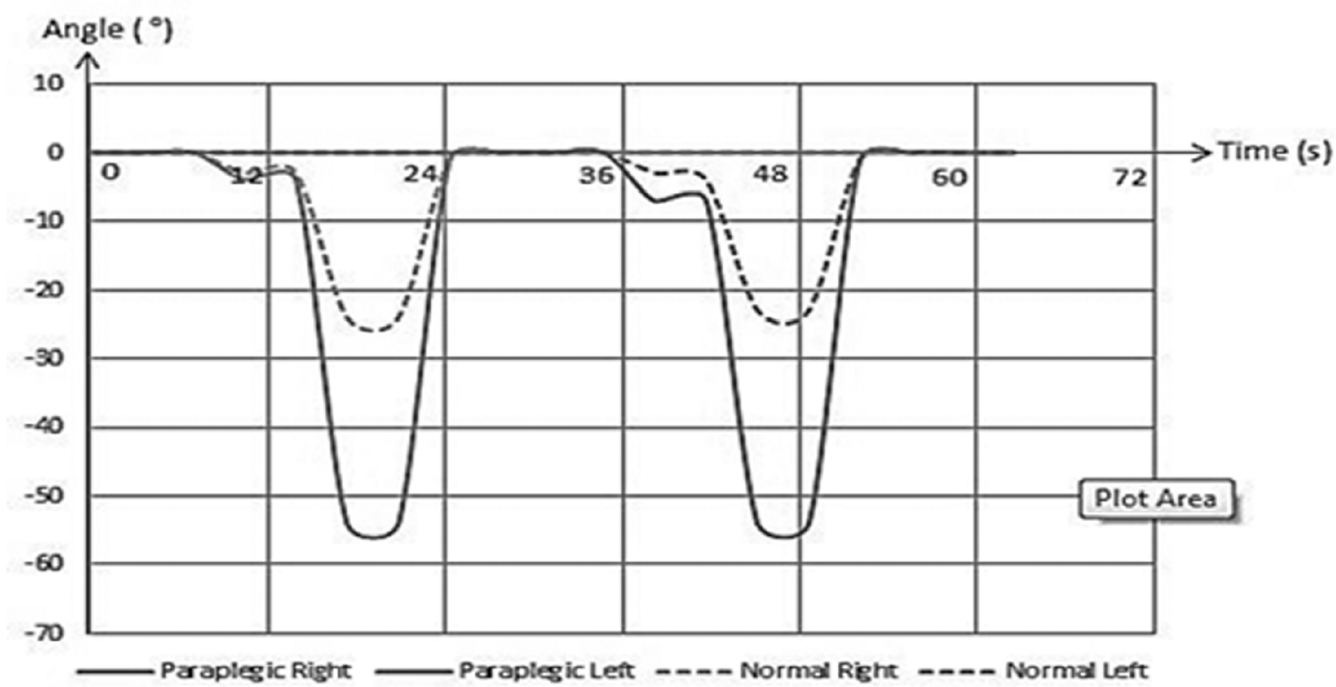


Figure 6: Knee angles for one gait cycle of paraplegic & normal subjects

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