SMEIR

The 8th International and 19th National Conference
on Manufacturing Engineering
ICME2023, 9-10 March 2023, Mashhad, Iran

Ferdowsi University
of Mashhad

A Fuzzy Gait Phase Detection for Rehabilitation of Hemiplegic Patients with a Hip Exoskeleton Robot

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Abstract

Movement disorders, caused by a variety of factors like aging, stroke, and spinal cord injuries, may largely decrease the quality of life of the affected people. Compared to traditional methods, robotic neurological rehabilitation methods have shown promising results in improving the performance of the patients. In this paper, a novel algorithm is proposed for rehabilitation of hemiplegic stroke patients, using a hip exoskeleton robot. The proposed algorithm includes a fuzzy inference engine that receives the angle and the angular velocity of the hip joint and estimates the current gait phase of the user. Upon detecting the initiation of the swing phase of the affected leg, the corresponding hip motor of the robot applies a predefined assistive torque for a given period of time. When the assist period is finished, a zero-impedance controller will take over the control of the robot with a minimum contact force. The performance of the proposed algorithm is experimentally evaluated using a prototype of a custom-made hip exoskeleton. The experimental results verify the successful performance of the designed fuzzy inference engine in proper timing of the assistive torque, by the precise detection of the correct gait phase of the hemiplegic stroke patients.

Keywords: *Robotic rehabilitation, Hip exoskeleton robot, Hemiplegic stroke patients, Rehabilitation strategy, Fuzzy gait phase detection.*

Introduction

Observing the age trends of the population in different decades, it is evident that the average age of the population is increasing in different countries, including Iran. Figure 1 depicts the percent of the elderly population and its ascending trend for Iran country. Aging will be associated with various problems, such as weakening the neuromuscular system and movement disorders. On the other hand, injuries and natural and unnatural events such as stroke and surgery will also cause movement disorders in people. According to the latest available statistics, every year, about 795 thousand people experience a stroke [1], which, along with the number of joint replacement surgeries, the number of MS patients, and the number of older people, shows the high number of people with movement disorders. These people may be subject to multiple problems such as depression, staying at home, dependence on others, and the reduced quality of life [2]. Moreover, patients with moderate to severe stroke, suffer from with several abnormal features, including irregular stride time and length, reduced walking speed, impaired control of joints and postures, muscle weakness, and abnormal patterns in muscles activities, especially on the affected side. These problems strongly affect their mobility and daily life activities [3]. Reduction of the adverse effects of these problems requires carefully designed rehabilitation processes.

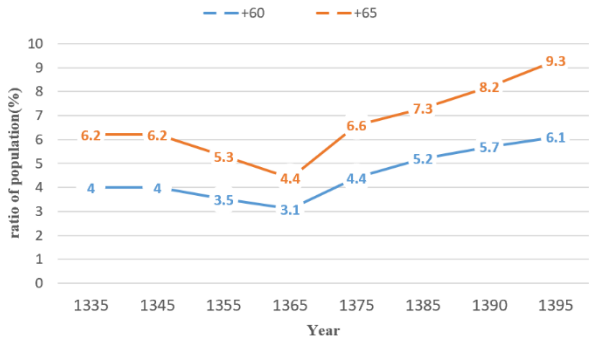


Figure 1: The diagram of the ratio of the elderly population of Iran between 1335 and 1395 AH [4]

Compared to the traditional methods of physiotherapy, robotic rehabilitation methods may increase the speed and the effectiveness of treatment, reduce dependence on others, and reduce the complications of the therapy based on the implemented control strategies. In a study [5], it was shown that the use of an exsokeleton robot for stroke patients can be more effective than traditional physiotherapy, in terms of walking speed, walking endurance and balance.

Exoskeleton robots are a group of wearable robots that may help people in the field of rehabilitation by combining the machine power with human intelligence. In recent years, different control methods and rehabilitation strategies are proposed for exoskeleton robots. Wu et al.[6] have designed a hip exoskeleton robot (PH_EXOS) using Bowden cable with six degrees of freedom to interact with the user as well as possible. They have used a PID control for passive mode and a fuzzy adaptive controller for active control mode. Another control method is based on force sensors that measure the forces exerted by the user's muscles or the exoskeleton. These force signals can be used to estimate the user's intended movement and provide appropriate assistance. In [7], force sensors(FSR) are used to control the robot. In this method, by measuring the interaction between the user’s leg and the robot, the force required to help the person is estimated. A controller for exoskeleton robot using Electromyography (EMG) sensors is introduced in [8]. Maghrebi et al [9], have designed a hybrid control algorithm for a hip exoskeleton robot, consisting of a sliding mode controller and an impedance controller. In this method, the trajectory of the unaffected leg is recorded and considered as the desired trajectory, to be implemented on the affected leg by the designed controller. A zero-impedance controller is also designed to eliminate resistive forces on the healthy leg. The method is implemented on FUM-HEXA, a custom-made hip exoskeleton robot, designed and manufactured at the center of advanced rehabilitation and robotics researches at Ferdowsi University of Mashhad [10]. Delayed output feedback control (DOFC) [11] is another method of controlling assistive wearable robots. In this method the assistive torque is simply defined proportional to a delayed feedback from of the angle difference between the two legs. A problem with this method is that if the person moves at different speeds and in different conditions, the time delay must change accordingly. Kalani et al [12], used a deep reinforcement learning algorithm to find the optimal time delay in various conditions. The results verified that a proper adjustment of the time delay is an essential requirement for the efficiency of the DOFC algorithm.

Control systems for lower-body wearable robots can be implemented in passive or cooperative ways. In the passive methods, the robot imposes a specific trajectory on the wearer’s limb. In the cooperative methods, the person interacts with the robot in the process of movement. A part of the movement duties is the responsibility of the wearer and the robot has an auxiliary role. Studies have shown that if the patient interacts with the robot and performs part of the movement tasks voluntarily, the effectiveness and speed of the treatment increase [13]. Based on this theory, another method designed to control lower-body wearable robots is a strategy called assist-as-needed (AAN). In this method, the patient voluntarily participates in the treatment process and the robot applies the assistive torques in proportion to her/his need. For example, in [14], an AAN controller is designed by combining an adaptive torque controller and an impedance controller. In this research, the level of the assistance need of the patient is defined by a strength index that includes the magnitude of the interaction forces and the position tracking errors. The patient should be the initiator of the movement. Then, the assistance level is calculated based on the value of the strength index and the robot applies assistive torques on the affected hip joint, accordingly

Some rehabilitation methods are designed to provide the assistive torques in specific phases of the gait. In these methods, different sensors, such as IMU, FSR, EMG, etc., are used to detect the motion phase. For example, Shahmoradi and Shouraki [15] have proposed a method for detection and classification of different motion states using IMU and FSR sensors. In [16], insole sensors are used to measure the ground reaction forces and detect the motion phase. In [17], smart insole are used, along with a fuzzy algorithm, to detect the motion phase during the gait cycle. Also in [18], insole sensors are used along with an adaptive network-based fuzzy inference system, to detect the walking phases.

Despite the increasing number of works in this area, it is still an open area of research to design and optimize different strategies for the detection of human motion phases and for the control of exoskeleton robots. This research presents an intelligent phase detection algorithm using a fuzzy inference engine. The proposed fuzzy system is used to detect the motion phase of the users and to define the correct timing for the application of assistive forces. The proposed algorithm is experimentally implimented on the fourth version of the Hip Exoskeleton for Assist (FUM-HEXA-IV), designed and manufactured in the Center of Advanced Rehabilitation and Robotics Researches at Ferdowsi University of Mashhad (FUM-CARE).

This paper is structured as follows; Section II provides a summary of the mechanical design of the FUM-HEXA-IV robot and its physical characteristics. The proposed fuzzy phase detection strategy is detailed in Section III. Finally, Section IV provides the results of the implementation of the proposed algorithm on FUM-HEXA-IV with a hemiplegic stroke patient.

II. FUM-HEXA-IV Robot

The FUM-HEXA-IV robot is a wearable single-joint lower-body robot with an active Hip joint, designed and manufactured in the Center of Advanced Rehabilitation and Robotics Researches at Ferdowsi University of Mashhad (FUM-CARE). This robot is designed and built to rehabilitate neurological patients, especially stroke patients with hemiplegia. To improve the user comfort and the efficiency of the robot, the structure of the robot and its actuation mechanism is optimized to have a low weight while maintaining a high torque capcity. Moreover, the dimensions of the robot are adjustable to fit to the patients of different heights. Also, the control algorithm of the robot is designed to apply assistive torques with a magnitude and duration proportional to the patient’s need.

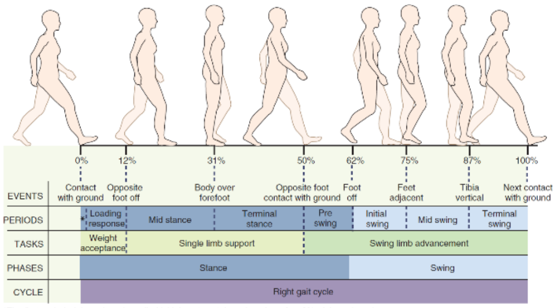
The robot weighs about 5.5 Kg and can apply a maximum torque of 16 N.m at each hip joint, actuated by a 160 Watt Maxon EC90 motor and a AG Harmonic Drive gearbox.

Figure 2: FUM-HEXA-IV Robot

III. Proposed Fuzzy Gait Phase Detection Algorithm

The human gait cycle of each leg generally consists of two main phases, stance and swing. At an average walking speed, the stance phase constitutes almost 60% of the gait cycle, and the swing phase forms the remaining 40%. The swing phase can be divided into three sub-phases: initial swing, mid swing, and terminal swing. The stance phase also includes five subphases: initial contact, loading response, mid stance, terminal stance, and pre-swing [19]. These subphases are depicted in Figure 3.

Different methods can be used to detect the gait phase, according to the data received from the sensors embedded in the robot. This paper proposes a fuzzy algorithm for this purpose. Considering the influence of many factors and the resulting uncertainty in detecting the motion phases, fuzzy logic can work better than deterministic methods and can perform better in neurological and stroke patients with abnormal movements.



*The first period of the gait cycle, called initial contact, takes place from 0 to 2% of the gait cycle

Figure 3: Human gait phases [19]

The block diagram of the proposed fuzzy algorithm is shown in Figure 4, where $\theta_{uh,h}$ represents the measured signal from the angle of the affected leg (uh) and healthy leg (h), $\dot{\theta}_{uh,h}$ the estimated angular velocity for the affected leg (uh) and healthy leg (h), $f_{uh,h}$ the raw signal measured from the contact force between the robot and the affected leg (uh) and healthy leg (h). Each motion phase can be expressed as the following logical conditions.

- **Rule I:**
  If the angle of the affected leg is big negative and its angular velocity is close to zero, then it is the pre-swing phase of the affected leg.
- **Rule II:**
  If the angle of the affected leg is big negative and its angular velocity is small positive, then it is the initial swing phase of the affected leg.
- **Rule III:**
  If the angular velocity of the affected leg is big positive then it is the mid-swing phase of the affected leg.
- **Rule IV:**
  If the angle of the affected leg is big positive and its angular velocity is close to zero, then it is the terminal swing phase of the affected leg.

To implement the fuzzy algorithm, the big positive, big negative, and close to zero terms, as well as, the motion phases are mathematically defined. This is done by setting membership functions, as shown in Figure 5. The membership functions and the parameters of these functions are determined empirically. By using these functions, the provided rules can be implemented. These rules can be mathematically expressed as follows.

- **Rule I:**
  If θ_{uh} is BNA and $\dot{\theta}_{uh}$ is ZS, Then Y is P_1 (1)
- **Rule II:**
  If θ_{uh} is BNA and $\dot{\theta}_{uh}$ is PS, Then Y is P_2 (2)
- **Rule III:**
  If $\dot{\theta}_{uh}$ is BPS, Then Y is P_3 (3)
- **Rule IV:**
  If θ_{uh} is BPA and $\dot{\theta}_{uh}$ is ZS, Then Y is P_4 (4)

where, Y is the output mediator variable, BPS represents big positive speed, PS is positive speed, ZS is a speed close to zero, BNS is big negative speed, BPA is big positive angle, ZA is an angle close to zero, and BNA is big negative angle. Also, P_1 to P_4 represent the pre-swing, initial swing, mid-swing, and terminal swing of the gait cycle, respectively. These categories and membership functions are shown in Figure 5 and Figure 6.

We used the product-inference rule as s-norm, the Singleton method as fuzzifier, and the Center of gravity defuzzifier to calculate the output of the fuzzy system as:

$$Y = \frac{\sum_{i=1}^{m} y^i g_i}{\sum_{i=1}^{m} g_i}$$

in which y^i is the central point of the considered membership functions for each motion phase, Y is the output of the system and g_i is obtained from the following relationship:

$$g_i = \mu_i(\theta_{un}) * \mu_i(\dot{\theta}_{uh}) \quad (6)$$

where, * is a t-norm multiplier and μ_i indicates the degree of membership of each entry in the condition specified in the i^{th} rule for that entry.

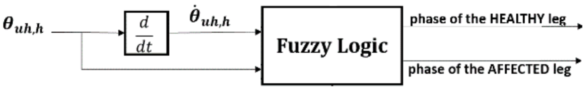


Figure 4: Block diagram of the fuzzy phase detection algorithm

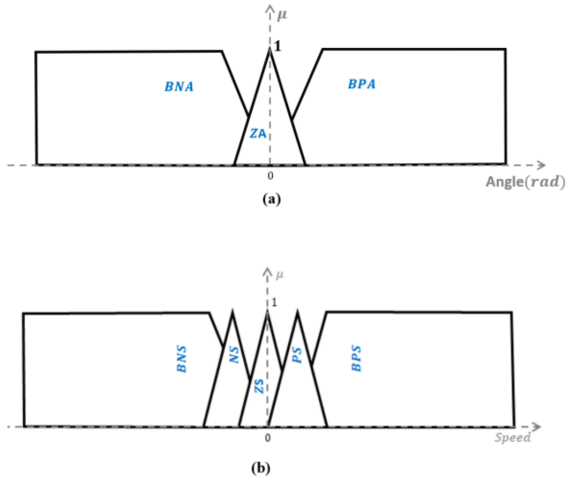


Figure 5: (a) The membership functions of the hip angle (b) The membership functions of the hip angular velocity

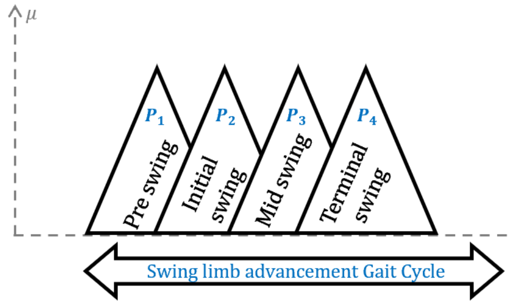


Figure 6: Subphases of the swing motion and their membership functions

In the case of entries for which no condition is included in a rule, the membership function is considered equal to one. According to the above relations, a numerical value for the intermediate output variable will be obtained, which should be converted into the movement phase.

For this purpose, membership Y in each movement phase is first calculated by membership functions and numerical ranges specified for each phase. Then, the movement phase is determined based on the maximum value of the membership function. In other words,

$$\text{Motion Phase} = P_j \ \Big|_{\mu_{P_j}(Y)=\max\limits_{i} \mu_{P_i}(Y)} \qquad (7)$$

After the movement phase of the user is detected, an auxiliary torque is applied for a certain period.

IV. Results and Discussion

In the first stage, to verify the performance of the fuzzy controller, the robot is worn by a healthy human and moves. According to the results, as expected and observed, the robot does not create any restrictions for the movements of the user. It accurately detects the motion phases and activates the actuators, accordingly. Then, to check the algorithm's result, the robot was tested for a hemiplegic stroke patient with a movement disorder in the left leg. First, a briefing session was held for the patient, the test method and objectives were presented to the patient and his companion, and the patient's informed consent to participate in the test was obtained. The patient wears the robot and moves without assistance; in this case, no force is applied to the patient from the robot side, and the robot does not show resistance to the person's movement; the purpose of this step is to check the person's movement process and symmetry.

Then the fuzzy controller of the robot is activated, and the patient is asked to move freely. During the patient's movement, the data related to the movement angle of the Hip joints, the force obtained from the load cell sensors in the right and left leg, and the time the patient takes a step are stored at the same rate.

One of the goals of implementing this controller is to detect the start of the swing phase and activate the robot motor on the involved leg. Figure 7 shows the trajectory of the hip joint of the right and left leg for three consecutive steps, along with the results of the fuzzy algorithm in detecting the subphases of the left leg motion. Figure 8 shows the hip joint angles and the robot force on the active left leg. It can be seen that upon detecting the beginning of the initial swing phase, the force of the robot on the left leg rises, and this continues until the required time is reached for the patient. As seen in the diagram, the applied force is reduced in the terminal swing phase.

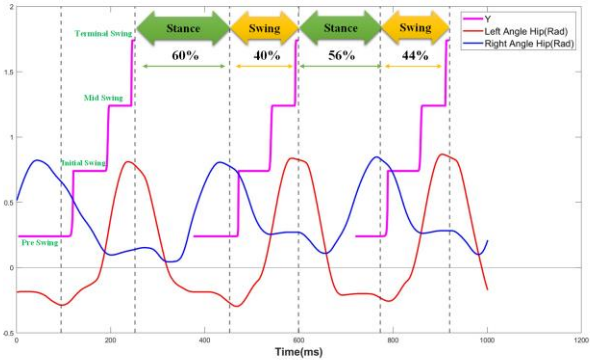


Figure 7: Trajectory of the right and left hip jointse for three consecutive steps along with the results of the fuzzy algorithm in the detection of the sub-phases.

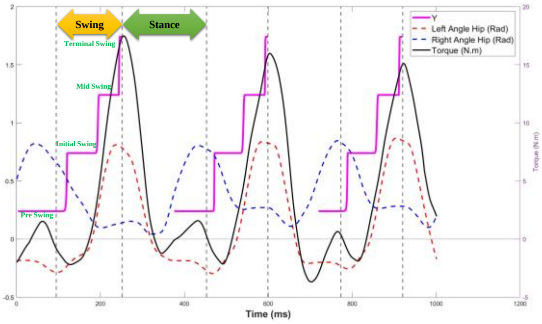


Figure 8: Trajectory of the right and left hip joints along with the detected subphases and applied assistive torques.

V. Conclusions

According to the tests and analysis of the data obtained from the robot, this algorithm can detect the subphase of the motion with high accuracy. according to the observations made by the physiotherapist supervising the test and analysis of the data taken from the robot, it can be seen that the controller has a strong recognition ability to coordinate and adapt to the person's movement and It does not restrict a person's movement.

in this method of phase detection we use fuzzy inference engine without auxiliary sensor like FSR, EMG and others. This method enables the detection of the different phases of human gait, including pre-swing, initial swing, mid swing and terminal swing which is essential for the synchronization of the exoskeleton's movement with the user's gait pattern.

Moreover, the use of fuzzy method allows for a robust and accurate detection of the gait phases, even in the presence of noise and uncertainties. Additionally, the low number of involved sensors reduces the complexity and cost of the exoskeleton design, making it more accessible and practical for a wide range of applications. Therefore, phase detection of human gait with the proposed fuzzy algorithm has significant potential for the development of wearable exoskeletons, especially for those intended for rehabilitation and mobility assistance.

For the future works, a clinical trial is planned to evaluate the performance of this method, accompanied by an assistive strategy, in improving the mobility and gait patterns of stroke patients. If the clinical trial shows promising results, phase detection of human gait with the proposed fuzzy inference engine would be a valuable tool for improving the quality of life of stroke patients and facilitating their recovery. Furthermore, this method has the potential to be adapted for other types of gait impairments and mobility disorders, making it a versatile and valuable technology in the field of wearable exoskeletons.

ACKNOWLEDGMENT

This research is supported by grant #101120 from the Ferdowsi University of Mashhad and grant #962297 from the National Institute for Medical Research Development of Iran. We want to thank all members of the FUM Center Advanced of Rehabilitation and Robotics (FUMCARE) at the Ferdowsi University of Mashhad for their kind participation and cooperation.

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