

Available online at www.sciencedirect.com**ScienceDirect**

Procedia Computer Science 42 (2014) 160 – 167

Procedia
Computer Science

International Conference on Robot PRIDE 2013-2014 - Medical and Rehabilitation Robotics and Instrumentation, ConfPRIDE 2013-2014

Adaptive Trajectory Control to Achieve Smooth Interaction Force in Robotic Rehabilitation Device

Tanvir Anwar^{a*}, Dr. Adel Al Juamily^{*†}

^aUniversity of Technology, Sydney School of Elec, Mech and Mechatronics

Abstract

One of the main objectives of a successful lower limb robotic rehabilitation device is to obtain a smooth human machine interaction in different phases of gait cycle at the interaction point. The input (interaction force, Joint angle) and output (impedance) relationship of the control system is nonlinear. This paper proposes a fuzzy rule based controller to be used to control the interaction force at the patient exoskeleton interaction point. In achieving the objective, impedance, driver torque and angular velocity have been modulated in a way such that there is a reduction of interaction force. Minimum interaction force at the interaction point and tracking the defined gait trajectory with minimum error are set as benchmark to evaluate the performance in many tasks. In this paper there is an evaluation of what degree of impedance is ideal for what type of interaction force and joint angle to maintain a trajectory tunnel. This paper describes the control architecture of one Degree of freedom lower limb exoskeleton that has been specifically designed in order to ensure a proper trajectory control for guiding patient's limb along an adaptive reference gait pattern. The proposed methodology satisfies all the desired criteria for the device to be an ideal robotic rehabilitation device.

© 2014 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/3.0/>).

Peer-review under responsibility of the Center for Humanoid Robots and Bio-Sensing (HuRoBs)

Keywords: Inertia, damping, stiffness coefficient, stance, swing phase, impedance, admittance, trajectory, PID, fuzzy logic, interaction Force, joint Angle

* Corresponding author. Tel.: +61-029-514-7962, 9514 7939; fax: +61 2 9514 2655.

E-mail address: tanvir.anwar@student.uts.edu.au; adel-al.juamily@uts.edu.au

1. Introduction

As stroke has been increasing alarmingly, robotic rehabilitation has become an important area of research to be used in rehabilitation after stroke. The survey shows about 29 people per 100000 suffer from stroke related diseases in Australia and there are approximately 250000 cases of spinal cord injuries per annum in the USA alone that lead to limb impairment. Certain part of brain suffers the loss of functionality to generate the neural signal necessary for movement of different limbs and organs of the body due to stroke or other injuries. Due to stroke the gait pattern deviates from the normal walking speed, endurance, symmetry, stride length. Post stroke rehabilitation triggers the same functionality in other part of the brain which then generate necessary neural signal. This is called brain plasticity. Brain plasticity restore the original gait cycle. An exoskeleton as a part of robotics rehabilitation is a powered structure participates in limb rehabilitation. It merges machine power and human intelligence in order to enhance the intelligence of the machine and power of the operator. Most of the exoskeleton generates trajectories by an actuator torque force at the joints. Trajectory consists of torque exerted, acceleration, velocity, position at exoskeleton human interaction point. Exoskeleton is mainly of two types which are Passive and active[1]. A **passive device** mainly assist patient by helping them to employ their own power without supplying energy to the user. The system developed by Walsh uses passive devices like springs to store energy released during negative work phases of the gait cycle and releases it during the positive work phases to assist. Another type passive system leg orthosis designed to assist hemiparesis patient to walk through the elimination of the effects of gravity. It is only composed of links and springs, which balance the effect of gravity over range of motion[2, 3]. **Active devices**, on the other hand, behave as energy sources. They assist the elevation of the center of mass of the body (COM) during walking in a repetitive manner. For active assistance during gait rehabilitation, drive selection is one of the key issues, as patient joint require high torques during gait but, at the same time, aesthetic issues require compact and low weight drives. There are three different types of actuators and they are: hydraulic cylinders, electrical motors and pneumatic actuators[2].

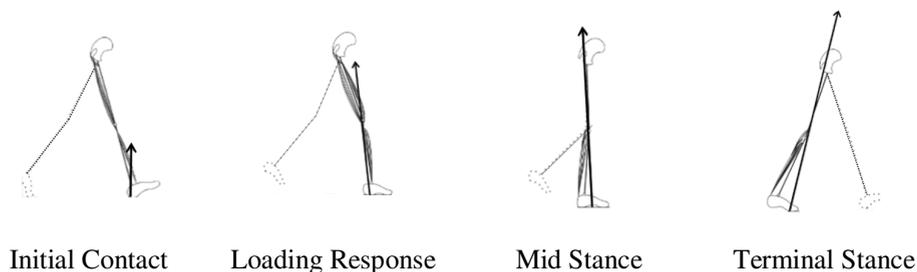
2. Background

The branching of current control algorithms is based on the strategy of provoking plasticity. Robotic Rehabilitation Device (RRD) is assistive controller in which patient must make effort to provoke plasticity. Too much assistance has negative consequences. So assistance is ensured when patient attain a threshold of force and velocity. One of the RRD is Lokomat that has used position, force and impedance controller to maintain an impedance tunnel [4]. Lokomat estimates interaction forces to adapt new reference trajectory which effectively reduce the interaction forces after desired assistance. In challenge-based robotic therapy control algorithms, it refers to controller that is some ways make a task more difficult or challenging to the user. It is just opposite of assistive controller. Gentle/s/g, MIT MANUS RRDs gives resistance in the opposite direction of the user movement. In counter balancing assistance, for upper limb, overhead slings, arm skateboards, harnesses are used to counter balance weight of a limb. For lower limb it is gravity balancing, passive exoskeleton. In active exoskeleton it is actuator torque that is used by NeReBot as RRD. A body weight supported (BWS) treadmill system consists of a treadmill and a mounting frame, with a suspension system and a harness used to remove a controllable portion of the weight from the patients' legs, providing stability to the trunk and safety to the patient. BWS system unloads body weight symmetrically from the lower limbs as they move forward. The movement is provided by a slow moving treadmill. The BWS system reduces the demand placed upon muscles, which may enable the patient to work on improving the coordination of the movement while gradually increasing the strength of the muscles. As patient progresses, the BWS can be gradually decreased, challenging the patient to assert more postural control and balance [2] and hence attaining more plasticity. The other type of signal driven controller is the skin surface electromyogram (EMG) which is one of the very important biological signals where human intention is directly reflected. It is used as a control signal for a robot system. Each muscle activity for a certain motion is highly nonlinear, because the responsibility of each muscle for the motion varies in accordance with joint angles. One muscle not only involved into one motion but also many other kinds of motion. Load acting on each individual joint affects activity level of them. A flexible and adaptive nonlinear control is applied to control the robot with skin surface EMG signals. Due to EMG application in real time control delay in exoskeleton motion has reduced significantly as it may give a lot of

stress to the user. The patterns of EMG signals for certain motion are extracted by performing experiment and using anatomical knowledge. We can separate EMG signals of shoulder from elbow posture region. Then each posture region can be divided into different muscle and contribution of each muscle towards a particular motion. Control rule is described by equation in order to take into account the sub effect of each muscle by setting their weight high or low. EMG features are lots of times extracted from noisy raw EMG data[5]. In EMG based assistance, EMG signals are collected from different muscles of shoulder, elbow, and legs. After some signal processing the assistance is triggered when the processed EMG signals increase above a threshold Mean Absolute Value (MAV), mean absolute slope, zero crossings, slope sign changes, or wavelength are common feature used. In other types of controller, Performance-Based Adaptation of task parameters, Control parameters are tuned according to the patient's need. Task parameters such as desired velocity and desired movement time can be adapted following adaptive laws (fuzzy Logic, Neural Network). Patient's intention is taken into account rather than imposing an inflexible control strategy. The state information from the robot and the human might be continuous signal or a discrete value. The continuous signals that are detected from robot are i) robots joint angles, ii) the joint force and iii) the participant's velocity. The discrete value is detected from the participant's progress during the tracking task. The discrete states can be defined as a set of linguistic variable like difficult, easy, stop and pause. Robot and Human state information is monitored to trigger relevant events to adjust the trajectory[6] in trying to achieve smooth interaction and higher degree of plasticity. In all the above rehabilitation methodology, the patient has been put into an environment that motivates the patient to assist himself more than seeking assistance from the Robotic Rehabilitation Device so that plasticity is provoked and relatively faster recovery is achieved.

3. Exoskeleton Dynamics

There are three distinct phases of human gait cycle. The intended phase of gait by patient needs to be extracted. The disturbing interaction force can be minimized by applying different dynamics of swing, support and stance phase of the gait. In this way, the exoskeleton dynamic model deficiency is taken care of significantly. BLEEX had divided the dynamic of the gait cycle into three phases. The controller adapt specific model appropriate for that phase only. Switching dynamic model from phase to phase overcomes the model deficiency and there is a reduction of interaction forces. BLEEX has used position controller for stance phase and sensitivity in amplification controller for swing phase. Position controller in the master slave stance strategy helps the slave (exoskeleton) follow the master (leg) with minimum error. Intention is extracted from the gradient of ground reaction force and the intensity of it along vertical and horizontal axis as the intention vectors shown in figure 1. HALL also adapted similar dynamic model shifting strategy from phase to phase like BLEEX[7]. In HALL the intended Phase changes have been detected from center of gravity (COG) transfer as it is shown in figure 1, increase of Floor Reaction Force (FRF), Knee joint angle. A set of inequalities are to be satisfied for standing, sitting and walking Phase conditions. Controller has applied gravity compensator algorithms for weight bearing and balance control algorithms based on wearers COG[8]. Figure 1 exhibit different movement phase a patient experiences in daily activities.



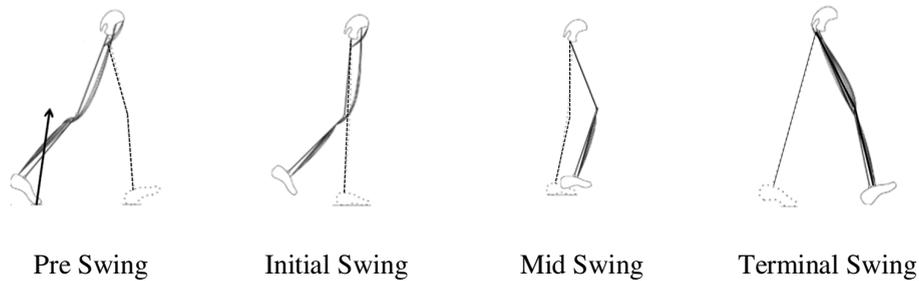


Fig. 1. (a) Intention Extraction from Ground Reaction Force.

Figure 1 shows how force experienced by the feet changing direction and intensity. These variable forces can be used to classify gait into many different classes for actuator control signal. As to the intention from EMG in lower limb, there is different combination of muscle activation correspond to different posture of limb. Extensive signal processing with very tight window is required to extract EMG signal relevant to a particular posture. Computational Technique like Artificial Neural Network, SVM is used to extract intention. EMG is also used to generate required torque for exoskeleton actuator. In all those methodologies above, there is shortcoming in achieving minimum interaction forces and tracking of the trajectories. Because patient used to be the passive element in the close loop control system until recently EMG has been used to send signal to the controller directly. This way patient becomes an active element of the close loop control system.

4. Adaptive Features of Robotic Rehabilitation Device

An exoskeleton with an actuation system actively adjusts the joint stiffness with zero, constant and variable impedance. In general we can define the “correct” gait motion in following three ways, Firstly, tolerate deviation from a given reference trajectory at all joints by the use of a complaint device or controller within a virtual “tunnel”. If it is too stiff, patient feels passively moved. If it is too soft, patient is not corrected in space and might have undesired pattern. the overall behavior of the algorithm is that it enforces only small deviations from the reference motion when the patient does not want to change the motion, and allows for larger deviations when the patient wants to walk in his/her own way[4]. Secondly, cycle to cycle or phase to phase adaptation to minimize the interaction torque is also implemented. Thirdly, musculoskeletal model is used to define trajectory, since 27 musculo tendon actuators and joint stiffness of the leg generated trajectory is also implemented in many RRD[4]. To control various parameters of trajectory, it is required to use position controller for flexion-extension and trajectory tunnel, force for angular acceleration and impedance controller for stiffness. Forward and Inverse kinematics is widely used in position control and Forward and Inverse dynamics is used for force control in the control loops. But these controllers are not enough to make the RRD very robust. So in high level controller it uses Neural Network, Fuzzy Logic, finite state machine and various other algorithms for robustness. Higher level controller operates in discrete domain whereas low level controller operates in continuous domain. The decision making module of high level controller generates sequence of control actions using its decision rules. These decisions are based on online data collected from various sensors (position, velocity, reaction force, EMG, errors etc.). The first algorithm collected interaction force from all force sensors and then estimates active patient torque and a variation in the reference trajectory. Then the angle trajectory adapts in a way that leads to reduction in the active patient interaction torque. In the second algorithm, it estimates human robot interaction torques and then translates this into the desired change in the trajectory acceleration. In the third algorithm, RRD provides high impedance that result in smaller position deviations and low in greater deviations. Impedance can be of zero order (stiffness) or 1st or 2nd order. The impedance control is realized by a nonlinear control law. The impedance control generates a pre-specified open loop relationship between the interaction torques and the allowed position derivations. This approach allows direct adaptation of the trajectory from the measured position deviation or from the estimated interaction torques[4]. The fourth algorithm when there is only little patient effort detected by the force sensors, then the controlled impedance

(stiffness, damping, and inertia) is set high in order to enforce a motion that is close to the desired reference motion. The impedance magnitude is reduced as soon as an increased patient effort is detected. With lower impedance magnitude greater deviations from the reference motion are possible, and the motion has to be generated to a greater extent by muscular forces rather than by the robot. Consequently, the robot assistance and reference motion enforcement is reduced.

5. The Proposed Methodology:

It is very conspicuous that impedance, driver actuator torque and position of the trajectory need to be regulated constantly for the entire gait cycle. All these regulation of parameters are for achieving reduction of interaction force at the human exoskeleton interaction point and tracking of the trajectory with minimum error. In achieving this objective, what is required is the justification of different degree of impedances against different types of interaction forces and joint angle. For low joint angle (indicating the commencement of the trajectory), a low value of impedance is imposed as actuator should inject impulse of energy to exoskeleton to have a comfortable start. An opposite condition of impedance (high) is desired when trajectory is completed for slow termination. At any point of the trajectory, if interaction force (the patient’s effort) is high then low impedance is imposed for smooth interaction. If interaction force is low then impedance is set high in order to enforce a motion that is close to the desired reference motion. For every other condition, impedance is decided based upon this fact that high impedance result in smaller position deviations and low in greater deviations. What is desired is that patient provokes the plasticity which results in quicker recovery. In regulating the position, an impedance trajectory tunnel has been imposed to give freedom to the patient. In this paper, a fuzzy rule base controller is used to modulate the impedance. In the controller block of figure 2, a virtual admittance controller is used to generate trajectory and PID controller is used to keep track of trajectory. Change of interaction force will decide the reference.

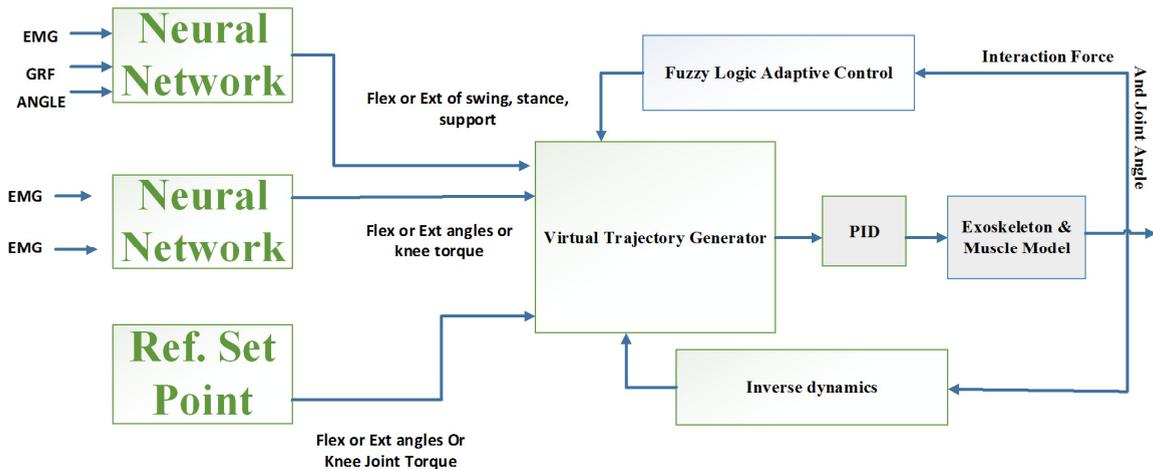


Fig.2. the hybrid control blocks in RRD

In implementing this scheme following values of various parameters are used to simulate the system. We have used exoskeleton inertia, damping and stiffness respectively $I_e = 0.199\text{Kg} - \text{m}$; $b_e = 1.32\text{Nms/rad}$; $K_e = 5.12\text{Nms/rad}$ for exoskeleton. The inertia of human limb will vary from person to person. The robotic rehabilitation device dynamics can be customized with the inertia, damping and stiffness of every individual human limb. But in our case we considered a general case applicable for all kinds of patients. We have taken human inertia, damping and stiffness respectively $I_h = 0.582\text{ Kg m}^2$; $b_h = 0.11\text{ Nms/rad}$; $K_h = 5\text{ Nm/rad}$ and for virtual model

we have taken the desired Inertia $I_e^d = 0.035 \text{ kg} - \text{m}^2$. the whole system has been tested for different values of desired damping and they are $b_e^d = 0, -0.667, -1.333$ and -2.0 Nm and we have taken $K_e^d = 5 \text{ Nm/rad}$ [11]. The impact of inertia and stiffness in the dynamics is not significant. So the damping has played the key role in dynamic response of the system. To compensate for inertia, damping and stiffness of motor shaft, exoskeleton, and gear box the inertia, damping and stiffness of virtual admittance controller has been taken as $I_d = I_h + I_e + I_m + I_s + I_g; D_d = D_h - D_e; K_d = K_h$; Where I_e^d, b_e^d and K_e^d are the desired inertia, damping and stiffness respectively. The PID controller seeks to minimize the error between the responses of the admittance model, $\theta_{ref}(t)$, and the actual response of the exoskeleton $\theta(t)$.

6. Analysis and Discussion

To bench mark our work two major criteria's are set here. Firstly it is reduction of interaction torque and secondly, coupled system should be able to follow the predefined angular position trajectory. Fuzzy logic has been used to incorporate wider range of interaction force and also taking instantaneous angular position of the joint into account. The ideal impedances have been justified throughout the trajectory. As it is very clear from simulation of the control blocks of figure 2 into MATLAB that the transient response of the output switches from over damping to critical damping as well as critical damping to under damping or vice versa. An ideal transient response is the one that avoid high inertia because it increases the overshoot. Overshoot increases vibration which is not desired at all. An ideal case also avoids too much damping because it generates rigidity and so does stiffness. The exploited relationship between damping and inertia against transient rise time t_r , derived in two regression models are used in adapting the impedance. The reference torque is taken 20 N-m which is normal walking torque of a healthy person. To complete the angle of extension and flexion of the joint, position controller is used which has applied forward kinematics to generate necessary control signal in the close loop of control system. In the feedback part of the control loop inverse kinematic is applied to calculate the actual position of the exoskeleton. The patient will exert different level of interaction torque. A task has been designed for the patient to target with the consideration that the Patient maintains a particular angular velocity and completes a full flexion or extension in a predefined time. The rules in fuzzy are set in a manner that the every point of the flexion and extension trajectory experiences minimum interaction force. Fuzzy rules are working as adaptive laws to tune the control parameters in the close loop. The Fuzzy control rules with input and output are Interaction force, Joint angle and Impedance respectively as shown in figure 3. In figure 4 show, Interaction Force has been divided into Low Interaction force: LF, Moderately Low Interaction Force: MLF, Medium Interaction Force: MF, Moderately High Interaction Force: MHF, High Interaction Force: HF. Joint Angle has been divided into Very Small Angle: VSA, Small Angle: SA, Medium Angle: MA, Big Angle: BA and Very Big Angle: VBA. Impedance has been divided into Very Low Impedance: VLI, Low Impedance: LI, Medium Impedance: MI, High Impedance: HI, Very High Impedance: VHI.

Table 1. Main rule database for the Fuzzy controller

If Interaction Force is LF	Joint Angle is VSA	Then Impedance is MI
If Interaction Force is LF	Joint Angle is SA	Then Impedance is MI
If Interaction Force is LF	Joint Angle is MA	Then Impedance is HI
If Interaction Force is LF	Joint Angle is BA	Then Impedance is HI
If Interaction Force is LF	Joint Angle is VBA	Then Impedance is HI
If Interaction Force is MLF	Joint Angle is VSA	Then Impedance is HI
If Interaction Force is MLF	Joint Angle is SA	Then Impedance is HI
If Interaction Force is MLF	Joint Angle is MA	Then Impedance is HI
If Interaction Force is MLF	Joint Angle is BA	Then Impedance is LI
If Interaction Force is MLF	Joint Angle is VBA	Then Impedance is LI
If Interaction Force is MF	Joint Angle is VSA	Then Impedance is MI
If Interaction Force is MF	Joint Angle is SA	Then Impedance is MI
If Interaction Force is MF	Joint Angle is MA	Then Impedance is MI
If Interaction Force is MF	Joint Angle is BA	Then Impedance is MI

If Interaction Force is MF	Joint Angle is VBA	Then Impedance is MI
If Interaction Force is MHF	Joint Angle is VSA	Then Impedance is MI
If Interaction Force is MHF	Joint Angle is SA	Then Impedance is LI
If Interaction Force is MHF	Joint Angle is MA	Then Impedance is LI
If Interaction Force is MHF	Joint Angle is BA	Then Impedance is LI
If Interaction Force is MHF	Joint Angle is VBA	Then Impedance is LI
If Interaction Force is HF	Joint Angle is VSA	Then Impedance is MI
If Interaction Force is HF	Joint Angle is SA	Then Impedance is HI
If Interaction Force is HF	Joint Angle is MA	Then Impedance is HI
If Interaction Force is HF	Joint Angle is BA	Then Impedance is VLI
If Interaction Force is HF	Joint Angle is VBA	Then Impedance is VLI

The operational range of knee flexion or extension angle is as shown in figure 4 is $[0\ 90^\circ]$, the triangle for interaction force is taken $[0\ 10]$ and range for impedance level is taken as $[0\ 10]$. Figure 6 depicts the input and output membership functions.

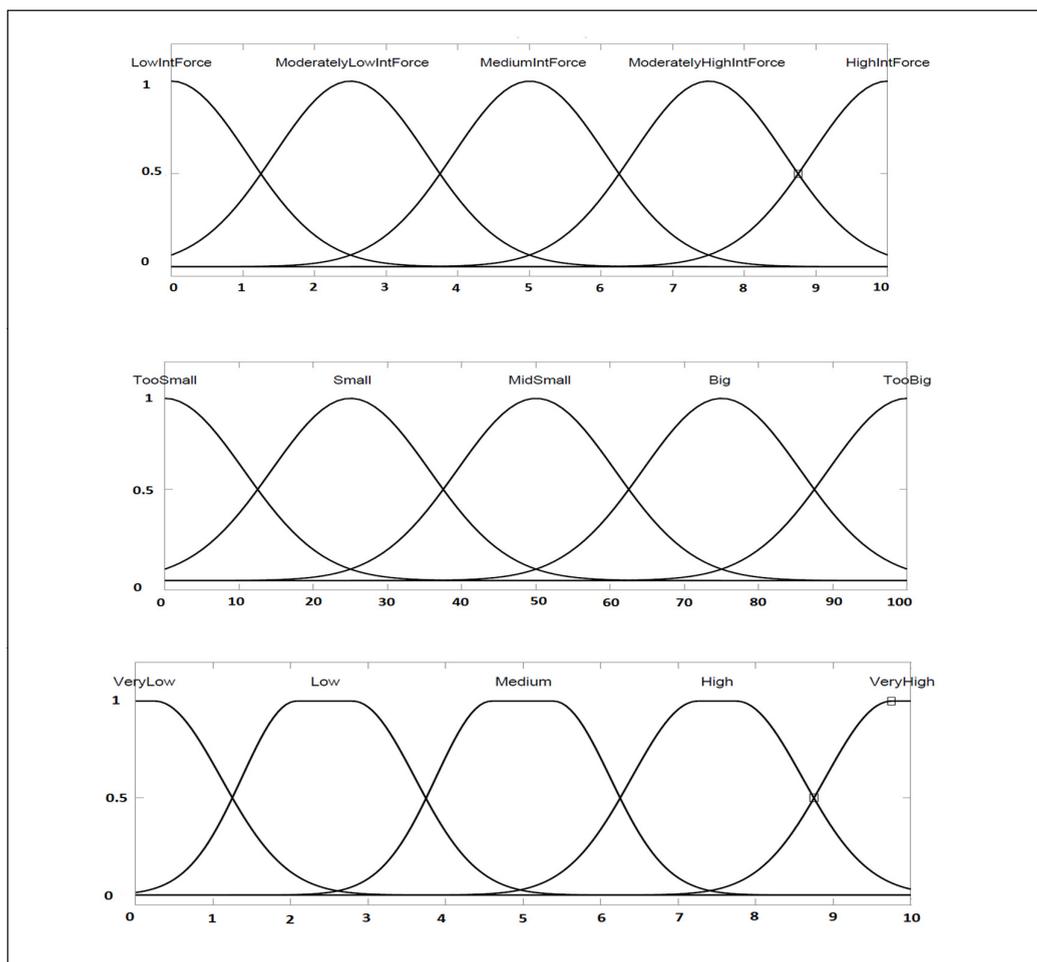


Fig.4. Membership functions of Fuzzy input and output

We have chosen gauss membership function for input interaction force and angle to the fuzzy adaptive controller. But we have chosen gauss2 membership function from the fuzzy toolbox for output impedance. To make many bins of input for interaction and joint angles I have preference to choose five membership functions. There are about 24 rules in the fuzzy inference engine between fuzzification and defuzzification of the fuzzy controller. A potentiometer at the knee joint and a tactile sensor located on the exoskeleton to sense the interaction of human limb supplies the crisp input to the fuzzification process of the fuzzy controller. A crisp impedance output from the defuzzification process is input to the virtual impedance controller to generate the desired acceleration or speed of the actuator motor. The membership degree is chosen to be between zero to one for all two input and one output membership function as shown in figure 4. A PID keeps tracks of the newly set reference angular acceleration of the actuator. Most of the rules are based on therapist experience over the years. Because there are patient with many different impairment, it is very difficult to model each patient and design a model based controller for each one of them. Most of the time, these models are very non-linear. So Fuzzy is a very excellent substitute of non-linear behavior of a system. As the patient progress with time, fuzzy controller is easy to be calibrated for the new phase of the patient. We can identify more parameters to input into the fuzzy controller to make our system more robust. We can even save the progress of the patient in database and use it later. The controller exhibits stability for all values of input interaction force and joint angle.

7. Conclusion

The proposed methodology is an excellent platform to harbor a complex hybrid adaptive control. The first and foremost step in the design is the parameterization or system identification of the entire system. The paper has presented a successful design of a MIMO control system dynamically changing the weight associated with each parameter to fulfill the objective of smooth exoskeleton interaction by the rule based Fuzzy system is adapting control laws to tune the control parameter to actuate the motor without really considering the dynamics of the exoskeleton and muscle. To couple this controller to an EMG signal of human limb, Neural Network is chosen for system identification to extract the desired joint angle and torque from impaired limb as future work.

Acknowledgements

I also acknowledge the help from my colleague Khairul Anam, Amara due to their all-time cooperation in helping me accomplish this paper.

References

- [1] Harwin, W.S., J.L. Patton, and V.R. Edgerton, Challenges and opportunities for robot-mediated neurorehabilitation. *Proceedings of the IEEE*, 2006. 94(9): p. 1717-1726.
- [2] Koceska, N., et al., Control Architecture of a 10 DOF Lower Limbs Exoskeleton for Gait Rehabilitation. *International Journal of Advanced Robotic Systems*, 2012: p. 1.
- [3] Aguirre-Ollinger, G., et al. Active-impedance control of a lower-limb assistive exoskeleton. 2007. *IEEE*.
- [4] Duschau-Wicke, A., et al., Path control: a method for patient-cooperative robot-aided gait rehabilitation. *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, 2010. 18(1): p. 38-48.
- [5] Fleischer, C. and G. Hommel, A Human-Exoskeleton Interface Utilizing Electromyography. *Robotics, IEEE Transactions on*, 2008. 24(4): p. 872-882.
- [6] Erol, D. and N. Sarkar, Design and Implementation of Control Architecture for Rehabilitation Robotic Systems. 2007.
- [7] Kazerooni, H., R. Steger, and L. Huang, Hybrid control of the Berkeley lower extremity exoskeleton (BLEEX). *The International Journal of Robotics Research*, 2006. 25(5-6): p. 561-573.
- [8] Hayashi, T., H. Kawamoto, and Y. Sankai. Control method of robot suit HAL working as operator's muscle using biological and dynamical information. 2005. *IEEE*.
- [9] Erol, D. and N. Sarkar. Intelligent control framework for robotic rehabilitation after stroke. 2007. *IEEE*.
- [10] Akdoğan, E. and M.A. Adli, The design and control of a therapeutic exercise robot for lower limb rehabilitation: *Physiotherobot. Mechatronics*, 2011. 21(3): p. 509-522.
- [11] Aguirre-Ollinger, G., et al., Design of an active one-degree-of-freedom lower-limb exoskeleton with inertia compensation. *The International Journal of Robotics Research*, 2011. 30(4): p. 486-499.