International Journal of
Applied Mathematics,
Electronics and Computers
ISSN: 2147-8228 http://ijamec.atscience.org

Advanced Technology and Science
Original Research Paper

Gain Parameter Adjustment Methods Comparison of Controller for Autonomous Rehabilitation Device

Ikbal Eski*[1], Ahmet Kirnap [1]

Accepted 3rd September 2016

Abstract: PID controller design and comparison between two different gain parameter adjustment method for autonomous physical rehabilitation device is presented in this paper. This device will be capable of doing repeated therapeutic exercises of shoulder joint. That devices main objective is reducing physiotherapist work load. The controllers tested with real angel values. Comparison of simulation results showed Ziegler_Nichols adjustment method has better performance than Matlab's auto-tune method.

Keywords:*PID controller, passive exercises, rehabilitation, autonomous control.*

1. Introduction

Controller design for rehabilitation machines has become important topic since we realized that the rehabilitation machines advantages for therapeutic exercises. Studies about gathering data for controller, controller design and mechanism design for rehabilitation devices are outlined in this section.

Zhou et al. at their works about human motion tracking and human motion tracking for rehabilitation, tested many motion tracking methods and their comparisons proved that inertial sensors is easy to use and they gives high accuracy data for motion tracking [1-6].

Rasyid et al. designed continuous passive motion device. The device designed for shoulder joint. Device can be used after performing an operation or for patients suffering from joint motion limitation because of early stage of frozen shoulder [7]. Mihelj et al. proposed and evaluated a strategy for patient-cooperative control of rehabilitation devices for upper limbs. At their work they used ARMin robot which is exoskeleton robot. While designing the controller, they aimed provide support to patient with minimum intervention. In this way patient can use trajectory what he or she wants while reaching the destination point. Optimizing the trajectory depends on patients self during the therapy. Some patients might never achieve optimal trajectories; however they might still be able to reach the target with adequate robot support. That situation is the goal of their proposed control strategy [8]. Birch et al. designed mobile device for rehabilitation of human hand. That device used either continuous passive motion (CPM) or continuous active motion (CAM) exercises. They used proportional-derivative control for CPM mode. At CPM mode device working with preset waypoints and at CAM mode device actively resist the movement of patient. Device can use for both the MCP and PIP joints. They made this work non-clinic, and they are planning to evaluate this device with rehabilitation professionals [9]. Saputra et al. designed and evaluated automatically working CPM for human knee joint. System stops and turning to beginning point when patients feel pain. They have provided that with using Analog-Digital Converter (ADC). When the DC motor received load, the voltage decrease detected by ADC and after 1.5 seconds motor rotates again with another direction. They used microcontroller to control this system[10]. Dong et al. developed prototype rehabilitation device for controlling human joint movement. They designed intelligent controller that can perform movement to patient which is applied by therapist. That device provides both isometric and isokinetic movements [11]. Hassani et al. developed powered orthotics for helping health staff during rehabilitation and to perform passive and active motions [12]. Human knee joint angle change estimated by Zhang et al. with using BP neural network. Six patients join the experiment to verify the efficiency of neural network. That neural network used in robot design which for active rehabilitation exercises [13]. Designing parallel rehabilitation robot for human ankle movement was proposed by Prashant et al. They discussed optimization problem with using kinematic analysis and genetic algorithm for proposed robot [14]. Wang et al. designed rehabilitation robot for human ankle, knee and hip joints and they discussed stability and dynamic performance of robot. In addition they used swarm algorithm at optimization problem [15]. Lee et al. placed artificial mechanism at human knee joint and they gave mathematical model for that artificial mechanism[16]. Angle change of human hip and knee joint from volunteers measured by Chua et al. and they used that data for designing rehabilitation robot [17]. Yildirim and Eski used vibration data of human hip and knee joints at designing neural network analyzer [18].

Experts about physiotherapy has to decide right therapy exercises that the therapy angles which are suitable for patient and will not exceed the pain limit of patient. Right therapy exercises and angles are unique for patient because it depends on many variable. For this reason therapy exercises decided clinic. Because of the uniqueness of therapy, physiotherapist has to show therapy exercise to therapy system.

In this paper, we designed controller with data's which are taken by using inertial sensors. This controller is tracking exercise trajectories for shoulder joint.

[1] Department of Mechatronic Engineering, Faculty of Engineering, Erciyes University, Kayseri, Turkey
** Corresponding Author:Email: ikbal@erciyes.edu.tr*
Note: This paper has been presented at the 3rd International Conference on Advanced Technology & Sciences (ICAT'16) held in Konya (Turkey), September 01-03, 2016.

2. Dynamic of Human Upper Limbs

There were several different modeling's including human upper limbs in the literature. In this paper, the assumptions were made that human arm consist of three rigid limbs and have three-degree of freedom. Each of the joints was modeled as one-degree of freedom joint.

Relationship between the external forces and displacements generated by external forces could be expressed by linear transfer function which generally called as mechanic impedance or admittance. Basic linear expression of one DOF (single joint) musculoskeletal system in Laplace domain:

$$\theta(s) = \frac{1}{Is^2+Bs+K}[T_m(s) + T_e(s)] \tag{1}$$

where Θ is the joint angle, I is the inertia moment, B is the joint viscosity, K is the joint stiffness, T_m is the torque of muscle and T_e is the external torque. Here, the visco-elastic joint features depending on joints itself, visco-elastic features of passive component of muscles and visco-elastic features of activated muscles. The muscles visco-elastic features can be divided into intrinsic system and reflexive system. B and K at Eq. 1 is include intrinsic system features but not include reflexive system. The muscles reflexive torque can be modeled as:

$$T_m(s) = -\frac{\beta_1 s+\beta_0}{\alpha s+1}e^{-\tau s}\theta(s) \tag{2}$$

where β_0 is the position feedback gain, β_1 is the velocity feedback gain, τ is the loop delay and α is the time constant. While using Eq. 1 for calculation of the human dynamics, if the reflexive torque is too small or muscle activation dynamics can be neglected, the joint dynamic equation will be second-order system [19].

Considering muscles are in fully relaxed condition and muscle activity will be nearly zero during the passive therapy exercises, the muscle reflexive torque T_m can be neglected because it will be nearly zero. According to this in Eq. 1 angle only depends on external torque and intrinsic system as Milner et al. [20] and Morita et al. [21] used at their work. So dynamic equations for human joints separately modeled as second-order system is given by:

$$I\ddot{\theta} + b\dot{\theta} + k\theta = T \tag{3}$$

3. System Modelling

For designing controller, firstly we need the dynamic model of shoulder, elbow and wrist joint. We use Eq. 3 and Fig. 1 for modelling human joints.

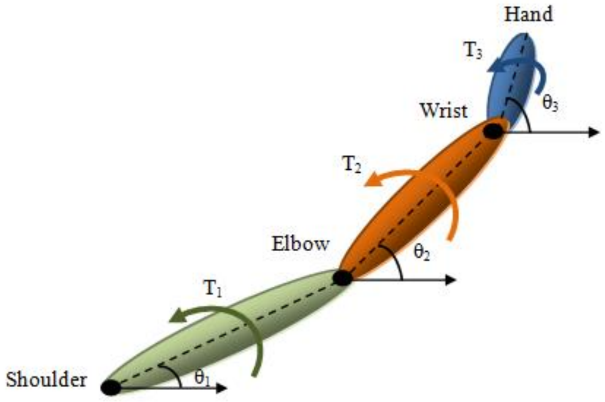

Figure 1. Angle and torques descriptions for joints of the human upper limbs

The dynamics of shoulder, elbow and wrist joint is given below:

$$(I_1 + I_2 + I_3)\ddot{\theta}_1 + B_1\dot{\theta}_1 + K_1\theta_1 = T_1 \tag{4}$$

$$(I_2 + I_3)\ddot{\theta}_2 + B_2\dot{\theta}_2 + K_2\theta_2 = T_2 \tag{5}$$

$$I_3\ddot{\theta}_3 + B_3\dot{\theta}_3 + K_3\theta_3 = T_3 \tag{6}$$

As you seen in the Fig. 1, Eq. 4 expressed for shoulder joint, Eq. 5 for elbow joint and Eq. 6 for wrist joint. State-space model for Eq. 4-6 is:

$$x(t) = Ax(t) + Bu(t) \tag{7}$$

$$y(t) = Cx(t) + Du(t)$$

$$x = \begin{bmatrix} \theta_1 \\ \dot{\theta}_1 \\ \theta_2 \\ \dot{\theta}_2 \\ \theta_3 \\ \dot{\theta}_3 \end{bmatrix} \tag{8}$$

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} = \begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} \tag{9}$$

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -\frac{K_1}{(I_1+I_2+I_3)} & \frac{B_1}{(I_1+I_2+I_3)} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{K_2}{(I_2+I_3)} & 1 & 0 & 0 \\ 0 & 0 & 0 & \frac{B_2}{(I_2+I_3)} & 0 & 1 \\ 0 & 0 & 0 & 0 & -\frac{K_3}{I_3} & -\frac{B_3}{I_3} \end{bmatrix} \tag{10}$$

$$B = \begin{bmatrix} 0 & 0 & 0 \\ \frac{1}{(I_1+I_2+I_3)} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \frac{1}{(I_2+I_3)} & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \frac{1}{I_3} \end{bmatrix} \tag{11}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \quad (12)$$

$$D = [0] \quad (13)$$

For shoulder, elbow and wrist, dynamic parameters, which for fully relaxed condition and with minimum muscle activity of human extremities, given in Table 1 [19,20,22-24].

Table 1. Transient response parameters of the control structures for shoulder, elbow and joints

I_3 (Hand)	Wrist joint	
	B_3	K_3
0.005 kg/m^3	0.003 Nms/rad	3 Nm/rad
I_2 (Forearm)	**Elbow joint**	
	B_2	K_2
0.013 kg/m^3	0.2 Nms/rad	2 Nm/rad
I_1 (Upper arm)	**Shoulder joint**	
	B_1	K_1
0.015 kg/m^3	0.3 Nms/rad	10 Nm/rad

4. Experimental and Simulation Results

At this section, data which are taken from patients has limitation on shoulder joint and control techniques developed based on these data results are given. According to taken data from patients elbow joint, PID (Tune) and PID (ZN) control systems are designed. Matlab's PID tuning algorithm and Ziegler-Nichols algorithm are used to adjustment of PID's gain parameters and gain parameter given in Table 2 Transient state responses of control structures for step input are shown for the elbow joint at Fig. 2, As seen in Table 3, the PID (ZN) control structure has given best results on rise time and settling time but overshoot.

Table 2. Control structures parameters for the shoulder joint

Control Structures	Kp	Ki	Kd	Filter coefficent (N)
PID (Tune)	18.31	729.33	0.08	243.3401
PID (ZN)	90	10	0.5625	-

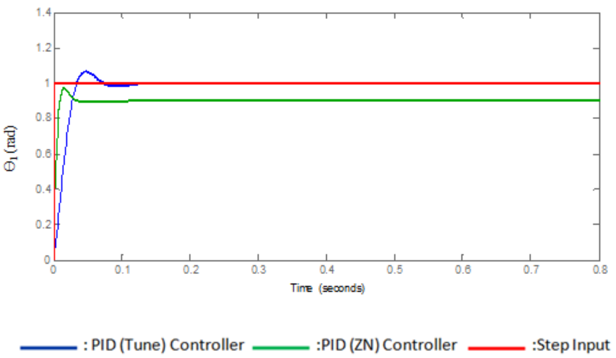

Figure 2. Control structures response for the shoulder joint using unit step input signal

Table 3. Transient response parameters of the control structures for the shoulder joint

Shoulder joint				
Control Structures	**Rise Time**	**Settling Time**	**Overshoot**	**SS Error**
PID (Tune)	0.021	0.0935	% 7.95	0
PID (ZN)	0.00894	0.045	% 0	0.098

Simulation results for proposed controllers with patient data's has shown at Fig.(3,4). Data's taken from patients who has shoulder joint limitation. Patient - 1 is 61 years old male and has limitation at right shoulder joint, Patient - 2 is 62 years old male and has limitation at left shoulder after fracture.

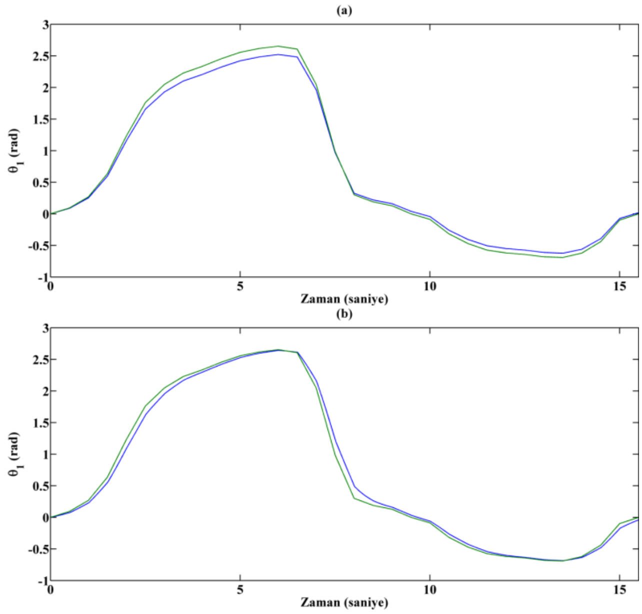

Figure 3. Shoulder joint angular variations of patient 1 using a) PID (Tune) controller b) PID (ZG) controller

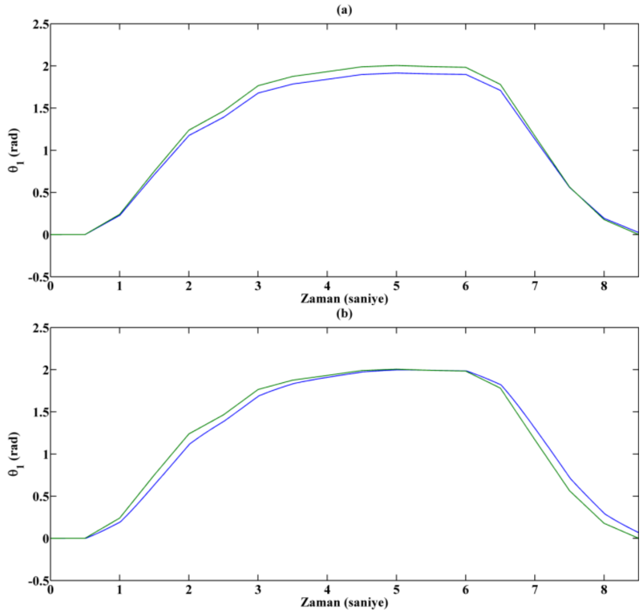

Figure 4. Shoulder joint angular variations of patient 2 using a) PID (Tune) controller b) PID (ZG) controller

As seen in figures, PID (ZN) has control system has better results than PID (Tune) on formed maximum error during movement.

5. Conclusions

In this paper, control structure designed according to taken data from patients who has limitation shoulder joint and different physical specifications. According to experimental and simulation results, the PID (ZN) control system is better than PID (Tune) on adapting and it has minimum steady - state error. Although, PID (ZN) gives better results than PID (Tune), for future work other intelligent control structures will be simulated and compared with PID (Tune) and PID (ZN) control systems.

Acknowledgments

We would like to thank Erciyes University Department of Physical Medicine and Rehabilitation physiotherapists and Erciyes University Scientific Research Projects Coordination Unit (ERU/BAP).

This work supported by Erciyes University Scientific Research Projects Coordination Unit (ERU/BAP). (Project Codes: FYL-2015-5884, FBA-2014-5332)

References

[1] H. Zhou and H. Hu, "Human motion tracking for rehabilitation—A survey," *Biomedical Signal Processing and Control*, vol. 3, pp. 1-18, 1// 2008.

[2] Z. Huiyu and H. Huosheng, "Inertial motion tracking of human arm movements in stroke rehabilitation," in Mechatronics and Automation, 2005 IEEE International Conference, 2005, pp. 1306-1311 Vol. 3.

[3] Z. Huiyu and H. Huosheng, "Kinematic model aided inertial motion tracking of human upper limb," in Information Acquisition, 2005 IEEE International Conference on, 2005, p. 6 pp.

[4] H. Zhou, H. Hu, and N. D. Harris, "Wearable inertial sensors for arm motion tracking in home-based rehabilitation," in IAS, 2006, pp. 930-937.

[5] H. Zhou and H. Hu, "Inertial sensors for motion detection of human upper limbs," *Sensor Review*, vol. 27, pp. 151-158, 2007.

[6] H. Zhou and H. Hu, "Upper limb motion estimation from inertial measurements," *International Journal of Information Technology*, vol. 13, pp. 1-14, 2007.

[7] H. N. Rasyid, T. R. Mengko, S. Soegijoko, and J. T. Pramudito, "Design and realization of personal computer-based continuous passive motion device to prevent shoulder joint stiffness," in Circuits and Systems, 2004. Proceedings. The 2004 IEEE Asia-Pacific Conference on, 2004, pp. 573-576 vol.1.

[8] M. Mihelj, T. Nef, and R. Riener, "A novel paradigm for patient-cooperative control of upper-limb rehabilitation robots," *Advanced Robotics*, vol. 21, pp. 843-867, 2007/01/01 2007.

[9] B. Birch, E. Haslam, I. Heerah, N. Dechev, and E. J. Park, "Design of a continuous passive and active motion device for hand rehabilitation," in Engineering in Medicine and Biology Society, 2008. EMBS 2008. 30th Annual International Conference of the IEEE, 2008, pp. 4306-4309.

[10] M. Saputra and A. Iskandar, "Development of automatic Continuous Passive Motion therapeutic system," in Instrumentation, Communications, Information Technology, and Biomedical Engineering (ICICI-BME), 2011 2nd International Conference on, 2011, pp. 376-379.

[11] S. Dong, K.-Q. Lu, J. Q. Sun, and K. Rudolph, "A prototype rehabilitation device with variable resistance and joint motion control," *Medical Engineering & Physics*, vol. 28, pp. 348-355, 5// 2006.

[12] W. Hassani, S. Mohammed, H. Rifaï, and Y. Amirat, "Powered orthosis for lower limb movements assistance and rehabilitation," *Control Engineering Practice*, vol. 26, pp. 245-253, 5// 2014.

[13] F. Zhang, P. Li, Z.-G. Hou, Z. Lu, Y. Chen, Q. Li, et al., "sEMG-based continuous estimation of joint angles of human legs by using BP neural network," *Neurocomputing*, vol. 78, pp. 139-148, 2/15/ 2012.

[14] P. K. Jamwal, S. Xie, and K. C. Aw, "Kinematic design optimization of a parallel ankle rehabilitation robot using modified genetic algorithm," *Robotics and Autonomous Systems*, vol. 57, pp. 1018-1027, 10/31/ 2009.

[15] W. Wang, Z.-G. Hou, L. Tong, F. Zhang, Y. Chen, and M. Tan, "A novel leg orthosis for lower limb rehabilitation robots of the sitting/lying type," *Mechanism and Machine Theory*, vol. 74, pp. 337-353, 4// 2014.

[16] K.-M. Lee and J. Guo, "Kinematic and dynamic analysis of an anatomically based knee joint," *Journal of Biomechanics*, vol. 43, pp. 1231-1236, 5/7/ 2010.

[17] M. C. Chua, A. S. Hyngstrom, A. V. Ng, and B. D. Schmit, "Relative changes in ankle and hip control during bilateral joint movements in persons with multiple sclerosis," *Clinical Neurophysiology*, vol. 125, pp. 1192-1201, 6// 2014.

[18] Ş. Yildirim, İ. Eski, and Y. Polat, "Design of adaptive neural predictor for failure analysis on hip and knee joints of humans," *Neural Computing and Applications*, vol. 23, pp. 73-87, 2012.

[19] S. Stroeve, "Impedance characteristics of a neuromusculoskeletal model of the human arm I. Posture control," *Biological Cybernetics*, vol. 81, pp. 475-494.

[20] T. E. Milner, "Adaptation to destabilizing dynamics by means of muscle cocontraction," *Experimental Brain Research*, vol. 143, pp. 406-416, 2002.

[21] S. Morita, T. Kondo, and K. Ito, "Estimation of forearm movement from EMG signal and application to prosthetic hand control," in Robotics and Automation, 2001. Proceedings 2001 ICRA. IEEE International Conference on, 2001, pp. 3692-3697 vol.4.

[22] K. J. Kuchenbecker, J. G. Park, and G. Niemeyer, "Characterizing the human wrist for improved haptic interaction," in ASME 2003 International Mechanical Engineering Congress and Exposition, 2003, pp. 591-598.

[23] N. Hogan, "Controlling impedance at the man/machine interface," in Robotics and Automation, 1989. Proceedings., 1989 IEEE International Conference on, 1989, pp. 1626-1631 vol.3.

[24] A. A. Frolov, R. Prokopenko, M. Dufosse, and F. B. Ouezdou, "Adjustment of the human arm viscoelastic properties to the direction of reaching," *Biological cybernetics*, vol. 94, pp. 97-109, 2006.