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PID Controller Design for Human Elbow Therapy

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Abstract:A controller design for mechatronic system which capable of doing passive therapeutic exercises of patients who have upper extremity limitation is presented in this paper. Expectation from controller is it should produce torque values can exactly repeat degree values depended on time which were taken from first therapy exercises of patients. The designed controller tested with real angle values which was taken from during elbow therapy. Simulation results showed that the proposed control system has good performance at tracking the therapy trajectory. Also that control system may be used for mechatronic upper limb therapy system which can be produced.

Keywords:*Controller design, limitation at human joints, therapeutic exercises, therapy system.*

1. Introduction

Autonomous rehabilitation machines advantages realized by people day by day. Controllers are most important part of that machines so controller design is the most important topic. Several studies about human motion tracking, rehabilitation machines and controller design for that machines are outlined in this section.

Zhou et al. compared many human motion tracking methods with each other. Their conclusion is inertial sensors is the best method for human motion tracking in terms of ease of use and data accuracy [1-6]. Continuous passive motion device for shoulder is designed by Rasyid et al.. The device can be used for joint motion limitation [7]. Mihelj et al. used ARMin exoskeleton robot at their work and they proposed new patient-cooperative control strategy for upper limb rehabilitation device. 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 [8]. Birch et al. designed rehabilitation device can be used either continuous passive motion (CPM) or continuous active motion (CAM) for human hand rehabilitation. Device actively resisting the movement at CAM mode and at CPM mode they used PD control [9]. Saputra et al. used microcontroller to control automatically working CPM device. That device use for knee joint rehabilitation. When patients feel pain, DC motor overloaded so device stops movement [10]. Dong et al. developed intelligent controller and prototype rehabilitation device for human joints [11]. Hassani et al. developed device that perform passive and active motions. That devices main objective is helping health staff [12]. Zhang et al. designed intelligent neural network controller for active rehabilitation device. They used BP neural network for estimation of human knee joint angle change [13]. Prashant et al. designed parallel rehabilitation robot for human ankle movement. They used kinematic analysis and genetic algorithm for optimization [14]. Rehabilitation robot for human ankle, knee and hip joints designed by Wang et al.. They used swarm algorithm for optimization problem [15]. Lee et al. placed artificial mechanism at human knee joint and they gave mathematical model for that artificial mechanism [16]. Chua et al. measured angle change of human hip and knee joints and they designed rehabilitation robot [17]. Yildirim and Eski designed neural network analyzer for human hip and knee joints and they used vibration data of human hip and knee joints [18].

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

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:

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

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:

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

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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.

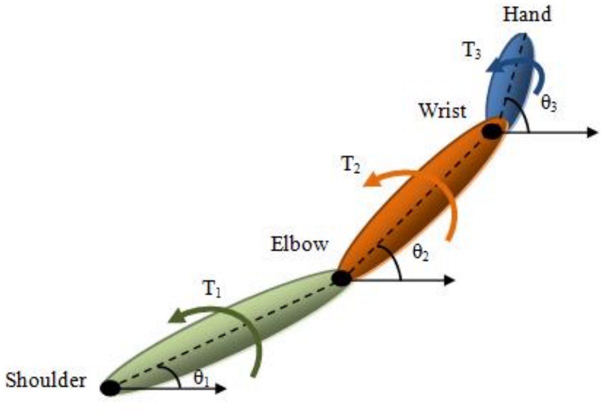

Figure 1. Angle and torques descriptions for joints of the human upper limb

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:

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

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

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

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

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

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

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \tag{12}$$

$$D = [0] \tag{13}$$

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 wrist 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 elbow 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 elbow joint

Control Structures	**Kp**	**Ki**	**Kd**	**Filter coefficent (N)**
PID (Tune)	4.14	27.97	0.152	1849.93
PID (ZN)	12	120	0.3	-

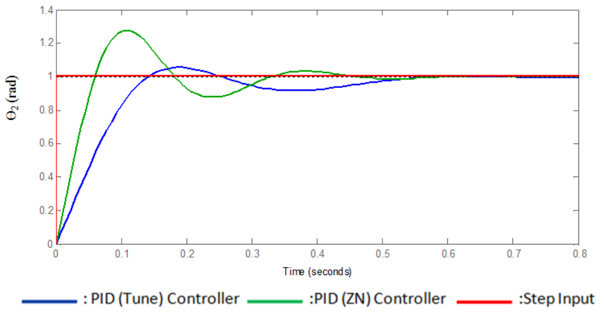

Figure 2. Control structures response for the elbow joint using unit step input signal

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

Elbow joint				
Control Structures	**Rise Time**	**Settling Time**	**Overshoot**	**SS Error**
PID (Tune)	0.102	0.513	%5.33	0
PID (ZN)	0.0467	0.421	%27.7	0

Simulation results for proposed controllers with patient data's has shown at Fig.(3,4). Data's taken from patients who has elbow joint limitation. Patient - 1 is 61 years old male and has limitation at right elbow joint, Patient - 2 is 19 years old male and has limitation at right elbow after fracture.

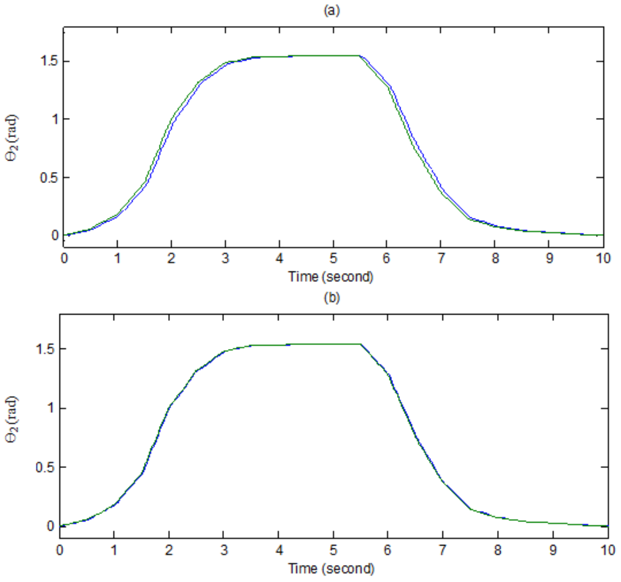

Figure 3. Elbow joint angular variations of patient 1 using a) PID (Tune) controller b) PID (ZG) controller

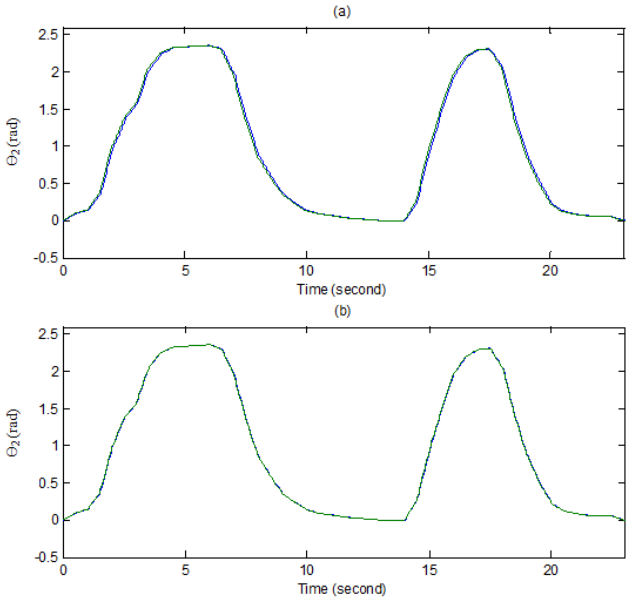

Figure 4. Elbow joint angular variations of patient 2 using a) PID (Tune) controller b) PID (ZG) controller

As seen in figures, PID (ZN) control system has minimum steady-state error and giving better results on adapting comparing with the PID (Tune) control systems.

5. Conclusions

In this paper, control structure designed according to taken data from patients who has limitation elbow 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.

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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.