Active Force Control System for Tremor Suppression in Elbow Joint

Seyedehmarzieh Hosseini
School of Electrical, Mechanical & Mechatronic Systems
University of Technology Sydney, UTS
Sydney, Australia
Seyedehmarzieh.Hosseini@student.uts.edu.au

Adel Al-Jumaily
School of Electrical, Mechanical & Mechatronic Systems
University of Technology Sydney, UTS
Sydney, Australia
Adel.Al-Jumaily@uts.edu.au

***Abstract*— Tremor is a neurological disorder characterized by involuntary oscillations. Difficulties associated with tremor in patients with Parkinson's disease have motivated the researchers to work on developing various methods for tremor suppression. Active Force Control (AFC) method for tremor attenuation in human body parts is considered in this work. This paper proposes a new AFC system based on a piezoelectric actuator. A one-degree-of-freedom musculoskeletal model of the elbow joint with two links and one joint is developed. The model includes two muscles, biceps, and triceps as the flexor and the extensor of the elbow joint. First, simulation of the tremor generation in the model is performed and then the performance of AFC system for suppressing elbow joint tremor is investigated. A single piezoelectric actuator is embedded in AFC system for controlling the behaviour of the classic proportional-derivative controller. MATLAB Simulink is used to analyse the model. Results show that the AFC-based system with a piezoelectric actuator and a PD controller is very effective in suppressing the human hand tremor.**

Keywords—tremor suppression; musculoskeletal model; elbow join; functional electrical stimulation

I. INTRODUCTION

Tremor is a neurological disorder that categorized by unconscious oscillations of parts of the body. The most famous characteristics for this disability are involuntary, roughly recurring, and approximately sinusoidal [1, 2]. Previous researches showed that healthy people exhibit a slight degree of muscle movement which is called physiological tremor [3, 4]. However, patients with pathological tremor have annoying oscillations on their body parts. People with Parkinson's disease are the group of patients who have this pathological tremor especially with their upper limbs and therefore have so many difficulties in their daily life. Physical tasks such as eating, drinking, writing, walking, and some of other daily tasks become difficult by the interference of tremor [3, 5, 6]. Therefore, studying the effective ways to attenuate the tremor is essential for affected people.

Several research works have been performed to study and control the effects of human hand tremor. Medical and Surgical treatments such as drugs, surgery, deep brain stimulation (DBS) and thalamic stimulator used to reduce hand tremor. However, the drug treatments often reduce the progress of tremor, but most drugs have their inherent disadvantages. Also, surgery is associated with a risk of operation on brain [7].

In previous works, some researchers used Active Force Control (AFC) method for tremor attenuation in human body parts [4, 5, 7].In these studies, a 4-DOF mas-spring-damper model of the hand was used.

In this paper, an AFC method is developed for analyzing the behavior of hand tremor. A one-degree-of-freedom (1-DOF) musculoskeletal model of the elbow joint with two links, one joint and two muscles is used. First, the electrical pulse is employed to simulate the tremor in elbow joint. Then, The AFC method with piezoelectric actuator and PID controller is used for investigating the elbow tremor behavior. A MATLAB-Simulink simulation is used for analyzing the model in AFC control system.

II. HUMAN HAND MODEL

A. Musculoskeletal Model

There are some musculoskeletal models that have been established to specify the characteristics of the biodynamic response of the human hand and arm under vibration [8-10]. To investigate the human tremor, it is necessary to determine the biodynamic response of human tremor to apperceive the relation between the force and motion of the human tremor. In this paper, a two-dimensional (2D) model of the arm with one degree of freedom (elbow flexion-extension) in a 2D plane is adopted. This model includes two muscles, biceps, and triceps. These two muscles are a couple of adversary muscles that work for flexion and extension of the elbow joint. The biceps muscle group includes long and short head though the triceps contains long, medial and lateral heads [9]. Since the tremor control in a single joint in a 2D plane is considered in this paper, only uniarticular muscles of elbow joint are taken into account in the analyses. Thus, triceps lateral head (LtH) and biceps long head (LH) are nominated for simulation of tremor. Fig. 1 shows a simplified musculoskeletal model [9].

In current work, the forearm is considered only and is modelled as a pendulum. The equation of motion of the elbow with tremor is:

$$T_t + T_p = (\frac{1}{4}ml^2 + I)\ddot{\theta} + \frac{1}{2}mgl\cos\theta n \qquad (1)$$

where T_t is the generated moment by muscle through active electrical stimulation, T_p denotes the internal passive moment, m indicates the forearm mass, I shows the moment of inertia, l is the forearm length, and g signifies the gravitational constant. The value of the related parameters used in the calculation is listed in Table I.

TABLE I. THE PARAMETER VALUES FOR THE FOREARM

m(kg)	*I(kgm²)*	*l(m)*
1.6	0.013	0.32

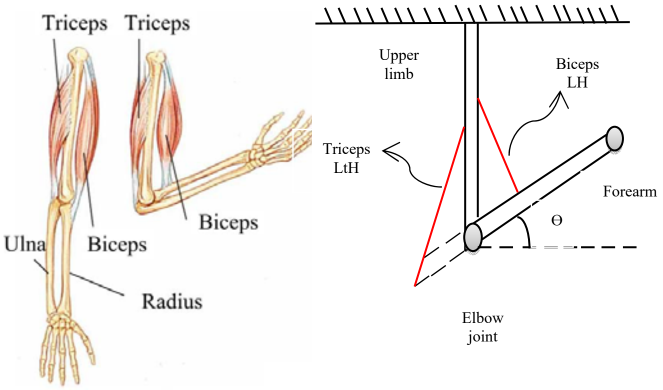

Fig. 1. A physiological model of the elbow joint (Left), simplified musculoskeletal model (Right) [9].

B. Muscle Model

The muscle model is developed from the classic Hill-type muscle model [12, 13]. In this model, the response of the muscle to a stimulation signal is made of two parts: activation dynamics and contraction dynamics. The muscle model is illustrated in Fig. 2.

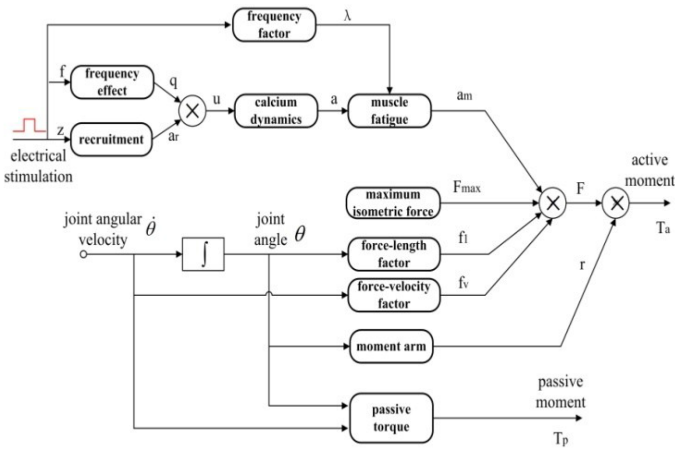

Fig. 2. Block diagram of muscle model [10].

1) Muscle Contraction Dynamics

Muscle contraction property is resulted from the mechanical structure of the muscle.

a) Active Force: The generated force by muscle through the stimulation is called the active force as:

$$F = F_{\max} \times f_l \times f_v \times a_m \tag{2}$$

where $F_{\max}$ is the muscle maximum isometric force, f_l is the force-length factor, f_v is the force-velocity factor, and a_m is the muscle activation with fatigue. $a_m = ap$, where p is the muscle fatigue factor and a is the muscle activation without fatigue which will be introduced later.

The active moment for 1-DoF elbow joint in flexion-extension is：

$$T_t = \sum_{i=1}^{2} F_i r_i \tag{3}$$

where F_i denotes the muscle force, r_i shows the moment arm, and i indicates the number of muscles, biceps LH and triceps LtH.

b) Muscle length factor: Changing muscle length forcefully affects on the active force. The relationship between the muscle force and muscle fibre length can be described by a Gaussian-like function:

$$f_l = \exp\left[-\left(\frac{\bar{l}-1}{\varepsilon}\right)^2\right] \tag{4}$$

where f_l is a normalized factor, $\bar{l}$ is the normalized muscle length with respect to the optimal muscle length; $\bar{l} = l_m / l_{opt}$ and $l_m = r(\theta - \theta_r)$.

c) Force-Velocity Factor: The muscle force is affected by muscle velocity, and the factor f_v signifies this relationship as:

$$f_v = 0.54\arctan(5.69\bar{v} + 0.51) + 0.745 \tag{5}$$

where $\bar{v}$ is the normalized muscle velocity with respect to the maximum contraction (shortening) velocity $v_{\max}$ of the muscle; $\bar{v} = v_m / v_{\max}$ and $v_m = r\dot{\theta}$. Table II shows the parameters for two muscles[11, 14].

TABLE II. THE PARAMETERS VALUES FOR MUSCLES

Muscles	l_{opt} **(m)**	v_{max} **(m/s)**	F_{max}**(N)**	***r(m)***
BICEPS	0.136	0.68	900	0.03
TRICEPS	0.084	0.42	900	-0.03

d) Passive Torque: The passive element (PE) in the muscle model produces a passive torque. For the elbow joint, it is given as [15]:

$$T_p = 0.2\dot{\theta} - 7.8\,\mathrm{sgn}(\theta - \pi/2)\left[\exp(36/\pi\left|\theta - \pi/2\right|) - 1\right] \times 10^{-7} \tag{6}$$

where *sgn*() is the signum function that identifies the sign of its argument.

2) Muscle Activation Dynamics

When electrical pulses stimulate the muscle, there is a dynamic process for the force generation in the muscle. This electrical parameter of the muscle is referred to as activation dynamics [10].

a) Muscle Recruitment Curve. This property can be modelled by a piecewise function with three values: a threshold pulse width (PW_d), a saturation pulse width (PW_s) and the pulse width of the electrical pulse (z). The normalized muscle recruitment curve, a_r, can be described as:

$$a_r = \begin{cases} 0 & z \le PW_d \\ \frac{1}{PW_s - PW_d}(z - PW_d) & PW_s \le z \le PW_d \\ 1 & z \ge PW_s \end{cases} \quad (7)$$

b) Frequency Characteristics: The force that is produced by a muscle is affected by frequency changing. This force-frequency function can be given by:

$$q(f) = \frac{(af)^2}{1+(af)^2} \quad (8)$$

where f is the frequency of stimulation and q represents the characteristic factor.

c) Calcium Dynamics: **The activation and relaxation process in the muscles are not** concurrently. In fact, there is a time delay for this manner always. Calcium dynamics is modelled as:

$$\dot{a} = \frac{1}{\tau_{ac}}(u - ua) + \frac{1}{\tau_{ad}}(u - a) \quad (9)$$

where a denotes the muscle activation without fatigue, $u = a_r q$; τ_{ac} signifies activation time constant, and τ_{da} shows the de-activation time constant.

d) Muscle Fatigue: Muscle fatigue has a relationship with the frequency of the stimulation and activation level, a.

$$\dot{p} = \frac{a\lambda(p_{\min} - p)}{\tau_{fat}} + \frac{(1-p)(1-a\lambda)}{\tau_{rec}} \quad (10)$$

$$\lambda = 1 - \beta + \beta(\frac{f}{100}) \quad (11)$$

where in this equation p represent the fatigue, τ_{fat} shows the fatigue time constant, τ_{rec} denotes the recovery time constant, p_{min} signifies the minimum fitness, λ is the frequency factor on fatigue, and β indicates the shaping factor. Table III displays the value of parameters related to contraction and activation dynamics [8, 11].

TABLE III. THE PARAMETER VALUES FOR THE ELBOW MUSCULOSKELETAL MODEL

PW_s (μs)	PW_d (μs)	τ_{ac} (ms)	τ_{da} (ms)	τ_{fat} (ms)	τ_{rec} (ms)	β $(-)$	ε $(-)$	$p_{\min}$ $(-)$
100	500	40	70	18	30	0.6	0.4	0.4

III. ACTIVE FORCE CONTROL METHOD

AFC is a robust controller that is introduced by Hewit [16]. In fact, AFC introduces a cancelling "anti-vibration" wave through a suitable rank of secondary sources. These secondary sources are unified through an electronic system using a particular signal processing algorithm for the certain termination pattern [17].

Today's active vibration control is a very effective research area that has different applications in many technologies [18, 19]. A typical active vibration control system has mechanical and electronic components in control system. The principle constituents of any active vibration control system are the mechanical construction influenced by the commotion, sensors for measuring the vibration, controllers, and actuators for suppressing the influence of the disturbance on the structure [20].

For suppressing the upper limb tremor with the use of AFC scheme, Fig. 3 is suggested. In this loop, a proportional–derivative (PD) controller controls the actuator for damping hand tremor. From Newton second law of motion, the main AFC equation will be expressed as:

$$\tau_d' = \tau - I'\ddot{\theta} \quad (12)$$

Where, τ_d' is estimated disturbance torque, τ is applied torque to the system, I' is estimated the vibratory inertia and $\ddot{\theta}$ is measured acceleration signal. The value of estimated inertia can be caught by using crude approximation method [4].

As it's shown in Fig. 3, the aim of proposed design is to make constant output respect to the disturbance on the system. This design is an effective control system if the system output is invariant. In Fig. 3 *TF* is the transfer function of the actuator, u is the desired position, θ is the actual position of the hand, and τ_d is the electrical pulse for tremor stimulation.

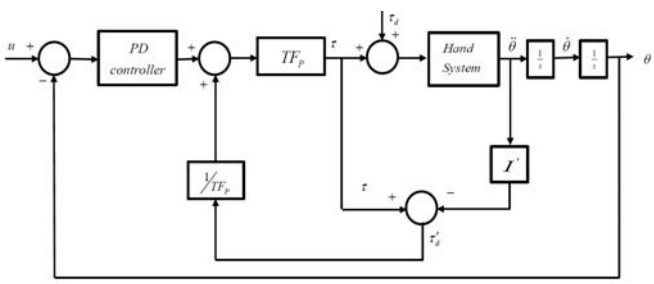

Fig. 3. A block diagram of proposed design for the control system.

IV. PID CONTROLLERS

A proportional–integral–derivative controller (PID controller) is a control mechanism which used in control system. The produced signal of PID controller is proportional to the error signal that is sensed by a sensor. This error signal is decreased and finally gets to a minimum value over time by setting a control variable of the system. For having the desired result with these controllers, finding appropriate parameters of PID controller is noteworthy. A classic PID controller is described as:

$$\text{output}(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \quad (13)$$

Where *output(t)* represents the controller output and *e(t)* is the error. Also, K_p, K_i and K_d are the proportional, integral and derivative gain, respectively. According to the system, a PID controller may be used just with one or two terms to make the proper control for the system. This is attained by setting the other parameters to zero. A PID controller will be called a PI, PD, P or I controller in the deficiency of the respective control actions [21]. In this study, a PD controller is used and heuristic method can be used for determining the PD parameters.

V. Transfer Function of Actuators

In this study, a piezoelectric actuator is embedded in the AFC system. Piezoelectric actuators have an effective role in today's technology. These actuators have been used in many applications and fields. One of these areas is active vibration control. The Piezoelectric actuators have small dimension and weight and can be simply driven by voltage. Furthermore, these actuators are easily controlled and can provide fast response [7, 22]. The piezoelectric transfer function can be expressed by the following equation [23].

$$F_a = \frac{2wt}{l} \cdot \frac{d_{31}}{S_{11}} V \quad (14)$$

where, F_a is the maximum force of the piezoelectric actuator, w is cantilever width, t is cantilever thickness, l is cantilever length, d_{31} is piezoelectric constant, S_{11} is an elastic constant of the piezoelectric material, V is input voltage [V].

In this study a bimorph-type piezoelectric actuator is used. Parameters for transfer function of this actuator are; $w=0.0318m$, $t= 0.005m$, $l= 0.0635$, $d_{31}=190\times10^{-12}mv^{-1}$, $S_{11}=1.613\times10^{-11}m^2N^{-1}$ [7].

VI. Simulation of Control System

As it was discussed in previous parts, in this paper, the elbow joint is modelled as a 1-DOF musculoskeletal model that consists of two muscles and one skeleton. As we need to control the joint tremor, a control scheme is proposed, Fig. 3. In this control system, AFC method is used. A PD controller and a piezoelectric actuator are embedded in the control system. To study the result of the control system, the elbow joint is simulated in MATLAB-Simulink. Upper limb (elbow joint) tremor can be attained when tremulous stimulation activates the biceps and triceps muscles. Artificial tremor can be generated by artificial electrical pulses via functional electrical stimulation (FES) technique. Three variables are needed for defining an electrical pulse, i.e. pulse width, pulse frequency, and pulse amplitude. In this paper only pulse width (PW) is controlled. The other two variables are as constants. The pulse frequency is set at 20 Hz and pulse amplitude is 25 *mA*. Regarding the EMG pattern that attained from patients [13], the pulse width of electrical stimulation for biceps and triceps are 300 μs and 200 μs, respectively. Then displacements plots show the joint behaviour in this control system.

VII. Results

As mentioned previously, the proposed system was simulated in MATLAB to investigate the effect of an AFC control system to reduce the elbow joint tremor with the help of a piezoelectric actuator and a PID controller.

The displacement signal for the tremor of the elbow joint without any control system is illustrated in Fig. 4 for 10 seconds. From this figure, it can be found that the displacement is between -5° to +6° which is within the target range as the actual human hand postural tremor in Parkinson's disease is about ±6° [7, 24].

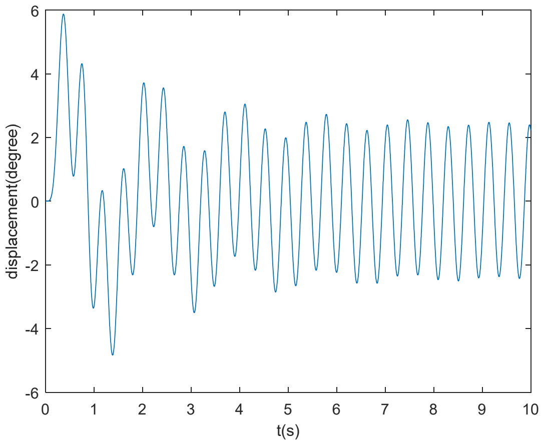

Fig. 4. Displacement result for 1-DOF musculoskeletal model of the elbow joint from MATLAB simulation.

The results for the displacement of the elbow joint with an AFC method and a piezoelectric actuator is shown in Fig. 5. As this figure shows, during simulation time, the tremor decreases incredibly and is between -1.5×10^{-5} [deg] to $+1.5\times10^{-5}$ [deg] that is much smaller than joint angle without an AFC system. It is clear that an AFC control system with a PD controller and a piezoelectric actuator is a very effective system for suppressing tremor.

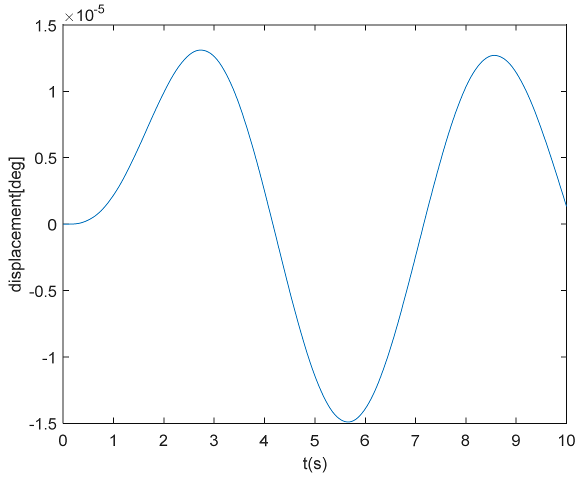

Fig. 5. Displacement result for the 1-DOF musculoskeletal model of the elbow joint from MATLAB simulation with AFC control system.

Simulation result for a musculoskeletal model of elbow joint for 40 *s* is shown in Fig. 6. During this time, the joint tremor is suppressed totally, and the displacement is about zero starting from 30 *s*. This result indicates that the proposed AFC control system with a piezoelectric actuator and a PID controller is an effective system for tremor suppression.

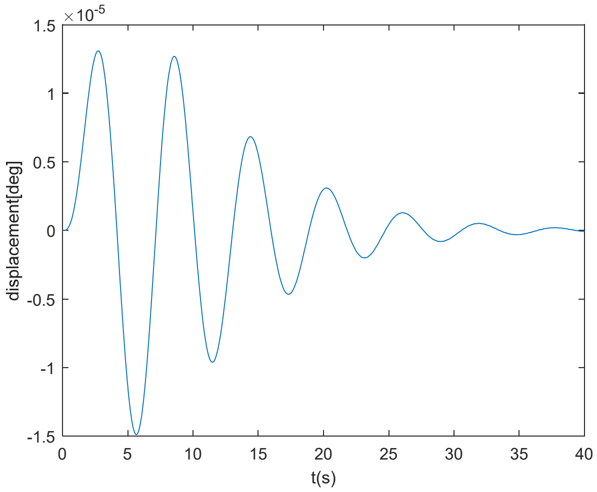

Fig. 6. Displacement result for the 1-DOF musculoskeletal model of elbow joint from MATLAB simulation with AFC control system in 40 sec.

VIII. Conclusion

This study presents an investigation for tremor suppression from the human elbow joint using active force control method. The elbow joint is modeled with two limbs, one joint and two muscles. An electrical pulse stimulates the muscle, and an AFC system controls the tremor of the elbow joint. From simulation results, the AFC method with a PD controller and a piezoelectric actuator has a significant effect on reducing tremor. As shown in the Fig.4 and Fig. 6, when there is a control system, the amplitude of tremor decreases from ±6 [deg] to $\pm1.5\times10^{-5}$ [deg]. It is shown that the proposed AFC is very practicable in tremor attenuation.

References

[1] C. N. Riviere, R. S. Rader, and N. V. Thakor, "Adaptive cancelling of physiological tremor for improved precision in microsurgery," *Biomedical Engineering, IEEE Transactions on,* vol. 45, pp. 839-846, 1998.

[2] W. T. Ang, P. Pradeep, and C. Riviere, "Active tremor compensation in microsurgery," in *Engineering in Medicine and Biology Society, 2004. IEMBS'04. 26th Annual International Conference of the IEEE*, 2004, pp. 2738-2741.

[3] G. K. Wenning, S. Kiechl, K. Seppi, J. Müller, B. Högl, M. Saletu*, et al.*, "Prevalence of movement disorders in men and women aged 50–89 years (Bruneck Study cohort): a population-based study," *The lancet neurology,* vol. 4, pp. 815-820, 2005.

[4] A. As'arry, M. M. Zain, M. Mailah, M. Hussein, and Z. Yusop, "Active tremor control in 4-DOFs biodynamic hand model," *International Journal of Mathematical Models and Methods in Applied Sciences,* vol. 5, pp. 1068-1076, 2011.

[5] M. Hussein, A. As' arry, M. M. Zain, M. Mailah, and M. Abdullah, "Experimental study of human hand-arm model response," in *Mechatronics and its Applications, 2009. ISMA'09. 6th International Symposium on*, 2009, pp. 1-6.

[6] M. Z. M. Zain, A. As' arry, S. Kazi, M. Mailah, M. Hussein, and M. Abdullah, "Development of experimental-rig for human postural tremor behaviour," *International Journal of Human Factors Modelling and Simulation,* vol. 1, pp. 339-351, 2010.

[7] S. KAZI, M. MAILAH, and Z. M. ZAIN, "Suppression of Hand Postural Tremor Via Active Force Control Method."

[8] M. A. Lemay and P. E. Crago, "A dynamic model for simulating movements of the elbow, forearm, and wrist," *Journal of biomechanics,* vol. 29, pp. 1319-1330, 1996.

[9] D. Zhang and W. T. Ang, "Tremor suppression of elbow joint via functional electrical stimulation: A simulation study," in *Automation Science and Engineering, 2006. CASE'06. IEEE International Conference on*, 2006, pp. 182-187.

[10] P. Yao, D. Zhang, and M. Hayashibe, "Simulation of tremor on 3-dimentional musculoskeletal model of wrist joint and experimental verification?," in *Engineering in Medicine and Biology Society (EMBC), 2012 Annual International Conference of the IEEE*, 2012, pp. 4823-4826.

[11] M. Ferrarin, F. Palazzo, R. Riener, and J. Quintern, "Model-based control of FES-induced single joint movements," *Neural Systems and Rehabilitation Engineering, IEEE Transactions on,* vol. 9, pp. 245-257, 2001.

[12] N. Lan, "Stability analysis for postural control in a two-joint limb system," *Neural Systems and Rehabilitation Engineering, IEEE Transactions on,* vol. 10, pp. 249-259, 2002.

[13] D. Zhang, P. Poignet, F. Widjaja, and W. T. Ang, "Neural oscillator based control for pathological tremor suppression via functional electrical stimulation," *Control Engineering Practice,* vol. 19, pp. 74-88, 2011.

[14] R.-F. Fung, Y.-T. Liu, and C.-C. Wang, "Dynamic model of an electromagnetic actuator for vibration control of a cantilever beam with a tip mass," *Journal of Sound and Vibration,* vol. 288, pp. 957-980, 2005.

[15] T. Edrich, R. Riener, and J. Quintern, "Analysis of passive elastic joint moment in paraplegics," *Biomedical Engineering, IEEE Transactions on,* vol. 47, pp. 1058-1065, 2000.

[16] J. Hewit and J. Burdess, "Fast dynamic decoupled control for robotics, using active force control," *Mechanism and Machine Theory,* vol. 16, pp. 535-542, 1981.

[17] X. Yu, "Simulation study of tremor suppression and experiment of energy harvesting with piezoelectric materials," UNIVERSITY OF NORTH TEXAS, 2012.

[18] W. H. M. Isa, Z. Taha, I. M. Khairuddin, A. P. A. Majeed, K. F. Muhammad, M. A. Hashem*, et al.*, "An intelligent active force control algorithm to control an upper extremity exoskeleton for motor recovery," in *IOP Conference Series: Materials Science and Engineering*, 2016, p. 012136.
[19] F. B. Hoogterp, J. H. Beno, and D. A. Weeks, "An energy efficient electromagnetic active suspension system," *CEM Publications,* 2015.
[20] R. Alkhatib and M. Golnaraghi, "Active structural vibration control: a review," *Shock and Vibration Digest,* vol. 35, p. 367, 2003.
[21] A. Noshadi, M. Mailah, and A. Zolfagharian, "Active force control of 3-RRR planar parallel manipulator," in *Mechanical and Electrical Technology (ICMET), 2010 2nd International Conference on*, 2010, pp. 77-81.
[22] P. K. Sharma and S. Bhaduri, "Active Vibration Control Structures Using Piezoelectric Materials: A Review," 2015.
[23] S. Yun, K. Lee, H. Kim, and H. So, "Development of the pneumatic valve with bimorph type PZT actuator," *Materials chemistry and physics,* vol. 97, pp. 1-4, 2006.
[24] K. E. Norman, R. Edwards, and A. Beuter, "The measurement of tremor using a velocity transducer: comparison to simultaneous recordings using transducers of displacement, acceleration and muscle activity," *Journal of neuroscience methods,* vol. 92, pp. 41-54, 1999.