Assistive-as-needed strategy for upper-limb robotic systems: 
A preliminary evaluation of the impedance control architecture

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Abstract. Rehabilitation is a necessary restoration process of recovering impaired joint motion and muscle strength. Recent trends of rehabilitation have also moved towards providing more participation of the patient in therapy rather than simple passive treatments as it has been demonstrated to be non-trivial in promoting neural plasticity meant to promote motor recovery process. This paper presents an assistive control strategy based on impedance control technique. Dynamic modelling of upper arm is obtained by utilising the Euler-Lagrange formulation. The proportional-derivative (PD), computed torque control (CTC) impedance based framework is applied to examine its effectiveness in performing joint-space control with objectives specified in rehabilitating the elbow joint along the sagittal plane. A feasibility study through simulation was carried out to investigate the efficacy of the proposed controller on acceleration-based impedance model. The results show that impedance controller is more suitable as it allows the cooperative effort of the patient.

1. Introduction
Over the past two decades, the number of live expectancy among the elderly, particularly those in the age group of 60 years and above has increased significantly [1]. In Malaysia, the percentage of elderly in the population is about 8.3\% [2]. In addition, the annual report of Malaysian Ministry of Health’s in 2011 reported that the Malaysian population between the age group of 0 to 18 years old suffers from both physical disabilities due to traumatic injuries and cerebral palsy at around 11\% and 7\%, respectively [3]. Furthermore, the report also highlighted that there is a significant growth of stroke patients on the annual basis. These data reflect the size of the segments in the society that are diagnosed with disabilities which in turn depriving them of performing activities of daily living (ADL) [4].

In order to help the patient in regaining and relearning the existing motor skills for ADL, the patients’ needs to undergo rehabilitation process. [2]. For the first stage of rehabilitation process, the purpose is to reduce spasticity and muscle tone of impaired limb and increase its movable region or functional range of motion (ROM). Direct involvement is predicted to be sufficient on the condition of recovery.
The involvement of robotic platforms to grant rehabilitation exercise is a comparatively recent area within the field of robotics in healthcare. The primary objective of implementation of robotic platform is to aid the patient to flex out the impaired limb to move along the predefined trajectory. In order to control the robotic platform, many position-based control schemes have been introduced and implemented.

In order to make the patient contributes during the specialized training, an assistance force or resistance force is usually supplied by the robotic platform, notably to rehabilitate the responsive impaired limb. During this stage, the amount of force and/or torque exerted by the robot to the impaired limb is imperative. Therefore, different type of control strategies has been developed to address this issue. For instance, in [5] fuzzy logic is incorporated with hybrid position/force control for the robotic platform to control the elbow and shoulder of the patient. Active force-based control technique has been employed both for upper and lower-limb exoskeletons for passive based rehabilitation therapy [2,6,7]. Impedance control is another type of force control method, which is different from direct force control in a sense that the control law is realised by regulating the dynamic relationship between the robot and the patient [8]. Therefore, various type of control strategies involving impedance controller has been established. Anklebot was reported to utilise adaptive impedance controller [9]. The parameter for impedance controller is obtained by measuring the dynamic contribution from the patient. In [10] the impedance controller is used to control the upper-limb exoskeleton where the input for the controller is taken by measuring the signal from EMG attach to the arm.

This paper aims at benchmarking different existing control strategies namely PD and computed torque control (CTC) based impedance control in order to promote the assist-as-needed strategy for upper limb rehabilitation robot system. The modeling of the robotic platform is described in section 2. It follows in section 3, the results and discussion on simulation study. The conclusion of this paper is described in section 4.

2. Upper-Limb Dynamics and Controller Strategy

2.1. Dynamic Model of the Upper-Limb

The upper-limb dynamics of the human limb and robotic platform are modeled as the motion of an open kinematic chain rigid joint as shown in Figure 1. The single-link model restricted to the sagittal plane, and the human-machine interaction is assumed to be seamless. Furthermore, the frictional elements that act on both the robotic platform and human joints, as well as other unmodelled variables, are also ignored. This model provides movement as in the flexion and extension of the elbow

![Figure 1. The upper-limb.](image)

In the figure shown, \( L \) represent the length segments of the limb and the robotic platform and \( \theta \) is the angular position of the link. By applying the Newton-Euler formulation, the dynamics of the robotic platform can be written in the following standard form as shown in Equation 1

\[
\tau = D(\theta)\dot{\theta} + C(\theta, \dot{\theta}) + G(\theta) + \tau_d
\]

where \( \tau \) is the input signal represents the actuated torque vector at the joint, \( D \) is the uniformly positive definite inertia of the robotic platform and limb, \( C \) is the Coriolis and centripetal torque vector, \( G \) is the
gravitational torque vector (this term is neglected as the motion of the forearm limb is constrained along the horizontal plane) whilst $\tau_d$ is the external disturbance torque vector. The components of following equation that represents the system can be derived as follows where the component for inertia is
\[ D = mL^2 \] (2)
whereas the Coriolis components are
\[ C = 0 \] (3)
and for the gravitational terms
\[ G = mgL\cos(\theta) = 0 \] (4)
where $m$ is the combination of both masses. The anthropometric parameters of human segments used in this study were adopted from [12]. The remaining parameters are listed in section 3.

2.2. Controller Strategy
The primary purpose of robotics based rehabilitation is to assist patients to undergo rehabilitation in addition to complement the dependency on the therapists. However, to complete the prescribed exercise regime demands significant effort from the patient. Therefore, the strategy of assist-as-needed is paramount to contribute the minimal amount of robot assistance to aid the patients in rehabilitation. There are various methods that have been developed by researchers, and the most basic type of controllers found from the literature and often applied in robotic rehabilitation is impedance controller [11]. The objective of utilising impedance controller is to ensure the impaired upper-limb to move on a specific path during the therapy sessions. In this paper, the impedance controller is expressed by equation 5.
\[ F = M(\ddot{x} - \ddot{x}_d) + B(\dot{x} - \dot{x}_d) + K(x - x_d) \] (5)
The impedance model represents a mass-spring-damper system, where $M, B, K$ is the inertia, damping and stiffness factor of the robot respectively. $F$ on the other hand, is the force input from the subjects’ upper-limb.
\[ \ddot{x} = \ddot{x}_d + M^{-1} \left( B(\dot{x}_d - x) + K(x_d - x) + F \right) \] (6)
Then, the impedance controller has been rearranged as in equation 6 to form the acceleration based impedance controller, in order to describe the model of interaction between the robot and the subjects’ upper extremity force input. Conversely, the stiffness, $K$ is the gain factor of displacement, the damping, $B$ is the gain factor of the velocity and the inertia, $M$ is the gain factor of acceleration, respectively. From the equation 6, $x, \dot{x}$ refer to the actual motion and velocity from the robot, while $x_d$ and $\dot{x}_d$ is represented the desired motion and desired velocity of the robot. Whilst, $\ddot{x}$ is the acceleration that used as an input for the inverse dynamics, and $\ddot{x}_d$ is the desired acceleration of the robot.

Figure 2 depicted how the impedance control is being applied to the system.

![Figure 2. Control Strategy.](image-url)
3. Result and Discussion
In this study, the simulation works were performed in MATLAB/Simulink computing platform. The simulation parameters employed in this study are tabulated in Table 1 and 2, respectively. The trajectory planner is used as the signal input is derived based on equation 4 [12].

$$a = a_i + \frac{3a_f}{t_f^2} t^2 - \frac{2a_f}{t_f^3} t^3$$

(7)

Where $a$ is the robot joint, $a_i$ represent the initial position of robot joint, while $a_f$ is the final desired of position joint. The time taken for robot motion takes place is represent as $t_f$ while $t$ is the real-time simulation counter.

**Table 1.** Upper-limb parameters.

| Parameters                                           | Values         |
|------------------------------------------------------|----------------|
| Limb and robotic platform robot lengths ($L$)        | 0.3 m          |
| Upper arm masses ($m_{upperarm}$)                    | 1.91 kg        |
| Robotic platform masses ($m_{exo}$)                  | 0.2 kg         |
| Mass moment of inertia of limb ($J_{limb}$)          | 0.2374 kg.m²   |
| Mass moment of inertia of robotic platform ($J_{exo}$)| 0.0131 kg.m²   |

**Table 2.** Controller parameters.

| Control Parameters | Gains |
|--------------------|-------|
| $K_p$              | 360   |
| $K_d$              | 60    |

The simulation time selected for this study is 10 seconds, whilst the fixed-step size of 0.01 is chosen by utilising the ode2 (Heun) solver algorithm.

**Figure 3.** Angle of elbow extension based on Signal Input.
It could be observed from the preliminary simulation analysis as depicted in Figure 3, that the PD impedance based control scheme tracks well the desired trajectory in comparison to the PD-CTC impedance based scheme. Table 3 tabulates the trajectory error in terms of root-mean-square-error (RMSE) of the compared control schemes. This observation is rather interesting, if passive based rehabilitation (robot perform the rehabilitation without the force/torque from the patient) is concerned, the ability of the PD architecture to track well the desired trajectory is laudable, however, from an active based rehabilitation (the patient will use their strength to complete the rehabilitation) standpoint, the PD-CTC control scheme performs better as it allows or exhibits the natural ability of the impaired limb to perform the task provided. The utilisation of the classical PD impedance scheme somewhat imposes motion of the affected limb or in other words cancels out the influence of the impedance-based controller. Whilst, the whole idea of implementing the impedance controller is to observe the robotic dynamic behaviour according to the natural torque imposed by the patient’s limb. It is observed that as the limb is relaxed, it behaves as an admittance and the robotic platform acts as an impedance. As the patient tries to move the limb, the limb can be seen as to have an increase in the impedance but if the robotic platform is operating with a higher impedance, the limb will not respond to the robotic platform. Modulation of impedance allows patient-generated forces to cause a deviation from the joint’s target position. This effectively produces an artificial compliance or softness in the interaction between the patient’s limb and the robotic platform. A reduced impedance causes the robotic platform to produce a smaller corrective response to position error caused by patient-generated forces. Consequently, there is a trade-off between allowable interaction force and allowable deviation from the desired position which is analogous to the behaviour of a spring.

**Figure 4.** Angular speed of elbow extension.

**Table 3.** Trajectory error comparison.

| Control Scheme | RMSE (°) |
|----------------|----------|
| PD             | 107.7    |
| PD-CTC         | 108.2    |
4. Conclusion
It is evident from the study that although the conventional PD impedance based control strategy provides excellent joint trajectory tracking, for active based rehabilitation therapy, the PD-CTC impedance based scheme is more suitable as it allows the cooperative effort of the patients rather than solely based the robotic induced torque by the robotic platform. As this work is preliminary in its nature, other forms of task-based trajectories, as well as operating conditions, will be considered in future studies.

Acknowledgment
The work presented was carried out in the Biomechatronics Research Laboratory of International Islamic University Malaysia. The author wishes to gratefully acknowledge the E-Science grant funding (SF15-015-0065) from the Ministry of Science, Technology and Innovation Malaysia.

References
[1] Organization W H 2013 The World Health Report 2013: Research for universal health coverage. Sci. Transl. Med. 5 146
[2] Khairuddin I M, Taha Z, Majeed A P P A, Deboucha A H, Razman M A M, Jaafar A A and Mohamed Z 2016 A hybrid joint based controller for an upper extremity exoskeleton IOP Conf. Ser. Mater. Sci. Eng. 114 12133
[3] MOH 2011 Annual Report Ministry of Health 2011 351
[4] Lo H S and Xie S Q 2012 Exoskeleton robots for upper-limb rehabilitation: State of the art and future prospects Med. Eng. Phys. 34 261–8
[5] Ju M-S, Lin C-C K, Lin D-H, Hwang I-S and Chen S-M 2005 A rehabilitation robot with force-position hybrid fuzzy controller: hybrid fuzzy control of rehabilitation robot. IEEE Trans. Neural Syst. Rehabil. Eng. 13 349–58
[6] Majeed A P P A, Taha Z, Khairuddin I M, Wong M Y, Abdullah M A and Razman M A M 2016 The Control of an Upper-Limb Exoskeleton by Means of a Particle Swarm Optimized Active Force Control for Motor Recovery International Conference on Movement, Health and Exercise (Springer) pp 56–62
[7] Taha Z, Abdul Majeed A P P, Zainal Abidin A F, Hashem Ali M A, Khairuddin I M, Deboucha A and Wong Paul Tze M Y 2017 A hybrid active force control of a lower limb exoskeleton for gait rehabilitation BioMed. Eng. / Biomed. Tech.
[8] Hogan N 1985 Impedance Control: An Approach to Manipulation Am. Control Conf. 1984 IS - SN - YO - 304–13
[9] Perez-Ibarra J C, Siqueira A A G and Krebs H I 2015 Assist-As-needed ankle rehabilitation based on adaptive impedance control IEEE International Conference on Rehabilitation Robotics vol 2015–Septe pp 723–8
[10] Kiguchi K and Hayashi Y 2012 An EMG-based control for an upper-limb power-assist exoskeleton robot IEEE Trans. Syst. Man, Cybern. Part B Cybern. 42 1064–71
[11] Marchal-Crespo L and Reinkensmeyer D J 2009 Review of control strategies for robotic movement training after neurologic injury. J. Neuroeng. Rehabil. 6 20
[12] Sidek S N, Mat H, Yusof H and Puzi A 2017 Modified Ashworth Scale ( MAS ) Integrated Adaptive Impedance Control Framework for Upper Extremity Training Platform 893–8