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Development of Robot-Assisted Therapy Device for Lower-Limb Rehabilitation

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Abstract

Not only patients who undergo total knee replacement or surgery need physical therapy but also some stroke survivors with a variety of levels of disability always need lower-limb recovery activities of daily living. Several studies have been reported that the use of rehabilitation robotic devices shows the better improvement outcomes in stroke patients than the conventional therapy (nurses or therapists actively help patients with exercise-based rehabilitation). This research presents the development of a one translational degrees-of-freedom robot based lower-limb rehabilitation, in which the device is considered portable for home setting and allowed effective movement of the knee joint flexion and extension. Regarding to varying required knee-joint angles with clinically guided treatment, a closed-loop Proportional (P) control algorithm has been designed and experimentally tuned to ensure best performance achieved. Moreover, the system outputs indicated that there was small oscillation moderating in the signal; therefore the frequency domain evaluation was investigate using Fast Fourier Transform (FFT), and to suitably identify the noise signals, a high-pass filter with a cut-off frequency was used. It can be shown that based on the obtained results, it was confirmed that the best performance has been observed with proportional gain of K_P = 6.5. An increase in a K_P gain provides an increase in higher frequency of the system response; however, if the K_P is too high, the robot assisted therapy device has very high unstable oscillation which could damage the robot itself. Moreover, all participants indicated that the developed robot-assisted therapy device has been able to effectively perform human-like functions in the lower-limb rehabilitation tasks, and the overall mean rating of 3.72 (out of 5) with the corresponding standard deviation of 0.75 indicates their satisfaction with the robot's performance.

***Keywords**:* Lower-limb rehabilitation; Proportional (P) control, Fast Fourier Transform (FFT); A one translational degrees-of-freedom robot

1. Introduction

World stroke organization (WSO) announces that stroke (in which frequently leads to hemi paresis or partial paralysis) is the third frequent cause of death over the age of 60 years in the world [1]. This affects the patient's ability to perform activities of daily living. Not only the stroke survivors with a variety of levels of disability but also patients who undergo total knee replacement or surgery need actively physical therapy involving rehabilitation to recover the loss of motor functions [2, 3]. The purpose of rehabilitation therapy is to allow the patients to exercise based specific movement which facilitate effective motor plasticity to the patients and minimize functional deficits. Several studies have been reported that the use of rehabilitation robotic devices shows the better improvement outcomes in stroke patients than the conventional therapy (nurses or therapists actively help patients with exercise-based rehabilitation) [4].

This paper reports that using robots to help to intensify motor rehabilitation of the lower limbs after stroke showed benefits for an electromechanical gait trainer, with significantly more patients resuming walking as compared to conventional physiotherapy. More trials, including comparative studies found that the physical-therapy-rehabilitation robots cannot be considered as a substitute for the patient-therapist relationship [10].

Robotic devices for exercise-based rehabilitation treatment are an emerging field of research challenges which is expected to grow as a solution to automate training. This research therefore focuses on the development of a one translational degrees-of-freedom robot based lower-limb rehabilitation called a Continuous Passive Motion (CMP) machine which allows more intensive repetitive motions. The device can be an alternative choice to replace the physical training effort of a therapist in improving motor function recovery in individuals with the diseases as motioned. In addition, the designed robot was considered portable for home setting and allowed effective movement of the knee joint flexion and extension. Regarding to varying required knee-joint angles with clinically guided treatment, a closed-loop proportional (P) control algorithm has been designed and experimentally tuned to ensure best performance achieved [5]. Moreover, the system indicated that there was small oscillation moderating in the signal; therefore the frequency domain evaluation was investigate using Fast Fourier Transform (FFT) [6], and to suitably identify the noise signal, a high-pass filter with a cut-off frequency was used.

2. Methods

2.1 Conceptual Design

The conceptual design of the robotics device is to allow the knee joint to permit flexion and extension in which the exercise-based movement is to duplicate the lower limb movement conducted by the patients during the rehabilitation. Traditional rehabilitation therapies are very labour intensive especially for lower-limb rehabilitation, often requiring more couple therapists together to manually assist the flexion and extension of the lower leg relative to the thigh in the training process. This specifically provides therapy for long time periods. Hence, using robotic devices allowing more intensive repetitive motions for exercise-based rehabilitation in a consistent and precise manner is a good solution to automate-training implementation. This developed robot-assisted therapy device is considered portable, compact and cheaper compared to existing commercial products which could be applied in the home-setting environment in the very near future. However, this functional mobility improvement process is strictly discussed and advised with physical therapists and doctors.

This equipment can be functioned to perform in an active mode in which it allows a physical therapy to control an automatic training program by setting a number of treatment cycles, length of motion, velocity and time of the robot-based rehabilitation exercise. During executing each task, some sets of data such as number of cycles, time, or velocity profiles were simultaneously collected using real-time continuous duration recording. The fundamental record may help a doctor in initial diagnosis of treating the patient later. In this way, the amount of treatment would be increased if patient's motor functional improvements are likely to be greater.

The system block diagram schematically shows in Figure 1 representing the development concept of the robot-assisted therapy device for lower-limb rehabilitation. It involves an incremental optical encoder used to detect an angle formed at the knee joint while taking flexion and extension exercise-based movement. The sensor outputs are connected to a signal conditioning system of buffers and line driver circuits. A DC motor was selected as an actuator of the system which can be digitally regulated by the current control circuits. User interface was developed via an external computer or using a keypad and LCD components provided. Furthermore, a microcontroller was developed to monitor and capture the sensor signals, and control the actuator based on proportional position control. However, to minimize signal loss and achieve device interface protection, the sensor outputs were dispatched to a buffer and driver device, SN74LS241, before further transmission to the micro-controller selected.

Figure 1 Schematic of the development concept of the robot-assisted therapy device for lower-limb rehabilitation

This test rig was design to perform movement along x-axis direction in which a maximum range of an angle formed at the knee joint (Θ) can be adjusted 0°-100°. The dimensions of the mechanical parts are designed and estimated based on Thai's physical characteristics of average body height. The lengths of upper and lower leg supporters were 40.3 and 42.2 centimetres respectively. However, these ranges of the device components can be appropriately adjustable for each individual patient. The platform was fabricated using aluminium which provided firm and stabilized mechanism. For safety, mechanically actuated limit switches were used between the upper and lower extremity ranges of motion to prevent from the exceeding the moving limits which cause serious damages to the structure of the device.

A compatible and stable microcontroller, Arduino Mega, was used to automatically control the device in real-time including measuring the angular velocity of the motor and generating Pulse Width Modulation (PWM) to drive motor based on Proportional (P) control. It has 54 digital input/output pins (of which 14 can be used as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header and a reset button.

A DC servo motor mounted with a set of metal gearbox (off-centred shaft) was implemented to perform high levels of torque. It is also working with an external 0.2deg-resolution incremental optical encoder which was used to directly measure knee joint angle. Therefore, this can work comfortably with high-resolution incremental feedback for speed or position closed-loop control algorithms. An ACME leadscrew made of high-quality stainless steel was selected as a linkage in the machine to convert turning motion into linear motion. This precision trapezoidal (metric) lead screws pitch and diameter are a perfect combination of high torque and speed and very low friction. Additionally, its finishing ends were designed to perfectly fit with a bearing and the DC motor, and therefore it works well and provides a higher efficiency of motion.

2.2 System mathematical model

This project applied the DC motor with high torque to primarily drive a variety of smoothly adjustable angles formed at the knee joint. Therefore, this section describes a simple mathematical relationship between the shaft angular position and DC voltage input to the motor. Figure 2 shows a schematic representation of the servo motor which is made up of the field coil in parallel with the armature.

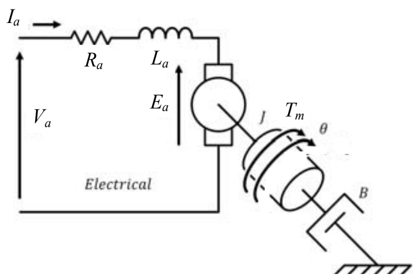

Figure 2 Schematic of the DC servo motor [7-8]

The dynamic behavioural characteristics of the motor can be derived by the following equations [7-8]. Applying Kirchhoff's voltage law gives:

$$V_a = (R_a \times I_a) + \left(L_a \times \frac{dI_a}{dt}\right) + E_a \qquad (1)$$

where,

$$E_a = K_b \times \omega \qquad (2)$$

$$T_m = K_t \times I_a \qquad (3)$$

The dynamic torque equation with momnet of inertia and coefficient can be derived as:

$$T_m = \left(J \times \frac{d^2\theta}{dt^2}\right) + \left(B \times \frac{d\theta}{dt}\right) \qquad (4)$$

Taking Laplace transform of all equations above gives:

$$V_a(s) - E_a(s) = I_a \times (R_a(s) + L_a s) \qquad (5)$$

$$E_a(s) = K_b \times s\theta(s) \qquad (6)$$

$$T_m(s) = K_t \times I_a(s) \qquad (7)$$

$$T_m = (sJ + B)s\theta(s) \qquad (8)$$

Here, the mathematical transfer function model shows in equation (9) and Figure 3 respectively.

$$\frac{\theta(s)}{V(s)} = \frac{K_t}{[(R_a(s)+L_a s)(sJ+B)s]+(K_t K_b s)} \qquad (9)$$

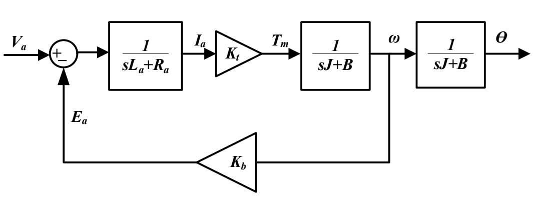

Figure 3 Block diagram representation of the DC servo motor

where,

R_a =Armature resistance in ohm
L_a =Armature inductance in Henry
i_a =Armature current in ampere
V_a =Armature voltage in volts
E_b =Back EMF in volts
K_b =Back EMF constant in volt/(rad/sec)
K_t =Torque constant in N-m/Ampere
T_m =Torque developed by the motor in N-m
$\theta(t)$ =Angular displacement of shaft in radians
J =Moment of inertia of the motor and load in $K{:}gm^2/rad$
B =Frictional constant of motor and load in N-m/(rad/sec)

2.3 Position control

A proportional integral derivative controller (PID) control [5] is a control-loop feedback controller which is normally used in industrial control systems. The control algorithm relies on measured process variables to automatically generate the system response in order to delivery optimal control of the system or even its stability without system overshoots and oscillation. Proportional (P) and integral (I) control account for present and past values of system errors respectively. Derivative (D) control accounts for possible future values of the error, based on its current rate of change. PID control continuously attempts to minimize the error over time where *e* represents a system difference between a desired set point and a measured process variable value. The control output (u) of the system can be calculated by a weighted sum [9]:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \qquad (10)$$

where K_p, K_i and K_d are respectively the coefficients for the proportional, integral, and derivative terms.

However, some simple applications may require using only one or two terms to provide the appropriate and optimized system control such as PI, PD, P or I controllers. In the control development of the robot-assisted therapy device for lower-limb rehabilitation, it was implemented by applying only proportional (P) control. This is because P controller is fairly common, since derivative action is sensitive to measurement noise, whereas the absence of an integral term may prevent the system from reaching its target value.

Proportional (P) controller was applied for control the angular position of the dc motor to activate desired angles for the knee flexion or extension. The proportional gain determines the angular displacement of response of the position feedback system and reduces steady-state error. However, too large a proportional gain could cause more oscillation and instability. During operation, the controller receives the signals from the encoder and computes the corrective action to send to the actuator.

The computation is based on the error (proportion) in which the mathematical model of the P controller is derived as follows:

$$u(t) = K_p e(t) \tag{11}$$

As the software control method uses sampling to calculate the control signals with regard to error at the sampling point, the controller integral must be discretized to obtain the expression in the following equation:

$$u(k) = K_p e(k) \tag{12}$$

where: k = sampling number k=0, 1, 2 …
$u(k)$ = output value sampling at the k times
$e(k)$ = error sampling at k times
T = sampling period

A recursive formula, Δu(t) for the incremental proportional control algorithm is applied to avoid calculating the sum of errors, so that:

$$\Delta u(k) = u(k) - u(k-1) \tag{13}$$

From equation (13), $u(k-1)$ for the proportional (P) controller can be expressed by equation (14).

$$u(k-1) = K_p \times e(k-1) \tag{14}$$

Subtracting equation (13)from equations (12/14) leads to equation (15):

$$\Delta u(k) = K_p \times [e(k) - e(k-1)] \tag{15}$$

An alternative form of equation (15) is presented in equation (16) .

$$\Delta u(k) = K_p \times \Delta e(k) \tag{16}$$

Ultimately, the overall $U(k)$ of the incremental proportional position control algorithm is as shown in equation (16), and schematic diagram of the system position control strategy based on proportional (P) control illustrates in Figure 4.

$$u(k) = u(k-1) + \Delta u(k) \tag{17}$$

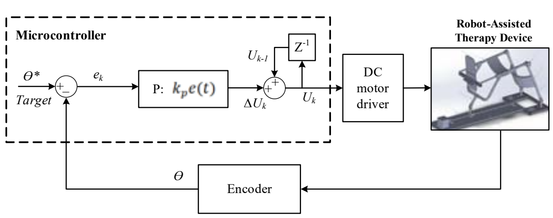

Figure 4 Schematic diagram of the system position control strategy based on Proportional (P) control

3. Evaluation of proportional position control

Proportional position controller is widely used because of their simplicity, robustness and successful practical application. Many tuning methods have been proposed for the proportional control algorithm such as Tyreus Luyben, Ziegler–Nichols, Cohen–Coon or Trial and Error methods [9]. The most effective methods always involve the development of the system process model as discussed in Section 2.2; nevertheless some important parameters required in the mathematical equation cannot be found. Therefore, manual tuning or trial and error technique is a typically good solution for this problem. The gain tuning deals with an online process and K_i and K_d values are initially set to zero before starting increasing K_p until approaching the optimized output of the system without unacceptable excessive response, oscillation and overshoot. Once, the proportional gain is higher, the faster response is obtain; however, it should be noted that the system oscillations will be introduced when the proportional control gain is too high.

This section explains the evaluation of the proportional algorithm based on position control system adopted for the robot-assisted therapy device. Proportional gain (K_p) can be experimentally tuned to ensure the reliability and stability of the robot control system in performing effective and accurate lower-Limb rehabilitation tasks under varying conditions such as clinically required knee-joint angles while performing the flexion or extension movements. The experiments have been strategically designed as detailed in the following sections.

3.1 Test procedure for lower-limb exercise-based rehabilitation

The experimental apparatus is shown in Figure 5, and involves a group of *eighteen* human participants (randomly selected) to perform a lower-limb exercise-based rehabilitation task. In this paper, a group of patients who undergo total knee replacement or surgery and some stroke survivors were not selected for testing. This is because the equipment is a prototype robot-assisted therapy device and needs to be improved continually before taking real tests. Before the tests were executed, a participant was requested to sit down in a comfortable position on opposite sides of the test rig as shown in Figure 5. The task was required to commence at the proposed home position (Θ =0°). A random required number of cycles and knee-joint angle target (Θ^*) were randomly selected by the test administrator in which a maximum range of an angle formed at the knee joint can be adjusted 0°-100°. According to the joint extension, the knee angle is moved toward to reach the required target position before moving backword (to home position) in the joint flexion phase, and then a cycle counter is activated simultaneously.

Figure 5 the robot assisted therapy task (exercise-based rehabilitation)

In the full-scale experiments, the participants were required to initially perform a preliminary set of trials before undertaking the real rehabilitation task. Some key parameters fundamentally are measured and collected in real-time for further investigation the human behavioural characteristics, namely actual knee-joint angle target (Θ) measured by the encoder, number of cycles, translational and rotational velocity. This may help a doctor in initial diagnosis of treating the patient later. Prior to starting the pilot tests each participant was asked to agree to the following rules: (i) each participant has to perform all assigned tasks to the best of their capacity; (ii) only one lower limb is allowed and twisting or bending the leg is not allowed. (iii) the participant has to make himself/herself naturally and comfortably while performing the rehabilitation therapy tasks.

3.2 Test Evaluation of lower-limb exercise-based rehabilitation

This study provides an understanding of how to optimize the proportional algorithm based on position control system adopted for the robot-assisted therapy device. The trial and error method based on experiments was carried out to establish an appropriate proportional control gain (K_p). Actual knee-joint angle (Θ) (from the sensor measuring) monitored and recorded in real-time during testing presents the output profile of the control system against time (t). An optimized gain was adopted when the system based position control approached to the minimum error (e) which is the difference between desired (Θ^*) and actual knee-joint angles measured by semi circle protractor (Θ') respectively.

$$\mathrm{e(t)} = \theta^* - \theta' \qquad (11)$$

To establish the reliability and stability of the control sysem under varying conditions, the actual knee-joint angle (Θ') outputs (sensed by semi circle protractor) were monitored and the results are as presented in Table 1.

Table 1 The test results for different values of the gain K_P ranging between 6.0-7.5 under varying required knee-joint angles from 0° to 100°

Θ(°)	Kp	Error (°)	
		Average	Std
25	6.0	4.2	0.15
	6.5	3.4	0.12
	7.0	3.5	0.10
	7.5	4.0	0.16
50	6.0	4.5	0.14
	6.5	3.0	0.13
	7.0	2.8	0.13
	7.5	3.1	0.15
75	6.0	4.4	0.11
	6.5	2.9	0.09
	7.0	2.8	0.08
	7.5	2.9	0.18
100	6.0	4.4	0.13
	6.5	3.6	0.08
	7.0	3.7	0.11
	7.5	3.5	0.17

Table 1 presents the test results for different values of the proportional gain K_P ranging between 6.0-7.5 with 0.5 resolution under varying required knee-joint angles with clinically guided treatment from 0°-100° with 25° resolution. The system performance can be identified based on the magnitude of knee-joint angle errors. After taking careful observation, it can be found that the best performance of this test is represented by the minimum errors, and was achieved at both gains (K_P) of 6.5 and 7.0, where their minimum error values and standard deviations adopted are closed. However, a careful observation of the system responses, when the proportional gain (K_p) was changed, revealed that there were some noise signals or small oscillation moderated the output profiles as shown in Figure 6. Therefore the frequency domain evaluation was investigated using Fast Fourier Transform (FFT), and to suitably identify the noise signal, a high-pass filter with a cut-off frequency was used.

Fast Fourier transform (FFT) [6] was applied to suitably identify the noise signal, and a high-pass filter with a cut-off frequency at 10Hz was used. Figures 7-8 illustrate some results of the FFT analysis over the K_P gains of 6.0 and 7.5 respectively under the condition of Θ = 100°. According to the results of FFT analysis, it can be highlighted that an increase in a K_P gain gives an increase in higher frequency of the system response; this provides an agreement with the FFT results of the K_P gains of 6.5 and 7.0 in which the density power spectrums of K_P of 6.5 are significantly lower than those of K_P of 7.0 in all cases. To sum up, it can be concluded that the optimized proportional gain of 6.5 shows the highest performance due to the low system errors with small oscillation moderated the signals. Next section evaluates how comfortable the participants felt in participating with the optimized-controlled robotic device which allows the knee joint to permit flexion and extension of the exercise-based movement using questionnaire responses.

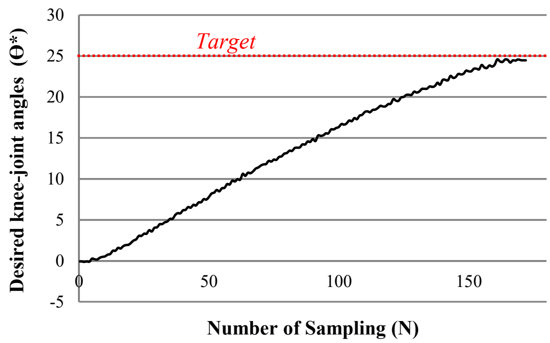

Figure 6 Actual knee-joint angle (Θ) profile monitored against number of sampling (N).

3.3 Analysis of Questionnaire Responses

Once the control system was implemented by the optimized gain K_p of 6.5, the survey responses conveying participants' preferences concerning in the therapy tasks are a statistically nonparametric type of data, which are not required to fit a normal distribution. The survey responses were based on the rating scale items and for the evaluation of the robot control system. The rating scale was specified as five points as follows: level 1 - poor or very dissatisfied; level 2 - fair or dissatisfied; level 3 - average or neither satisfied nor dissatisfied; level 4 - good or satisfied; and level 5 - very good or very satisfied.

Figure 9 shows a bar chart of the responses of the human participants showing how comfortable the participants were whilst performing the robotic rehabilitation therapy tasks. . The majority of the sample with 10 participants or 55.5% and 13 participants or 72.2% respectively were satisfied with the performance of the robot implemented by optimized proportional position control. Finally, all participants indicated that the developed robot-assisted therapy device has been able to effectively perform human-like functions in the lower-limb rehabilitation tasks, and the overall mean rating of 3.72 (out of 5) with the corresponding standard deviation of 0.75 indicates their satisfaction with the robot's performance.

4. Conclusion

This paper describes implementation of real-time position control system for the robot-assisted therapy device. It also outlines overall system design and its position control system. The developed device is considered portable for home setting and allowed effective movement of the knee joint flexion and extension. A closed-loop proportional (P) control algorithm has been designed and experimentally tuned to ensure best performance achieved under varying required knee-joint angles with clinically guided treatment.

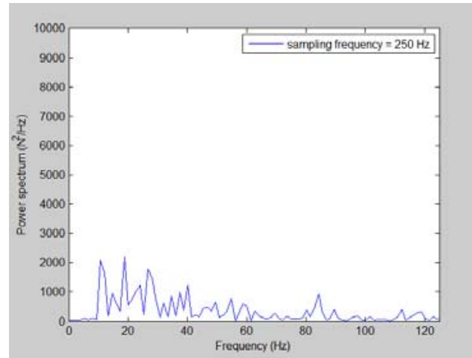

Figure 7 FFT analysis for the test over the K_P gain of 6.0

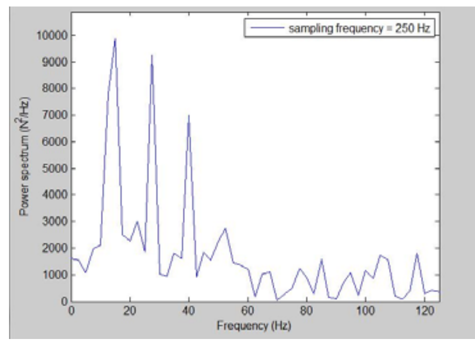

Figure 8 FFT analysis for the test over the K_P gain of 7.5

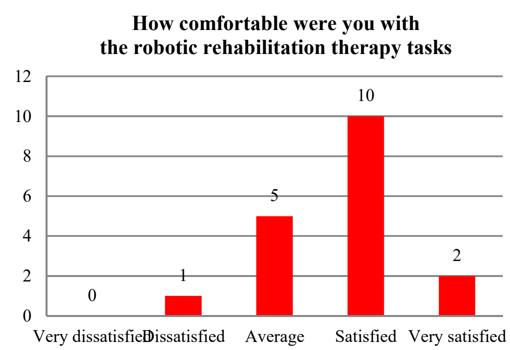

Figure 9 Responses of the human participants

Moreover, Fast Fourier Transform (FFT) was implemented to suitably identify the noise signal in the form of frequency domain evaluation. Finally, It can be shown that based on the obtained results, it was confirmed that the best performance has been observed with proportional gain of K_P = 6.5. In addition, an increase in a K_P gain leads to an increase in higher frequency of the system response; however, if the K_P is too high, the robot assisted therapy device has very high unstable oscillation which could damage the robot itself.

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