NEURAL NETWORK CONTROL OF PNEUMATIC ARTIFICIAL MUSCLE MANIPULATOR FOR KNEE REHABILITATION

Tu Diep Cong Thanh, Tran Thien Phuc
University of Technology, VNU-HCM

1. INTRODUCTION

There is an increasing trend in using robots for medical purposes. One specific area is the rehabilitation. There is some commercial exercise machines used for rehabilitation purposes. However, these machines have limited use because of their insufficient motion freedom. In addition, these types of machines are not actively controlled and therefore can not accommodate complicated exercises required during rehabilitation. An interesting alternative to electric actuators for medical purposes, particularly promising for rehabilitation, is a PAM actuator. PAM is a novel actuator which has greater proximity to human operator than the others. Besides, it inherits advantages from pneumatic actuator such as: cheap, quick respond time, simple execution (Table [1]), the most important characteristic of PAM which makes it an optimizing actuator for medical and welfare fields is the human compliance. However, the complex nonlinear dynamics of PAM make it challenging to realize the transient with respect to the changes in the physical condition of patients as well as the various treatment methods.

In order to realize satisfaction control performance of PAM manipulator, many control strategies have been proposed. Starting with linear control techniques, the strategy of PID control has been one of the most sophisticated methods and frequently used in the industry due to its simple architecture, easy tuning, cheap and excellent performance [1-2]. However, the conventional PID is difficult to determine the appropriate PID gains in case of nonlinear and unknown controlled plants. Various modified forms of this control strategy have been developed to improve its performance such as: an adaptive/self-tuning PID controller [3], self-tuning PID control structures [4], self-tuning PID controller [5], self-tuning predictive PID controller [6], and so on.. Though satisfactory performance can be obtained and the proposed controllers above provide better response, these controllers are still limited because of the limitation of capability of learning algorithm, automatically tuning control parameters and not yet handling nonlinear characteristic

To overcome these deficiencies, intelligent control techniques have emerged as highly potential methods. One of these novel intelligent theories includes well-known artificial neural network. There are many successful commercial and industrial applications using neural network based controlling techniques in recent years. A Kohonen-type neural network was used for the position control of robot end-effector within 1 cm after learning [7]. Recently, the authors have developed a feed forward neural network controller and accurate trajectory was obtained, with an error of 1[^{0}][8]. An intelligent control using a neuro-fuzzy network was proposed by Iskarous and Kawamura [9]. A hybrid network that combines fuzzy and neural network was used to model and control complex dynamic systems, such as the PAM system. An adaptive controller based on the neural network was applied to the artificial hand, which is composed of the PAM [10]. The controller adapts well with changing environment and shows good capability in managing complex nonlinearity of PAM. Here, we are going to apply this strategy into the knee rehabilitation device in the endeavor of automating medical systems and proving utilities of the proposed controller.

The organization of the paper is as follows: Section 2 is about the knee rehabilitation experimental setup. The proposed controller is mentioned in section 3 with structure and learning algorithm while the experiment results are taken up in section 4. Section 5 will conclude the paper.

2. EXPERIMENTAL SETUP

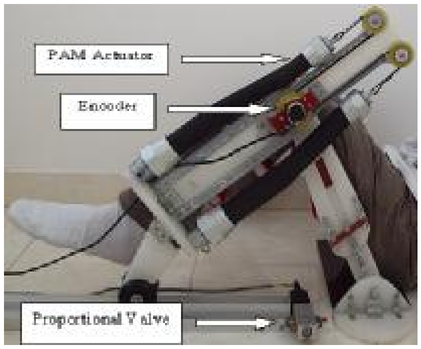
Recently, there are some commercial knee rehabilitation devices. These devices are excellent both in model and operations. However, there are still some limitations mainly originating from the very nature of the actuator – motor, which is lack of human compliance and make it potentially harmful to patients. Therefore, the knee rehabilitation device which uses PAM (FESTO, MAS-40-N-300-AA-MCFK) as actuator is constructed and the photograph of the device is shown in Fig. 1. The system includes a personal computer which used to control the proportional valve (FESTO, MPYE-5-1/8HF-710B) through D/A board (ADVANTECH, PCI 1711). The schematic diagram of the system and working principle can easily be seen in Fig.2 and Fig.3, respectively. A rotary encoder (METRONIX, H40-8-3600ZO) is used to measure the angular input from the device and fed back to the computer through a 32-bit digital counter board (ADVANTECH, PCI 1784). The lists of experimental hardware are tabulated in Table 2. The external load conditions are considered in two cases: with and without the patient. The experiments are conducted under the pressure of 0.4 [MPa] and all control software is coded in Visual Basic program language.

Table 1. Comparison of actuators

Actuator	Advantages	Disadvantages
Pneumatics	Cheap, quick response time, simple control	Position control difficult, fluid compressible, noisy
Hydraulics	High power/weight ratio, low backlash, very strong, direct drive possible	Less reliable, expensive, servo control complex, noisy
Electrics	Accurate position and velocity control, quiet, relative cheap.	Low power and torque/weight ratios, possible sparking

Table 2. Experimental hardware

No.	Name	Model name	Company
1	Proportional Valve	MPYE-5-1/8HF-710 B	Festo
2	Pneumatic Artificial Muscle	MAS-40-N-300-AA-MCFK	Festo
3	A/D board	PCI 1711	Advantech
4	Rotation Encoder	H40-8-3600ZO	Metronix
5	32-bit digital counter board	PCI 1784	Advantech



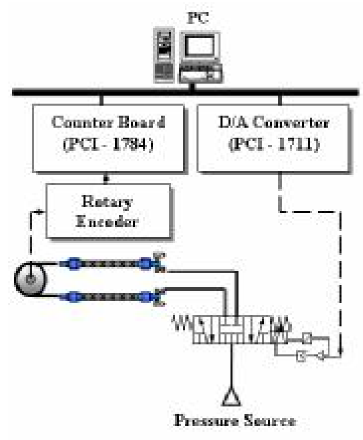


Fig.1. Photograph of the experimental apparatus **Fig.2.** Schematic diagram pf PAM manipulator

As being proved above, PAM is an optimistic actuator for medical and human welfare field and therefore rehabilitation. Nonetheless, it is rarely applied to this field due to the difficulty in position control.

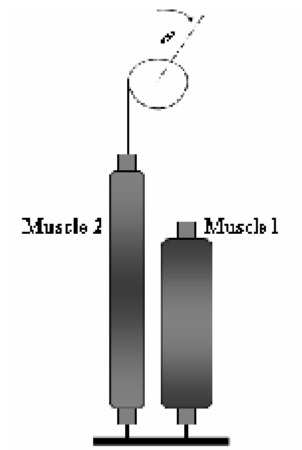


Fig.3. Working principle of PAM manipulators

3. CONTROL SYSTEM

The strategy of PID control has been one of the sophisticated methods and most frequently used in industry. This is because that the PID controller has a simple form and strong robustness in broad operating area. However, the requirement of control precision becomes higher and higher, as well as the plants become more and more complex. In order to achieve the satisfactory control performance, we have to consider the effect of the hysteresis and disturbance of the PAM manipulator. Hence, the conventional PID controller with fixed parameters may usually deteriorate the control performance. Various types of modified PID controllers have been developed such as intelligent PID control, self-tuning discrete PID controller, self-tuning predictive PID controller, and so on [11].

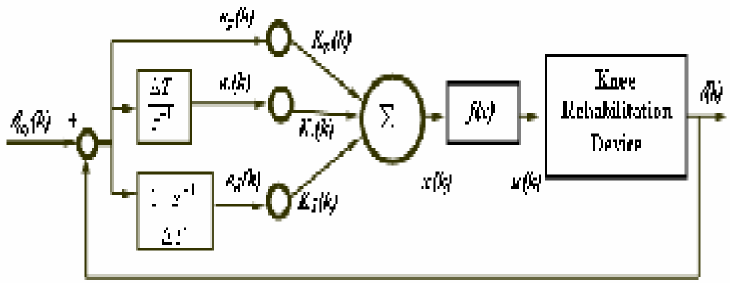


Fig. 4. Structure of proposed controller

However, if severe nonlinearity is involved in the controlled process, a nonlinear control scheme will be more useful, particularly in case of high nonlinearity of the PAM manipulator. Nowadays, neural networks have been proved to be a promising approach to solve complex nonlinear control problems. Hence, it motivates us to combine neural network with PID control. It is anticipated that the combination will take the advantage of simplicity of PID control and the neural network's powerful capability of learning, adaptability and tackling nonlinearity.

And the input signal of the sigmoid function in the output layer, x, becomes:

$$x(k) = e_p(k)\times K_p(k) + e_i(k)\times K_i(k) + e_d(k)\times K_d(k) \quad (1)$$

Where,

$$e_p(k) = q_{ref}(k) - q(k);$$

$$e_i(k) = \sum_{n=1}^{k} e_p(n)\Delta T$$

$$e_d(k) = \frac{e_p(k)(1-z^{-1})}{\Delta T} \quad (2)$$

ΔT : *sampling time,*

k : *discrete sequence*

z : *operator of* $Z-$*transform*

$q_{ref}(k)$ and $q\ (k)$ are the desired reference input and the output of system, respectively.

The control input, u, can be obtained from the following equation:

$$u(k) = f(x(k)) = \frac{1}{1+e^{-x(k)}} \quad (3)$$

To tune the gains of the proposed controller, the well-known steepest descent method using the following equation was applied:

$$K_p(k+1) = K_p(k) - h_p\frac{\partial E(k)}{\partial K_p}$$

$$K_i\ (k+1) = K_i\ (k) - h_i\frac{\partial E(k)}{\partial K_i} \quad (4)$$

$$K_d(k+1) = K_d(k) - h_d\frac{\partial E(k)}{\partial K_d}$$

Where h_p, h_i, h_d are learning rates determining convergence speed, and $E(k)$ is the error defined by the following equation:

$$E(k) = \frac{1}{2}\left(q_{ref}(k) - q\ (k)\right)^2 \tag{5}$$

From Eq. (5), using the chain rule, we get the following equations:

$$\begin{aligned}
\frac{\partial E(k)}{\partial K_p} &= \frac{\partial E(k)}{\partial q}\frac{\partial q(k)}{\partial u}\frac{\partial u(k)}{\partial x}\frac{\partial x(k)}{\partial K_p} \\
\frac{\partial E(k)}{\partial K_i} &= \frac{\partial E(k)}{\partial q}\frac{\partial q(k)}{\partial u}\frac{\partial u(k)}{\partial x}\frac{\partial x(k)}{\partial K_i} \\
\frac{\partial E(k)}{\partial K_d} &= \frac{\partial E(k)}{\partial q}\frac{\partial q(k)}{\partial u}\frac{\partial u(k)}{\partial x}\frac{\partial x(k)}{\partial K_d}
\end{aligned} \tag{6}$$

The following equations are derived by using Eqs. (1), (3) and (5):

$$\begin{aligned}
&\frac{\partial E(k)}{\partial q} = -\left(q_{ref}(k) - q(k)\right) = -e_p(k) \\
&\frac{\partial u(k)}{\partial x} = f'\left(x(k)\right); \ \frac{\partial x(k)}{\partial K_p} = e_p(k); \\
&\frac{\partial x(k)}{\partial K_i} = e_i(k); \quad \frac{\partial x(k)}{\partial K_d} = e_d(k)
\end{aligned} \tag{7}$$

And the following expression can be derived from these Eqs. (6) and (7).

$$\begin{aligned}
\frac{\partial E(k)}{\partial K_p} &= -e_p(k)\frac{\partial q(k)}{\partial u} f'\left(x(k)\right) e_p(k) \\
\frac{\partial E(k)}{\partial K_i} &= -e_p(k)\frac{\partial q(k)}{\partial u} f'\left(x(k)\right) e_i(k) \\
\frac{\partial E(k)}{\partial K_d} &= -e_p(k)\frac{\partial q(k)}{\partial u} f'\left(x(k)\right) e_d(k)
\end{aligned} \tag{8}$$

and
$$\begin{aligned}
f'(x(k)) &= \frac{e^{-x(k)}}{\left(1 + e^{-x(k)}\right)^2} \\
&= f(x(k))\left(1 - f(x(k)\right)
\end{aligned} \tag{9}$$

As done by Yamada and Yabuta, for convenience, $\frac{\partial q(k)}{\partial u} = 1$ is assumed [12]. Then the Eq. (6) is expressed as follows:

$$
\begin{aligned}
&K_p(k+1) = K_p(k) + \\
&h_p e_p(k) e_p(k)\left(1 - f(x(k))\right) f(x(k)) \\
&K_i(k+1) = K_i(k) + \\
&h_i e_p(k) e_i(k)\left(1 - f(x(k))\right) f(x(k)) \\
&K_d(k+1) = K_d(k) + \\
&h_d e_p(k) e_d(k)\left(1 - f(x(k))\right) f(x(k))
\end{aligned}
\qquad (10)
$$

The effectiveness of the proposed nonlinear PID control strategy with tuning algorithm of Kp, Ki, Kd will be demonstrated through experiments of position control with three kinds of treatment methods.

4. EXPERIMENTAL RESULTS

Experiments were carried out with respect to two conditions: without patient and with patient and three kinds of treatment methods (references are sinusoidal, triangular and trapezoidal). The comparisons of control performance between the conventional PID and the proposed controller were also performed.

Figure 5 shows the experimental results of conventional PID controller in two cases of the patient and with respect to three kinds of treatment methods.

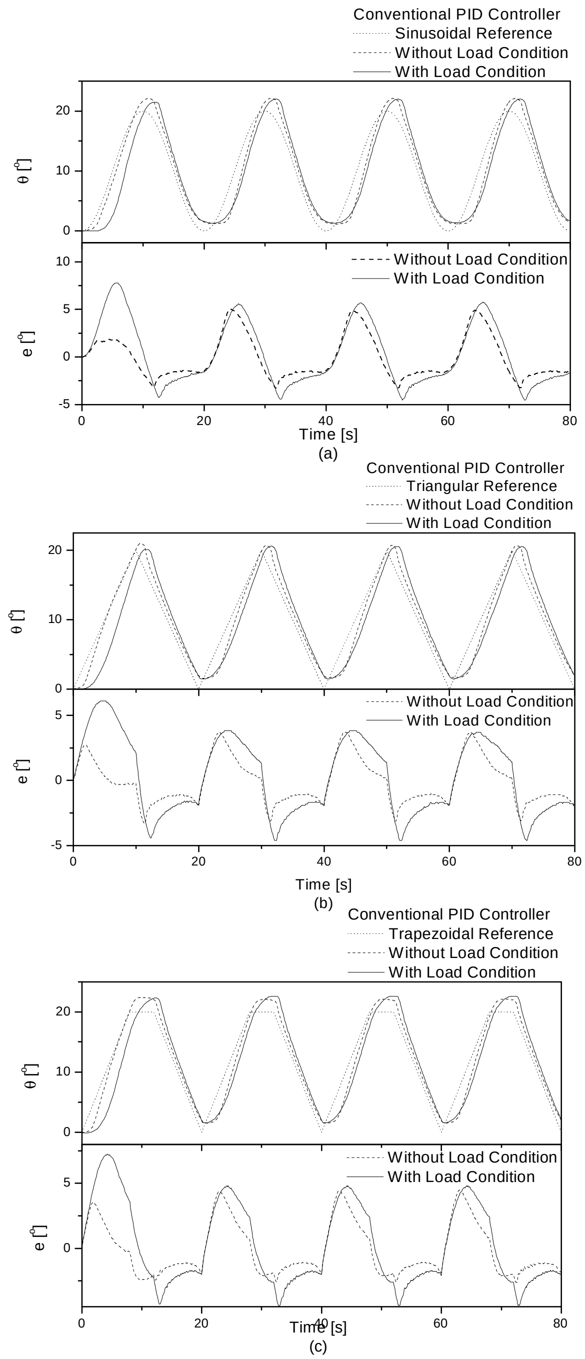


Fig.5. Experimental results of conventional PID controller in both conditions
(a): Sinusoidal Reference; (b): Triangular Reference; (c): Trapezoidal Reference

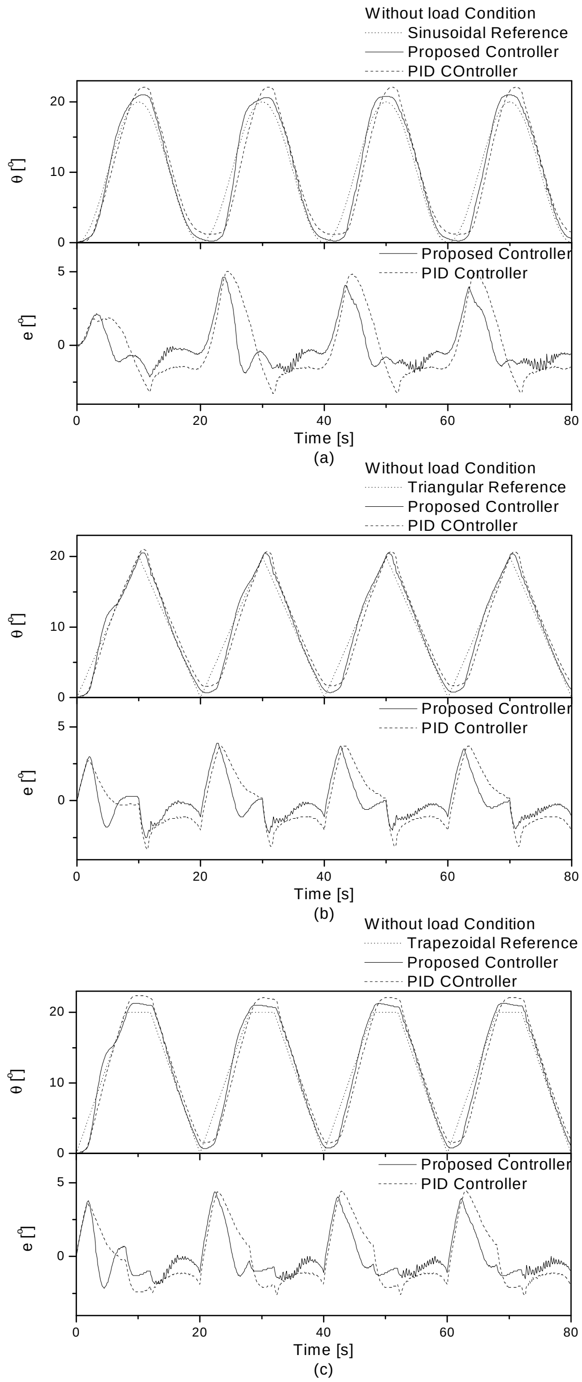


Fig.6. Comparison between conventional PID controller and Proposed Controller in case of without the patient

(a): Sinusoidal Reference; (b): Triangular Reference; (c): Trapezoidal Reference

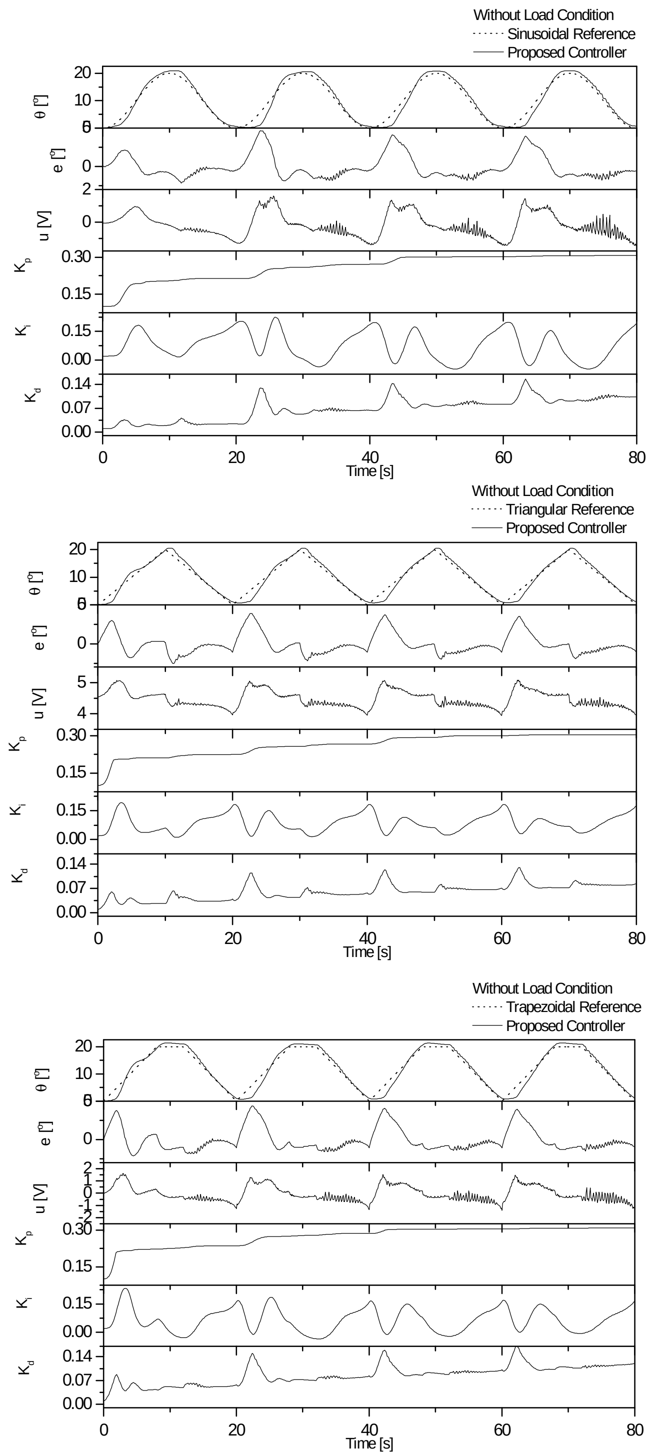


Fig.7. Experimental result of the proposed controller in case of without the patient
(a): Sinusoidal Reference; (b): Triangular Reference; (c): Trapezoidal Reference

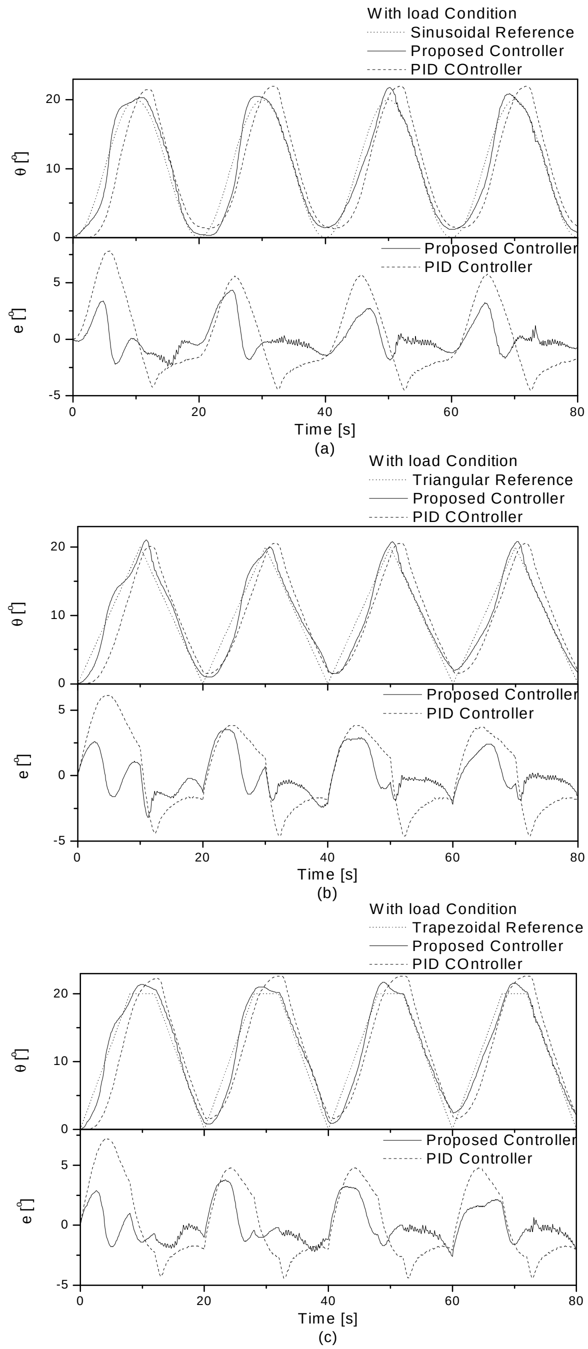


Fig.8. Comparison between conventional PID controller and Proposed Controller in case of with the patient
(a): Sinusoidal Reference; (b): Triangular Reference; (c): Trapezoidal Reference

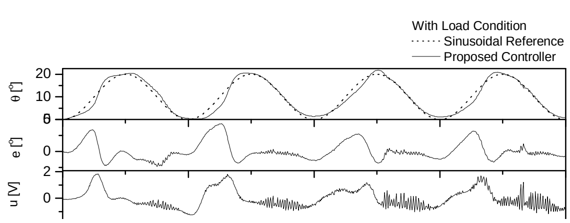


Fig.9. Experimental result of the proposed controller in case of with the patient
(a): Sinusoidal Reference; (b): Triangular Reference; (c): Trapezoidal Reference

The parameters of PID controller are chosen as follows: Kp = 0.1, Ki = 0.02, Kd = 0.01. These gains are obtained by trial-and-error through experiments. From Fig. 5, there was overshoot in the response of the system in case of without the patient and had a long settling time, more delay, large tracking error with respect to the condition with the patient addition. Therefore, it is requested that the control parameters should be adjusted according to the change of the external condition. Thus, the experiments were carried out to verify the effectiveness of the proposed controller. Fig.6 shows the comparison between the conventional PID controller and proposed controller in case of without the load condition and with respect to three kinds of the treatment methods and the updating of each control parameter (Kp, Ki, Kd) was shown in Fig 7.

In the experiment of the proposed controller, the initial values of Kp, Ki and Kd are set to be the same of the control parameters of PID controller.

The purpose of this experiment is to show the effectiveness of the adaptability of control parameter to get better performance. The learning rates in Eq. (10) are set to be $h_p = 0.01$, $h_i = 0.01$ and $h_d = 0.01$, which are also obtained by trial-and-error through experiments. From Fig. 6, it is understood that the system response of the proposed controller is good agreement with that of reference input and it is demonstrated that the proposed control algorithm is effective in case of without the patient addition. From Fig. 7, the change of each control parameter was shown, where these control parameter turn automatically in order to get high response and tracking performance.

Next, experiments were carried out to investigate the control performance with the patient addition. In Fig. 8, comparison between the conventional PID controller and the proposed controller was performed. The initial values of Kp, Ki and Kd , used in the experiment, are the same as those of no patient addition. The gain tuning of the proposed controller is shown in Fig. 9. The effectiveness of the proposed controller with respect to the patient addition is verified by the above experiments.

From the experiments, it was verified that the proposed control algorithm is a good strategy not only with Knee Rehabilitation Device but also many other medical devices using PAM manipulator.

5. CONCLUSION

It is shown that the proposed control method had a good performance for the Knee Rehabilitation Device using PAM actuator. It can be seen from experimental results that the controller had an adaptive control capability and the control parameters were optimized via the steepest descent algorithm. The controller designed by this method does not need any training procedure in advance, but it uses only the input and output of the plant for the adaptation of control parameter and can tune the parameters iteratively.

From the experiments of the position control of the PAM manipulator in this study, it was verified that the proposed control algorithm is one of effective method to develop a practically available Knee Rehabilitation Device by using PAM manipulator.

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