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Real-Time, Simultaneous and Proportional Myoelectric Control for Robotic Rehabilitation Therapy of Stroke Survivors

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Abstract

Objective : Conventional therapy approaches for stroke survivors have required considerable demands on therapist's effort and patient's expense. Thus, new robotics rehabilitation therapy technologies have been proposed but they have suffered from less than optimal control algorithms. This article presents a novel technical healthcare solution for the real-time, simultaneous and propositional myoelectric control for stroke survivors' upper limb robotic rehabilitation therapy.

Methods : To implement an appropriate computational algorithm for controlling a portable rehabilitative robot, a linear regression model was employed, and a simple game experiment was conducted to identify its potential of clinical utilization.

Results : The results suggest that the proposed device and computational algorithm can be used for stroke robot rehabilitation.

Conclusion : Moreover, we believe that these techniques will be used as a prominent tool in making a device or finding new therapy approaches in robot-assisted rehabilitation for stroke survivors.

Key words : Proportional control, Regression model, Robot rehabilitation, sEMG

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Ⅰ. Introduction

Robot-assisted therapeutic exercise (RATE) shows great promise as an intervention to minimize weakness caused by stroke and/or other central nervous system lesions. Conventional assisted therapeutic exercise requires the physical presence of an occupational therapist, physical therapist, or a technician working under their supervision. As a result of this requirement, participation in high-repetition exercises for an extended period of time creates a significant burden for therapists (Brochard, Robertson, Médée, & Remy-Neris, 2010) and relatively high cost for patients. RATE can contribute to lower cost and increased quality of rehabilitation services. The most common mode of providing RATE for stroke survivors has been through the use of electrically powered exoskeletal robots that have the potential to assist and/or resist the specific movements chosen as the focus of therapeutic exercise (Genna et al., 2014). Therefore, the need for optimal control methods is increasing.

Over the last few decades, control based on externally captured electromyographic signals (sEMG) has been suggested. However, control algorithms presented to date have many limitations. These include limited ability to simulate the smooth, multiple degree of freedom movements of non-disabled individuals, and an inability to employ more than one sEMG signal at a time (Geng, Tao, Chen, & Li, 2011; Young, Smith, Rouse, & Hargrove, 2013). These limitations may be overcome by using regression techniques (Jiang, Dosen, Muller, & Farina, 2012).

Regression techniques applied to sEMG signals have been used in control algorithms for prosthetic devices (Hahne et al., 2014). However, there is difference in sEMG pattern between amputees and stroke survivors (such as abnormal muscle activation (Dewald, Pope, Given, Buchanan, & Rymer, 1995) and excessive antagonist coactivation (Gowland, deBruin, Basmajian, Plews, & Burcea, 1992) which do not exist in amputees). Thus, optimal algorithms for control of RATE devices for stroke survivors must be different that those have been developed for prosthetic control.

The purpose of this study was to demonstrate the feasibility of a real-time, simultaneous and propositional myoelectric control technique for a prototype RATE device that will be a part of an integrated, game-based system of upper extremity rehabilitation for stroke survivors to use at their homes. We report here on 1) the development of an inexpensive sEMG hardware module, 2) a computationally efficient real time sEMG capture, processing, and control technique for a RATE and a sample gaming system, and 3) the results of a preliminary pilot study with the system using non-disabled subjects who performed normally and with simulated weakness.

Ⅱ. Method

1. Participants and Experimental Setup

Our subjects were 3 non-disabled volunteers (2 females and 1 male) between 25~35 years of age. Subjects were seated comfortably with their

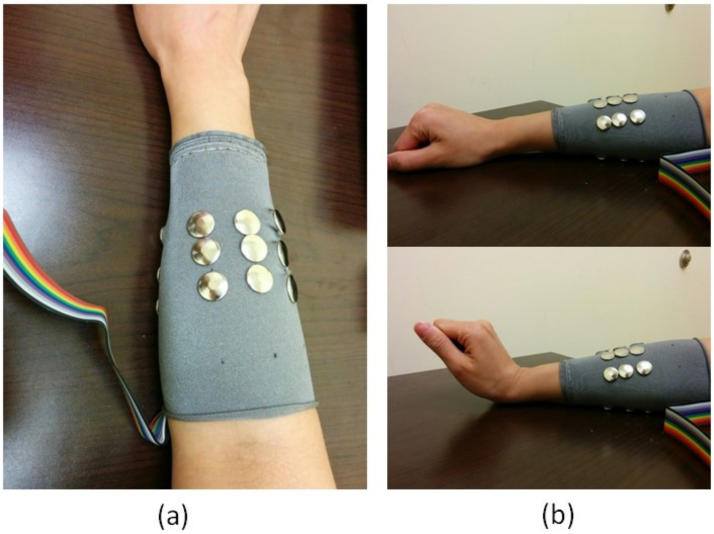

Figure 1. The home-made electrode
(a) Electrode array position on the forearm, (b) Natural and extension condition of right hand for experiment.

right hand placed on a table. sEMG electrode array was placed on middle of the dorsal aspect of their forearm (Figure 1). An electro-goniometer (Biometrics LTD, Newport, UK) was also attached to the right wrist to capture wrist angle when the accuracy of control algorithms was estimated.

2. Development of Cost-effective sEMG Sensing Module

To build the cost-effective sEMG module, we employed a commercially available control board (TI C28027 LaunchPad, Austin, Texas) and amplifier board (OLIMEX Shield EMG, (Plovdiv, Bulgaria). The total cost of the two boards was less than $170 (US). The control board has a power-isolated optical interface for communication with the host PC and for isolation of power to insure patient safety. The sensing module was capable of capturing six channels of sEMG signals at 3000 Hz(Figure 2).

3. Experimental Procedures

First, subjects were instructed to move their wrist from the clinically neutral position to maximal extension several times while observing their wrist angle displayed on a PC monitor by the home-made graphic user interface (GUI) software using MATLAB.

Before starting the game, the subjects changed a direction of their hand corresponding to displayed angle on PC monitor for the training. Then, subjects were taught how to play a game designed for this study. The game displayed balloons that appeared randomly on a screen in a location analgous to a wrist angle ranging from 0 degrees of natural position to 90 degrees of extension.

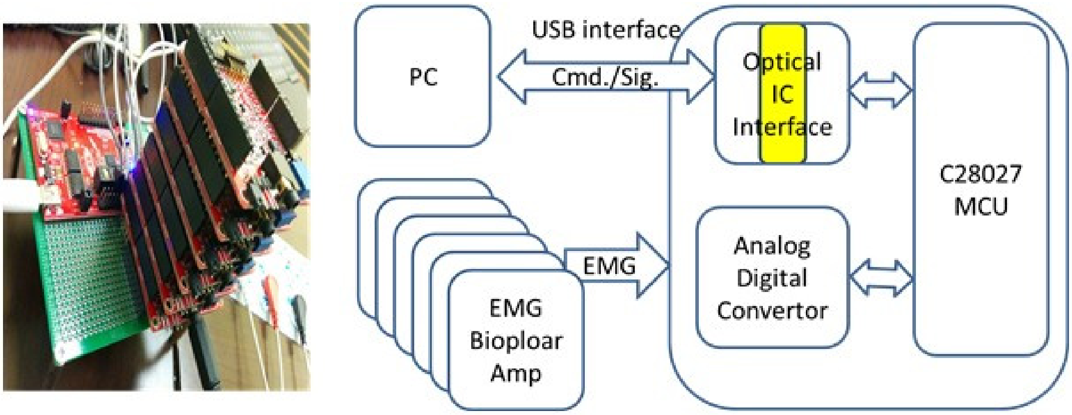

Figure 2. The EMG sensing module and structure diagram.

The goal of the game was for subjects to pop a balloon in 10 seconds or less by holding a given degree of wrist position for 1 second. If they were successful, the appeared object would pop with pleasant effect sound. If they were not successful, the object would vanish with quite gloomy sound and a new balloon would appear. The duration of each game was 1 minute. After the game, the results displayed, and the subject was able to repeat the game with the goal of improving their score (Figure 3).

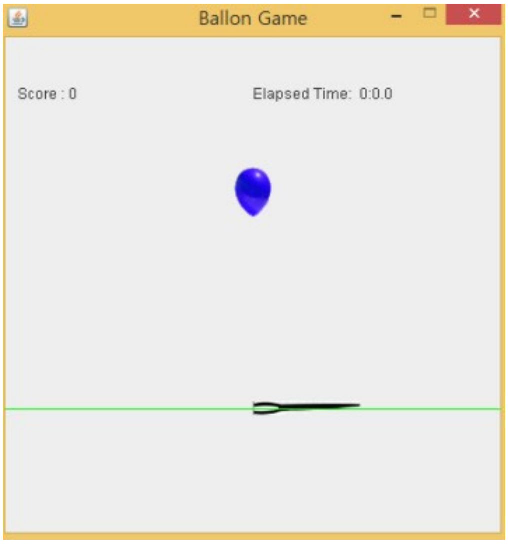

Figure 3. Scene of balloon game for rehabilitation

4. Data Analysis

1) Data Acquisition

During the experiment, the bipolar sEMG signals were obtained with 3000 Hz sampling rate using stainless dry electrode. The positive-, negative- and reference electrodes were placed on the middle of forearm (to measure the sEMG signals from muscles of wrist extensors) respectively. The measured sEMG signals were transferred from the sensing module to personal computer (PC) every 100ms (=300 samples), and updated the feature information to operate the game software and robot manipulation.

2) Preprocessing

The transferred data to PC were filtered using digital notching filter based on MATLAB function (iircomb) with default setting values to remove 60Hz noise and its harmonic components

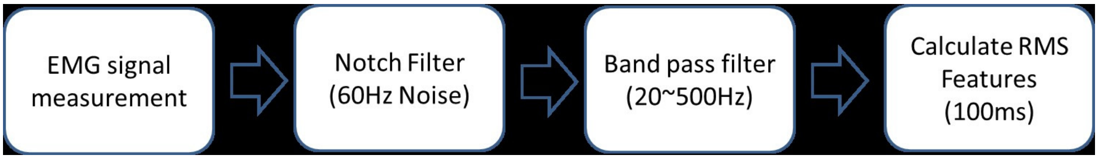

Figure 4. Procedure of preprocessing

that were interfered by electric power-line. Also, to extract the primary sEMG signal, between 20Hz and 500Hz, the IIR bandpass filter using MATLAB function (iirlpnorm) was utilized (Figure 4).

3) Feature Extraction and Multiple Regression Model

In order to implement the computationally efficient real-time control technique, logarithm of sEMG signal variance (Log-var) $f(n) = \log(\sum RMS(X))$, was employed to obtain a reasonable regression performance for stroke patients because the Log-var provided the best performance when linear regression model was applied.

Let $\boldsymbol{X} = R^{C\times T}$ denote the feature matrix, whose columns contain C dimensional feature vectors for the T-th time instance, and Y^T is a vector that corresponds to actual wrist angles for each time instance. A linear regression model has the form:

$$\hat{Y} = W^T X + w_O, \quad (1)$$

where $\hat{Y}$ is the approximation of Y, and W^T is a vector of regression coefficients. For simplicity, the bias w_O is included in W by extending X with the constant 1. To fit the linear model, the most widely used approach is to minimize the sum of squared errors of the linear regression model:

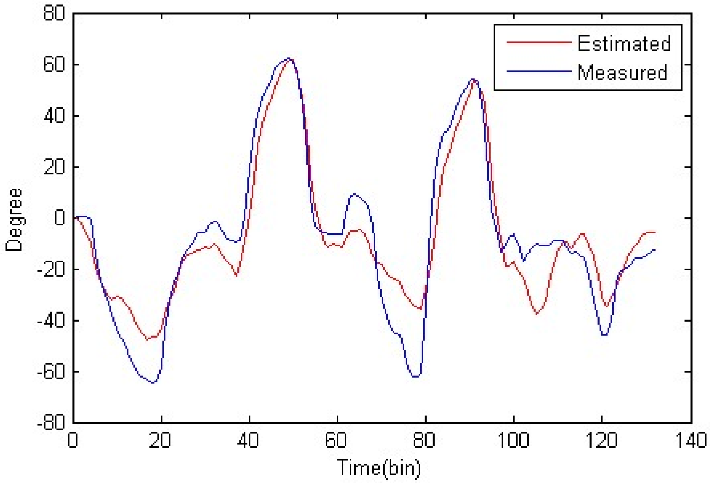

Figure 7. The estimated degree based on measured sEMG signals to compare the real degree of movement.

$$\widehat{W} = \arg_{\ominus}\sum (Y - W^T X)(Y - W^T X)^T, (2)$$

Once we obtain the coefficient matrix $\widehat{W}$ using training data set, we can compute a wrist angle at each time instance in real-time (100 ms interval):

$$\widehat{Y}(t) = \widehat{W}^T x(T), (3)$$

where, $\widehat{Y}(t)$ is estimated degree information that can be used to control an exoskeletal robot arm. Although this study employed a single degree of freedom (DOF) experiment, it can be utilized to multi-DOF experiment for the stroke rehabilitation therapy. Figure 5 shows the entire data analysis procedure.

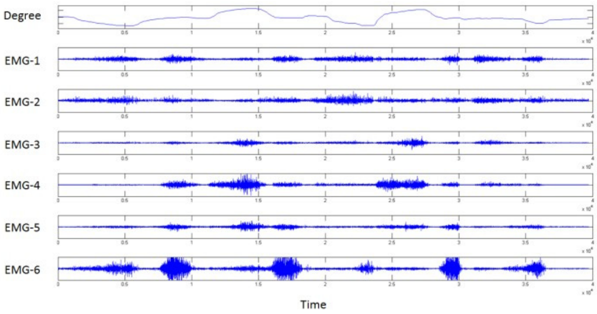

Figure 6. The measured sEMG signals and degree information of hand movement.

Ⅲ. Result

Figure 6 displays the wrist angle and sEMG signals during free movement to estimate the performance of the linear regression model for controlling exoskeletal robot arm. Figure 7 shows the estimated degree information that was used to control the rehabilitation game application. The mean of the degree error is 13.15°, and the standard deviation of the degree is 10.69°.

In order to identify the performance of stroke patients who have weak EMG power, we asked the subjects to do two tasks during training: (1) full degree of wrist movement, and (2) half degree of wrist movement. The full degree of wrist movement used 0 to maximum degree of wrist for the training. On the other hand, the half de-

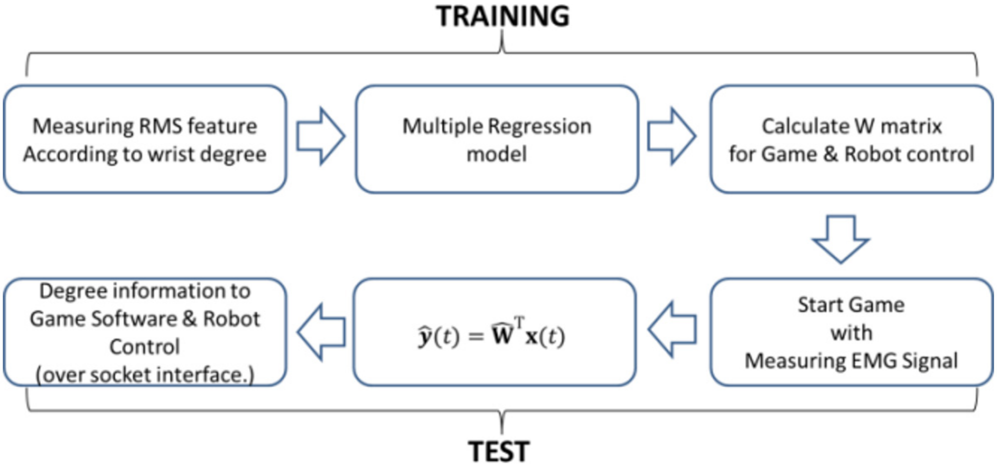

Figure 5. The procedure diagram for data analysis

Table 1. The score of rehabilitation game

	Subject 1			Subject 2			Subject 3		
Trial	1	2	3	1	2	3	1	2	3
Full	16	15	17	15	14	16	17	15	16
Half	14	12	11	12	13	15	12	12	15

gree of wrist movement used only 0 to 40 degree for the training. Table 1 shows the experiment results. According to the Table 1, 'half' task shows significantly lower scores than 'full' task based on a t-test (p-value = 0.002).

Ⅳ. Discussion

In this study, the simultaneous and proportional control algorithm for rehabilitation is demonstrated for robot-assisted rehabilitation therapy for stroke survivors. In the past, EMG electrode mapping of a single muscle was used to control a single DOF. For instance, EMG activation of biceps and triceps might be utilized to control elbow flexion and extension (Rosen, Brand, Fuchs, & Arcan, 2001; Stein, Narendran, McBean, Krebs, & Hughes, 2007). However, controlling multi-DOFs through the single muscle sEMG signals is not feasible. To surmount this limitation, multi-channel EMG has been applied and has been successfully performed. In addition, to reduce computational load for mobile (portable) exoskeleton rehabilitation robot, linear regression model is a prominent tool (Hahne et al., 2014).

1. Practicality for Stroke Rehabilitation

The developed system is cost-effective to build, and convenient for use (including training and practical rehabilitation-test). In our experiment, we spent less than 3 minutes applying the electrode array and instructing subjects to play the game. Results during game play with simulated weakness demonstrated possibility of using weak sEMG signals although it has lower scores than normal condition. In addition, the algorithm may have lower computational load than other classification algorithm/non-linear regression model. However, for the accurate comparison in computational load and accuracy, further study is necessary.

2. Simultaneous and Propositional control for rehabilitation

A general principle of motor skills training is that the training should simulate actual tasks as much as possible. Typical movements are controlled by a complex stream of multiple action potentials, not a simple burst of activity that exceeds some arbitrary level. Control based on a sEMG trigger includes the implicit assumption that the goal of training is to generate a given magnitude of sEMG for a minimal period of time. Proportional control allows robotic systems to respond to increases and/or decreases in multiple muscle activation(s) over periods of time (typical of normal movement). Proportional control of rehab robots simulates real-world activities better than trigger controls.

3. Expected clinical potential

Control based on triggering via the sEMG signal is useful in training patients to increase peak muscle activation. Real-time, proportional myoelectric control for robotic rehabilitation devices will also be useful to increase peak muscle activation, and will allow for the development of clinical protocols to assist with control of initiation, cessation, and modulation of many muscles simultaneously. This, in turn, will allow therapists to employ robotic devices with a wide variety of movement disorders.

4. Further study

A portable upper arm rehabilitation robot will be developed (Figure 8), and a related clinical pilot study will be conducted to find a specific feature of stroke survivors in order to develop an optimal computational & intelligence algorithm for rehabilitation therapy.

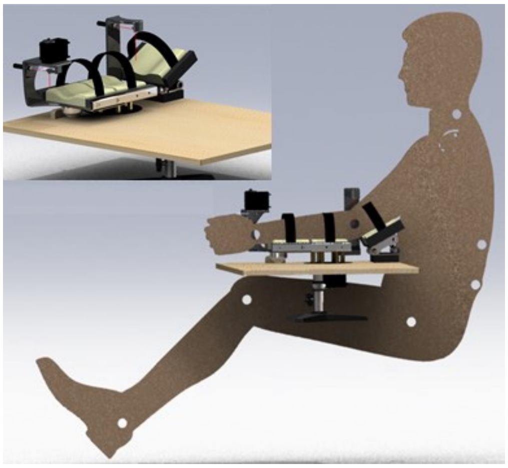

Figure 8. Design of portable rehabilitation system.

V. Conclusion

In this study, the real-time, simultaneous and proportional myoelectric control was demonstrated to explore its potential for robotic rehabilitation therapy for stroke survivors. Although this was a modest pilot study, it demonstrated feasibility of simultaneous, proportional control based on sEMG for RATE therapy. Especially, proposed proportional upper arm control with cost-effective robot system would be useful therapy model for remote self-training in the near future for enhancing the life quality of stroke survivors. Thereby, this approach may have a potential to enhance the quality of life for stroke survivors.

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국문초록

뇌졸중 환자의 로봇 재활 치료를 위한 실시간, 동시 및 비례형 근전도 제어

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목적 : 본 연구에서는 뇌졸중 환자의 치료 효과를 증진시키기 위한 방법으로, 로봇 기반에 연속적이며, 실시간으로 환자의 의지에 따른 표면 근전도 신호에 비례한 제어가 가능한 최적 알고리즘을 구현 및 재활로봇과 PC소프트웨어에 적용기술을 개발하였다.

연구방법 : 뇌졸중 환자의 치료를 위한 재활로봇 제어 알고리즘 개발을 위해서 본 연구에서는 선형 재귀모델을 이용하였다. 또한, 이를 PC 소프트웨어에 적용하여 실제 근전도 신호에 비례하여 게임을 진행할 수 있도록 환경을 구축하였으며, 이를 활용하여 모의 훈련을 진행하였다.

결과 : 모의실험 결과 실제 움직인 위치와 선형 재귀모델로부터 추정된 위치의 결과가 상당히 유사하게 나타나는 것을 확인할 수 있었다. 또한 3명의 피험자를 대상으로 실험 한 결과, 3번의 각기 다른 시도에 따라 훈련이 진행되면서 그 결과가 좋아짐을 확인할 수 있었다.

결론 : 본 연구에서는 재활로봇에 적용 가능한 실시간으로 동작하는 근전도에 비례한 움직임을 유도해 낼 수 있는 선형 재귀 모델을 개발하였다. 또한, 이를 활용한 소프트웨어도 함께 구축하여 그 활용 가능성이 높음을 확인하였다. 향후 실제 재활로봇에 적용하여 자가-재활 및 원격재활 로봇에 기본 알고리즘으로 널리 활용될 수 있을 것이라 기대된다.

주제어 : 로봇재활, 비례형 제어, 표면 근전도, 회귀모델