35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Effect of Vibrotactile Feedback on an EMG-Based Proportional Cursor Control System

Shunchong Li, Xingyu Chen, Dingguo Zhang, Xinjun Sheng and Xiangyang Zhu

Abstract— **Surface electromyography (sEMG) has been introduced into the bio-mechatronics systems, however, most of them are lack of the sensory feedback. In this paper, the effect of vibrotactile feedback for a myoelectric cursor control system is investigated quantitatively. Simultaneous and proportional control signals are extracted from EMG using a muscle synergy model. Different types of feedback including vibrotactile feedback and visual feedback are added, assessed and compared with each other. The results show that vibrotactile feedback is capable of improving the performance of EMG-based human machine interface.**

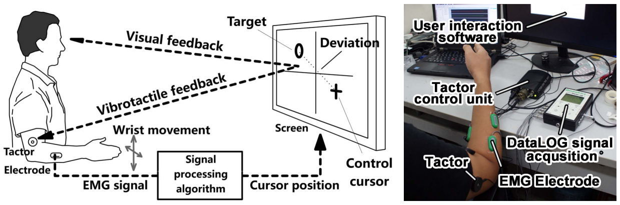
I. INTRODUCTION

Surface electromyography signal collected from skin contains important information about movement intents, hence it has been applied as a control source for many human machine interactive devices for decades.

However, most of these devices are based on pattern classification framework. The limitation is that only one pattern can be selected at each point and the control signal can not be continuous, which means it just allows a sequential and on-off control. Recently, EMG-based simultaneous and proportional control has been getting attention and addressed using different approaches [1]–[4].

Meanwhile, most myoelectric devices are still open-loop without any sensory feedback transferred to users. In prostheses field, lack of closed-loop control is a common reason why amputees prefer body-powered prostheses which convey some useful force feedback [5]. Amputees also complain about the heavy dependence on visual feedback required to operate myoelectric prostheses. It is pointed out that the focus of future research should be on the implementation of more kinds of sensory feedback [6].

Vibrotactile stimulation has become one of the most common and popular type of feedback because of its unobtrusive nature, easy applicability and comfort for the user. Several researchers have investigated vibrotactile feedback representing grasping force for myoelectric prosthetic applications [5] [7]. Moreover, Sienko *et al.* utilized multidirectional vibrotactile feedback to improve postural stability of patients with vestibular deficits [8]. Promising results have been shown from these literatures, and it has been demonstrated that vibration can offer effective sensory information. However the effect of vibrotactile feedback should be investigated more quantitatively and objectively.



(a) (b)

Fig. 1. (a) A schematic diagram of experiment setup (b) Equipments used in experiments

TABLE I

FOUR DIFFERENT EXPERIMENT MODES

Mode	I	II	III	IV
Visual Feedback	×	√	×	√
Vibrotactile Feedback	×	×	√	√

This paper presents an EMG-based cursor control experiment. Cursor control signal is extracted from sEMG signal collected from forearm in a simultaneous and proportional way. The subjects are asked to capture the target as soon as possible. Four different modes including no feedback, vibrotactile feedback, visual feedback and visual plus vibrotactile feedback are attempted, and the performance indices of these modes are compared with each other.

II. METHOD

A total of five healthy male subjects took part in this study. All participants were fully informed of the details of the experimental procedure and agreed through an informed consent.

A schematic diagram of experiment setup and equipments used in experiments are shown in Fig. 1. The user interaction software was self-developed, which was programmed in Visual C++. A random generated target was displayed on a screen, instructing subjects to move their wrists. Surface EMG signals were collected from the forearm and used to estimate the wrist movement, which was mapped to the position of a cursor on the screen. Subjects were asked to control the cursor to capture the target (see TABLE I).

A. EMG Collection

EMG signals were recorded using a DataLOG (Biometrics Ltd., UK). Five electrodes were placed on forearm muscles

*This work is supported by the National Basic Research Program of China (973 Program No.2011CB013305), the National Natural Science Foundation of China (No.51075265), and the Science and Technology Commission of Shanghai Municipality (No.11JC1406000).

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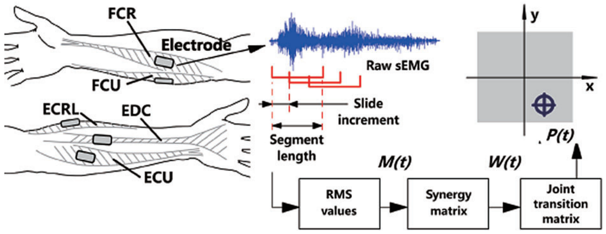


Fig. 2. A block diagram of EMG data processing algorithm

by medical adhesive tape (See Fig. 2). The sampling frequency was set at 1kHz.

B. EMG Processing

Fig. 2 shows a block diagram of sEMG processing algorithm. The sampled sEMG were pre-processed using the root mean square (RMS) with a 300 ms analysis window and 100 ms slide increment. These RMS values representing the **muscular activities** of tth segment were denoted as a column vector

$$M(t) = [m_1(t), m_2(t), m_3(t), m_4(t), m_5(t)]^T$$

Four directions of wrist movements (flexion,extension,radial deviation, and ulnar deviation) were represented as

$$W(t) = [w_1(t), w_2(t), w_3(t), w_4(t)]^T$$

$W(t)$ became zero vector when the wrist relaxed in the neutral position.

Jiang *et al.* proposed a generative model of sEMG, which is based on the neuroscientific knowledge that synergistic muscles share spinal neural drives, which correspond to the intended activations of different DOFs and are embedded within sEMG [9]. According to this model, extracting $W(t)$ from $M(t)$ becomes an linear BSS problem.

$$W(t) = \mathbf{S} \cdot M(t) \tag{1}$$

where $\mathbf{S}$ is called **synergy matrix**. It embodies human movement control strategies called **muscle synergy** from the viewpoint of neuroscience [4]. Each element s_{ij} maps from jth muscular activity to wrist movement magnitude in direction i.

A **non-negative matrix factorization** (NMF) algorithm was be adopted to construct the synergy matrix $\mathbf{S}$. NMF algorithm is able to extract the neural control information from sEMG and provide simultaneous and proportional control signals [2]. In NMF the element of the matrix $\mathbf{S}$ has a negative sign.

In order to find an approximate optimal $\mathbf{S}$, we defined $\mathbf{M} = [M(1), ..., M(T)]$ and $\mathbf{W} = [W(1), ..., W(T)]$, where T is the largest number of training data. Then a cost function was constructed

$$E = \| \mathbf{W} - \mathbf{S} \cdot \mathbf{M} \|^2 \ (s_{ij} \geq 0) \tag{2}$$

The optimization problem is to minimize (2). Detailed update rules to solve this problem was presented in [10].

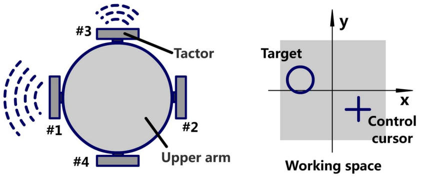


Fig. 3. Configuration of four tactors. In the situation as the right picture showed, if the target circle was located in the upper left of the control cursor, tactor 1 and tactor 3 would vibrate to instruct subject to move cursor getting closer to the target. The intensity of vibration was proportional to the deviation.

The position of the cursor was denoted as a coordinate vector $P(t) = [p_x(t), p_y(t)]^T$ in Cartesian space. It could be represented as

$$P(t) = \mathbf{J} \cdot W(t) \tag{3}$$

where transition matrix $\mathbf{J}$ is

$$\mathbf{J} = \begin{bmatrix} C & -C & 0 & 0 \\ 0 & 0 & C & -C \end{bmatrix} \tag{4}$$

in which C is a scale factor.

C. Vibrotactile Feedback

The vibrotactile feedback adopted C2 tactors. Four tactors, representing four direction deviation respectively (see Fig. 3), were mounted to the upper arms.

The frequency of the tactor was proportional to the deviation between the control cursor and the target ranging from 100 - 300 Hz. The inherent frequency of the tactor is about 300 Hz. Hence the larger the deviation was, the more intense vibratory sensation subject would feel. Vibration was expected to instruct subject to move the wrist getting closer to the target.

D. Experimental Protocol

The experiment consisted of two phases: **training** and **testing**.

During the training phase, subjects were asked to move their wrist towards limit positions of four directions in sequence according to the screen cues. The RMS values of sEMG were stored in matrix $\mathbf{M}$. Each direction need to hold 15 seconds to collect sufficient training data. These data were normalized ranging from 0 to 1 for each channel. Then the iteration process began to find an optimal synergy matrix $\mathbf{S}$.

After training, subjects could move their wrists optionally for 5–10 minutes to be familiar with user interaction software and operation.

For the testing phase, subjects were asked to position the control cross cursor into a random generated target circle in four different mode mentioned above, and each mode consisted of 25 trials. Subjects had at most 15 seconds to capture the target in one trial, if timeout happened this trial would be judged as failure.

TABLE II

NUMBER OF FAILED TRIALS OF ALL THE SUBJECTS IN FOUR DIFFERENT MODES

	S1	S2	S3	S4	S5
None	11	13	7	9	18
Visual	0	0	0	2	0
Vibrotactile	6	4	1	12	10
Vis.+Vib.	0	0	0	0	0

E. *Performance Analysis*

The performance of the subjects was evaluated using three indices as follow:

- Number of failed trials n in each experimental mode.
- Elapsed time t in a trial to capture target circle. If a trial is failed, t will no be recorded.
- Displacement ratio between cursor displacement and shortest route (straight line from start point to target point), denoted as d. Since target is generated in random, the distance between two points is varying, hence a proportion index is more reasonable.

III. RESULT

A. *Results of EMG Processing*

Fig. 4 shows a representative example of the target capture results from subject S3 during testing phase. With visual feedback, the elapsed time is the shortest and the trajectory oscillation is the smallest, which means the subjects can capture target fast and efficiently. In contrast, without any feedback the time consumption is the longest, and the trajectory changes drastically. The performance of the mode with vibrotactile feedback is in between. More details about elapsed time and distance ratio can been seen in Part C of this session.

B. *Number of Failed Trials*

TABLE II shows the number of failed trials of all the participants in different experiment modes. It can be seen that the subjects were able to accomplish the task perfectly with visual feedback. Paired t-tests are used to test statistical significance, and the results show obvious increase in success rate with the addition of visual feedback ($p = 0.003$). Vibrotactile feedback can also increase success rate ($p = 0.027$), but the effects is not so well as visual feedback ($p = 0.011$). However, it reveals no significant difference between MODE2 (only visual feedback) and MODE4 (visual plus vibrotactile feedback)($p = 0.374$).

C. *Elapsed Time and Displacement Ratio*

Comprehensive plots of all the subjects showing the means and standard deviation of elapsed time t and displacement ratio d for each experiment mode are shown in Fig. 5.

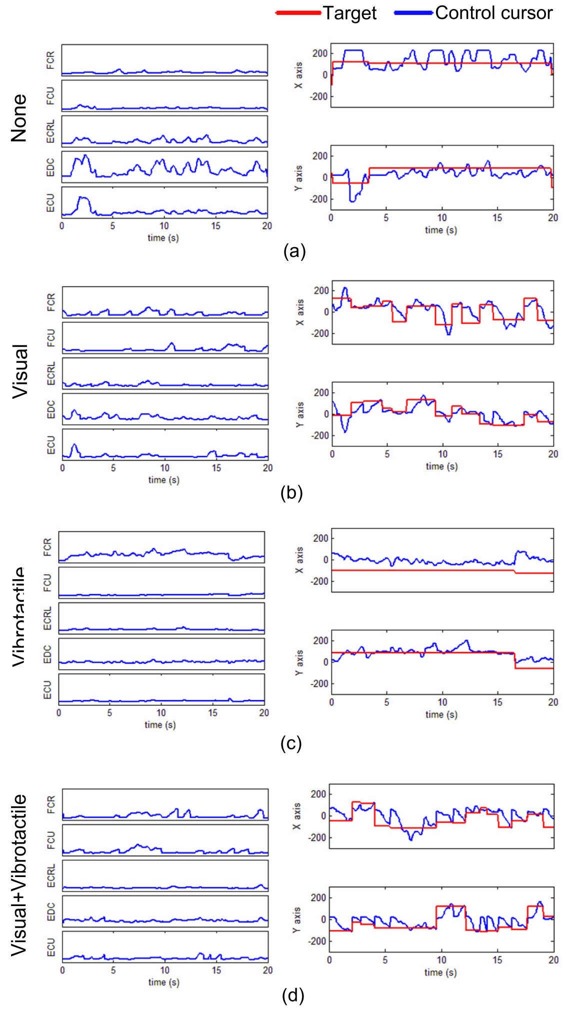


Fig. 4. The process of target capture. Each subplot for a experiment mode. The left column shows the normalized RMS values of sEMG. And the right column shows positions of the target (red line) and the control cursor (blue line).

TABLE III

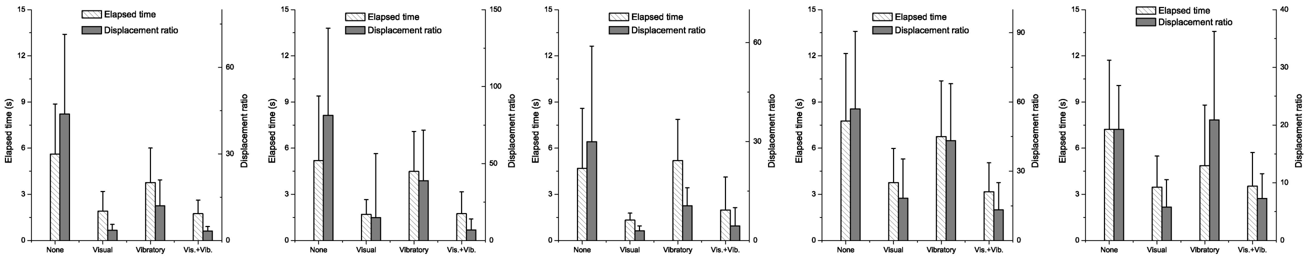
ANOVA RESULT FOR ELAPSED TIME AND DISPLACEMENT RATIO

	F-Value	$p-Value$
Elapsed time	14.85	0.00007
Displacement ratio	7.51	0.00234

In the modes with visual feedback, both elapsed time and displacement ratio is the smallest. MODE2 (only visual feedback) and MODE4 (visual plus vibrotactile feedback) had no obvious differences in performance. All the subjects reported that they almost relied on vision in the situations with visual feedback, but the vibrotactile feedback in MODE4 enhanced immersion sense.

For all the participants except subject 5, the mean and standard deviation of distance ratio in MODE3 (only vibrotactile feedback) are smaller than those in MODE1 (no feedback). During the experiment in MODE1, once subject can not find target rapidly, they had to go back to neutral position to restart searching, which resulted in longer displacement.

An ANOVA is performed. Note that the p-values are far less than 0.05. The results show significant effects of different types of feedback on both elapsed time and displacement ratio. (see TABLE III)



(a) Subject 1 (b) Subject 2 (c) Subject 3 (d) Subject 4 (e) Subject 5

Fig. 5. Comparison of elapsed time and displacement ratio between different experiment modes.

During the experiment, subject 5 reported that it was somewhat difficult to distinguish which tactor was vibrating. Hence the effect of vibrotactile feedback varies with different individuals.

IV. DISCUSSION

All the subjects showed abilities to control the cursor using sEMG signals. The muscle synergy model and NMF algorithm were effective to extract wrist movement intents simultaneously and proportionally. Although only four independent wrist movements were be used to train the synergy matrix, both direction and amplitude can be estimated in testing phase by combinations of these movements.

Four different experiment modes were proposed to investigate the effect of vibrotactile feedback, which was compared with no feedback and visual feedback. The results showed that the overall performance of the vibrotactile feedback mode ranged between visual feedback mode and no feedback mode. The subjects preferred to rely on vision in the situation that provided visual feedback. Vision is the primary sensory for human being [11]. It is well known that 80% of all information received through visual system. But when visual feedback is not sufficient, vibrotactile feedback can provide additional useful information so as to improve the performance of EMG-based human machine interface. It can be applied in dark environments or remote operation without clear realtime images from camera. Furthermore, even in circumstance with visual feedback, vibrotactile can also increase immersion of users.

In this experiment, we used vibrotactile feedback to display position deviation information in a 2D-plane cursor control task. In fact, vibrotactile feedback can also be mapped to other physical quantities, such as the joint angle or the grasping force of a prosthetic hand, which could be useful for indicating prostheses status to users and constructing a user-in-loop system. Moreover, the experimental system mentioned above could be used as a tool for neuromotor rehabilitation.

V. CONCLUSION AND FUTURE WORK

In this paper, the effect of vibrotactile feedback for a myoelectric cursor control system was investigated quantitatively. Surface EMG was used to create a mapping from wrist movements to control cursor position in proportional. Use of vibrotactile feedback has benefit of performance improvement for EMG-based human machine interface and shows promising results.

Moreover, different patterns of vibration will be attempted to find an optimal mode of vibrotactile feedback for different individuals. And the experiment containing amputee subjects will be conducted for the applications of assistive devices.

ACKNOWLEDGMENT

We would like to thank all subjects for their participation. We also thank Gan Huang, Jianwei Liu, and Peng Yao for their constructive feedback and insightful suggestion.

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