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Divide-and-conquer muscle synergies: A new feature space decomposition approach for simultaneous multifunction myoelectric control

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ABSTRACT

Simultaneous multifunctional control based on surface electromyography (sEMG) is a key issue for natural and intuitive use of upper-limb prostheses in clinical and commercial applications. However, muscle synergies make simultaneous multifunctional control technologically challenging. In this study, we proposed a new feature space decomposition approach to alleviate the difficulty brought by muscle synergies for simultaneous control of hand and wrist movements. In the feature space decomposition approach, Gaussian mixture modeling (GMM) clustering is used to split the whole feature space into a set of Gaussian clusters, each consisting of samples with similar characteristics, to "divide-and-conquer" the complex muscle synergies. Then, a hybrid simultaneous control strategy, which consists of switch control of hand movements and proportional control of wrist movements, is performed in each cluster, instead of in the whole feature space. In the experimental study, sEMG signals were recorded during static and dynamic muscle contraction involving 2-dimensional wrist rotation (flexion-extension and radial-ulnar deviation) and 3 basic hand movement patterns (relaxing, fisting and grasping). Results show that, the new feature space decomposition approach can increase the accuracy for switch control of hand movement patterns from 90.10% to 96.62%, and can improve the correlation between true and predicted values of wrist rotation angular velocity from 0.71 to 0.84 (for wrist flexion-extension) and from 0.67 to 0.82 (for wrist radial-ulnar deviation) for proportional control of wrist. The proposed feature space decomposition approach has the potential to yield simultaneous multifunctional control for sEMG-based upper-limb prosthesis.

1. Introduction

Upper-limb prosthesis could largely increase the functional capacity of amputees and further improve their quality of life. Nowadays, surface electromyography (sEMG) is the main signal source to provide multifunctional control for upper-limb prosthesis [1–4], because it could be used with pattern recognition techniques to provide a natural mapping from upper-limb muscle motions to prosthesis functions with high accuracy and easy operation.

At present, the most common strategy for sEMG-based prosthesis is switch control, which means the output of the control system is switched among a certain number of pre-specified contraction patterns (usually 4–10 sustained hand and wrist postures). In the past decades, switch control has been proven to be a simple and robust control strategy. Most of the sEMG sensing systems based on the switch control can achieve response time shorter than 300 ms and recognition accuracy above 90% [5]. However, the switch control strategy is one major reason causing the non-intuitive control of prosthesis [6], because it can only provide a discrete univariate output and cannot recognize continuous variables (such as the velocity of wrist rotation) or control multiple joints, which is far from practical requirements of daily use [7,8].

A natural neuromuscular control of prosthesis should be proportional (i.e., to yield continuous outputs) and simultaneous (i.e., to produce multiple outputs for different joints at the same time). For upper-limb prosthesis, simultaneous proportional control has been realized for shoulder and elbow [9]. A hand grasping force estimation has also been included in the simultaneous proportional control of robots [10]. Some studies have investigated simultaneous

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and proportional estimation of multiple degrees-of-freedom wrist movements for applications to myoelectric prosthesis control with amputations or congenitally deficient upper limbs [11–13].

However, simultaneous proportional control for wrist and finger motions still poses a great challenge, mainly because of the muscle synergies. Muscles of the forearm are distributed at three levels [14]: superficial, intermediate and deep. Flexors carpi radialis (FCR), flexors carpi ulnaris (FCU), extensor carpi radialis (ECR) and extensor carpi ulnaris (ECU) are layered in the superficial level of the forearm and they are most related to the flexion-extension of the wrist. Muscles related to the finger movement, such as flexor digitorum superficialis (FDS) and flexor digitorum profundus (FDP), are layered in the intermediate and deep levels of the forearm. As a consequence, it is difficult to isolate sEMG signals from each single muscle and to eliminate cross-talk from other muscles. Based on the hypothesis that behaviors might be produced through the combination of a small number of muscle synergies, several studies applied matrix factorization algorithms, like PCA, ICA, CSP, NMF, to identify relative activations between synergistic muscles for EMG-based prosthesis control.

- Principal Component Analysis (PCA) uses an orthogonal transformation to project the multi-channel EMG signal with the greatest variance on the first coordinate while the least variance in the data on the last coordinate. Hargrove et al. [15] used individual PCA to extract task-specific synergies so that the classification accuracy could be significantly improved.
- Independent Component Analysis (ICA) projects multi-channel EMG signal into statistically independent components. Staudenmann et al. [16] proved ICA could reduce the PCA-based predict error in muscle force estimation.
- Common Spatial Pattern (CSP) projects the signal to the new coordinate system with the aim of maximizing the difference in the variance between signal from two classes. Hahne et al. [17] demonstrated that CSP feature showed a high robustness against noise for myoelectric control.
- Non-negative matrix factorization (NMF) can decompose EMG signal into non-negative elements and it is another commonly used method for muscle synergies analysis [18–20].

Tresch et al. [21] compared the performance of PCA, ICA and NMF in identifying muscle synergies. It was found that PCA generally has lower performance than ICA and NMF, where ICA and NMF have comparable performance. In the comparison, the best algorithms were ICA applied to the subspace defined by PCA and a version of probabilistic ICA with nonnegativity constraints (pICA). It should be noted that all these blind source separation (BSS) methods are used on high-density EMG signal (HD-EMG) to identify time-invariant muscle synergies. It would be a challenge to identify time-variant muscle synergies from low-density EMG signal (LD-EMG). For LD-EMG, Huang et al. [22] embedded FIR filter in to CSP, which generates artificial channels with delayed signals and simultaneously filters in both the spatial and spectral domain to produce spectral features representing muscle synergies at particular spatial locations. For time-variant muscle synergies, wrist movements seriously interfere with the quality of sEMG signals from hand movements. During the wrist movements, the muscle synergies for hand movements would be time-variant, which makes the extremely difficult for by using BSS method. In [23], Reddy et al. showed the mutual influence for finger and wrist in their position estimation and applied a correction for the signal from FDS during wrist motion in their recognition model. They also showed that, the linear relationship between the wrist flexion-extension and the root mean square (RMS) of sEMG from FCU ($R^2 = 0.95$) was higher than that between finger position and the RMS of sEMG from FDS ($R^2 = 0.84$).

In the present study, we introduced a new feature space decomposition approach based on Gaussian mixture modeling (GMM) clustering to alleviate the difficulty brought by muscle synergies, and developed a hybrid simultaneous control strategy for both switch control of hand (i.e., to classify hand relaxing, fisting and grasping) and proportional control of wrist (to predict angular velocity of wrist rotation in the direction of wrist flexion-extension and radial-ulnar deviation). We designed a new experiment to record sEMG signals during a variety of static and dynamic hand and wrist movements involving wrist rotation and three hand patterns, and showed different patterns of muscle synergies in these hand/wrist movements. In the feature space decomposition approach, the GMM method groups samples into a finite number of clusters so that the samples in each cluster share similar characteristics in the feature space defined by time-domain (TD) sEMG features. We also investigated the distributions of TD features and showed that logarithm-transformed TD features are more Gaussian-like and thus are more suitable for GMM clustering. Next, the hybrid control strategy (including switch control of hand movements and proportional control of wrist movement) is performed for each cluster identified by GMM. For switch control of hand movements, a weighted Linear Discriminative Analysis (wLDA) classifier, which makes use of the prior probability of each cluster, to improve classification accuracy, is used; for proportional control of wrist movement, a multivariate linear regression (MLR) model is adopted. Experimental results show that the proposed feature space decomposition approach and hybrid simultaneous control strategy significantly improve the performance for both discrete classification of hand relaxing, fisting and grasping and continuous prediction of the angular velocity of wrist rotation in the direction of wrist flexion-extension and radial-ulnar deviation. Hence, the proposed feature space decomposition approach and hybrid control strategy can potentially make the prosthetic control more intuitive and reliable.

2. Materials and methods

2.1. Subjects

Eight subjects participated in this experiment (24.63 ± 4.27 years, 3 males 5 females). The sEMG signals were collected from their dominant arms (all subjects are all right handed). The experiments are in accordance with the Declaration of Helsinki. Ethical approval of the study was sought and obtained from the Bioethics Committee, School of Biomedicine Engineering, Shanghai Jiao Tong University (No. BM(E)2012045). Each subject was given the written informed consent prior to the experiment. No subject had a history of upper extremity or other musculoskeletal disorders.

2.2. Experimental procedures

To explore the role of muscle synergies, we compared the complex hand/wrist movements with pure hand movements in terms of the distributions of sEMG features and the performance in movement recognition. Fig. 1 illustrates the experimental setup. The experiment was carried out in 3 sections of hand and wrist movements: a dynamic section (10 min), a static section (3 min), and a repeated dynamic section (10 min). In each section, subjects were instructed to perform three types of hand movements alternately every 20 s, which were relaxing (all fingers relax), fisting (fingers flexed together in fist) and grasping (extension type grasp with a smartphone, 162 g of weight). In the static section, the subjects kept their wrists static. In the dynamic section, the subjects were asked to perform a full-amplitude wrist rotation in the clockwise direc-