Control of Powered Prosthetic Hand Using Multidimensional Ultrasound Signals: A Pilot Study

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Abstract. Various sophisticated signal processing techniques have been developed for EMG control strategy. However, some inherent properties of the signal prevent it from providing a natural control of powered prosthetic hand. This paper reported on a pilot study of an alternative, multidimensional ultrasound signals which can collect the architecture change of muscle during contraction. We designed a system to collect and analyze multi-channel A-mode ultrasound, joint angle, and surface EMG simultaneously. Using this system, we investigated the feasibility of controlling powered prosthesis by multidimensional ultrasound signals. In the experiment, the subjects were instructed to perform the wrist extension and flexion movement. Multi-channel ultrasound signals, collected from the forearm muscle, were used to estimate the wrist angle and then to control the power prosthesis. The results suggest that multidimensional ultrasound signals, based on further improvement, have great feasibility to be an alternative method to control prosthesis.

Keywords: Ultrasonography, Prosthesis, Multidimensional Ultrasound, Muscle.

1 Introduction

Powered prostheses have been used for decades to provide an artificial extension for amputees. A typical powered prosthesis is comprised of mechanical and electrical components, capable of extracting features or patterns from the electrophysiological signal to drive the mechanical actuators.

Electromyography (EMG) signal has been widely used for controlling prosthetic devices [1]. Various signal processing techniques have been proposed for EMG control strategy [2]. All the efforts aim to improve the flexibility of EMG control along with the reduction of control complexity for users. However, there still exist some inherent limitations of EMG control which are difficult to overcome. For example, it is difficult to provide a natural control of the prosthesis with multiple degrees of freedom (DoF) based on multi-channel EMG signals. Most of the current commercially available hand prostheses still use two-channel EMG inputs to provide one or two DoF(s) [3]. Brain activity is another kind of electrophysiological signal that can be potentially used for the prosthetic control. This control approach is often termed as brain-machine interface (BMI), human-machine interface (HMI), and neuroprosthesis [4] Various brain signals have been intensively investigated such as

C. Stephanidis (Ed.): Universal Access in HCI, Part IV, HCII 2011, LNCS 6768, pp. 322–327, 2011.

EEG, MEG, ECoG, and cortical neural signal [5]. However, there are still many conceptual and technological obstacles before developing neuroprosthetic devices for clinical applications. In addition to the electrophysiological signal, mechanical signals generated by muscle contraction have also been used for prosthetic control, including mechanomyography (MMG) signal [6] and myokinemetric (MK) signal [7].

Due to its ability to reflect the architecture of muscle and tissue, ultrasonography has been used to estimate muscle dimensional change [8]. Zheng et al reported the continuous monitoring of muscle activity by real-time ultrasound imaging and first suggested its potentials for the prosthetic control [9]. They also developed an A-mode ultrasound system to investigate feasibility of the new control method [10]. Based on this system, the performance of real-time ultrasound control for powered prosthesis with normal subjects was investigated [11].

The aim of this study was to extend ultrasound signal from one dimension to multi-dimension and investigate the potential for controlling prosthetic hand. A system equipped with multi-channel A-mode ultrasound was applied to detect dimensional changes of forearm antagonistic muscles. The relationships between 2-D ultrasound signals and wrist angle were quantitatively studied. The results were used to assess the potential of multidimensional ultrasound signals as a noninvasive method for prosthetic hand control.

2 Methods

2.1 Hardware Setup

As shown in Fig. 1, two ultrasound transducers (model V129; GE Panametrics, Inc., West Chester, OH, USA) were used to measure the dimensional change of antagonistic muscles. The ultrasound signals were transmitted, received and digitized by an 8-channel ultrasound phase array system (PCIAD850, PHA8; US Ultratek Inc, CA, USA). The pulse repetition frequency was 100 Hz and the sampling frequency was 50 MHz. An electronic goniometer (TSD130; BIOPAC System Inc., CA, USA) was attached in the middle of the posterior hand to measure the wrist angle during wrist extension. The collected angle signal was digitized by the NI DAQ card (NI-DAQ 6024E; National Instruments Corporation, Austin, TX, USA) with sampling rate of 2.0 KHz. A prosthetic hand (MH22; Shanghai Kesheng Prostheses Co., Shanghai, China) was controlled to open and close by the analog pulse outputted from the same DAQ card. The signal acquisition, synchronization, and display, as well as prosthetic control tasks were achieved using a custom-designed software developed in Labview.

2.2 Experiment Procedure

Two healthy subjects volunteered to participate in this study. In the experiment, each subject was seated in a comfortable chair with his forearm resting on the table. The ultrasound transducers were attached to the belly of extensor carpi radialis and flexor carpi radialis respectively. Each subject was asked to perform wrist extension for two cycles with guided moving speed. Six repeated trials were performed, with a rest of 5 minutes between two adjacent trials. The angle of the wrist was detected by the goniometer simultaneously. Both ultrasound and angle signals were digitized and stored in the computer for further processing.

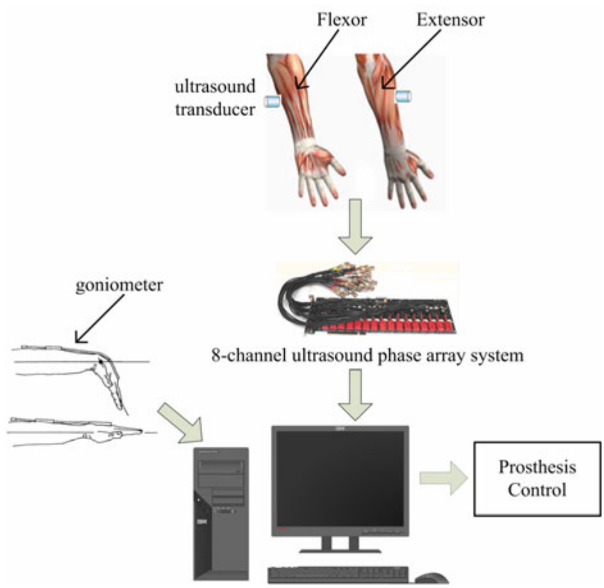

Fig. 1. The illustration of the hardware setup. Two ultrasound transducers were applied to measure the dimensional change of antagonistic muscles. The electronic goniometer was attached to the forearm to detect the wrist angle.

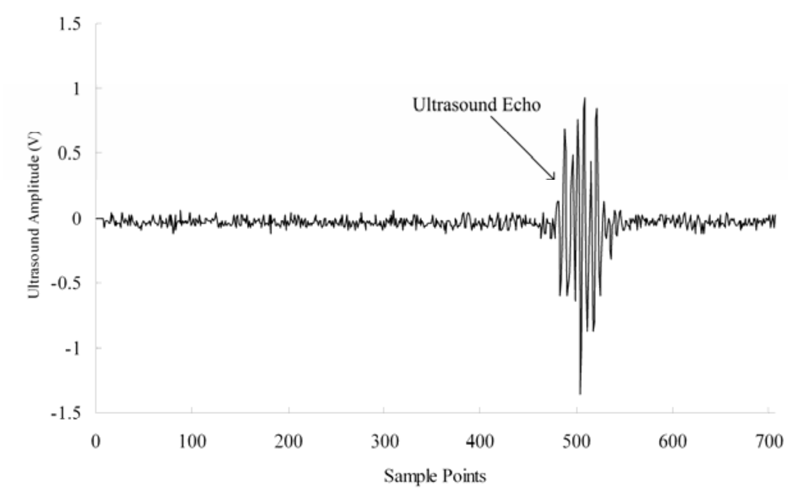

Fig. 2. A typical frame of one channel A-mode ultrasound signal. The position of the ultrasound echo reflects the muscle deformation.

2.3 Signal Processing

All the signals were processed and analyzed in Matlab program. Two-channel A-mode ultrasound signals were captured respectively frame by frame according to pulse repetition frequency. A typical ultrasound frame of one channel was shown in Fig. 2.

The A-mode ultrasound echo reflected from the muscle-bone interfaces was manually selected in the first frame as reference. To estimate the echo shift, which reflected the dimensional change of specific muscle, we utilized the cross-correlation algorithm to search the segment of signal most similar to the reference echo signal in each frame. The equation used to calculate the normalized one-dimensional cross-correlation coefficient was as follow:

$$R_{xy} = \frac{\sum_{i=0}^{N-1}[x(i)-\bar{X}][y(i)-\bar{Y}]}{\sqrt{\sum_{i=0}^{N-1}[x(i)-\bar{X}]^2 \sum_{j=0}^{N-1}[y(j)-\bar{Y}]^2}} \quad (1)$$

where $x(i)$ is the reference signal, $y(i)$is the selected signal, and $\bar{X}$ and $\bar{Y}$ are the means respectively. During the search process of each frame, the segment of signal with maximal cross-correlation coefficient was considered as the echo signal. Two echo shift series, $S_1(n)$, $S_2(n)$, were extracted from two ultrasound channels. The dimensional changes of extensor and flexor muscles in wrist extension movement were represented by these echo shift series.

The wrist angle signal was segmented as 32-point epochs. The middle of each epoch was aligned in time with the corresponding ultrasound frame according to the timestamp; hence the epochs were synchronized with the echo shift sequence in time domain. The root mean square (RMS) values $Z(n)$ were calculated for each epoch.

2.4 Data Analysis

Multivariable linear regression was conducted to model the relationship between forearm movement and dimensional changes of extensor and flexor muscles. The regression equation is as follow:

$$Z(n) = \beta_1 S_1(n) + \beta_2 S_2(n) + \varepsilon(n) \quad (2)$$

where β_1, β_2 are the regression coefficients, ε is the random noise.

Ordinary Least Squares (OLS) method was applied to estimate the coefficients in Eq.2. This OLS estimator minimizes the sum of squared residuals, and leads to a closed-form expression for the estimated value of β_1 and β_2. For each subject, the data sets of the first three trials were used for estimation and the data sets of other trials were used to test the estimation performance which was quantified using the normalized root mean square error (RMSE) by the following equation, where $\hat{Z}(n)$ is the estimated angle.

$$\text{RMSE} = \sqrt{\frac{1}{\text{N}}\sum_{n=1}^{N}(Z(n)-\hat{Z}(n))^2} \qquad (3)$$

2.5 Prosthesis Control

The estimated angle signal was then applied to investigate its potential in prosthesis control. It was used to open and close the prosthesis through the DAQ card. The amplitude of the signal linearly correlated with the opening position of the prosthesis. The linear algorithm helped the subjects to control the prosthetic hand according to his wrist angle with a few conscious efforts.

3 Preliminary Results

For each subject, the data sets of the first three trials were applied for the multivariable linear regression. The relationship between the wrist angle measured by the goniometer and the corresponding estimated angle in the other trials was further investigated. Fig. 3 illustrates a typical data set of the measured and estimated angles. The overall mean value of the normalized RMSE was 12.5%. In the prosthetic hand control experiment, the hand could smoothly open and close based on the linear control. Further study is being conducted to quantitatively evaluate the control performance.

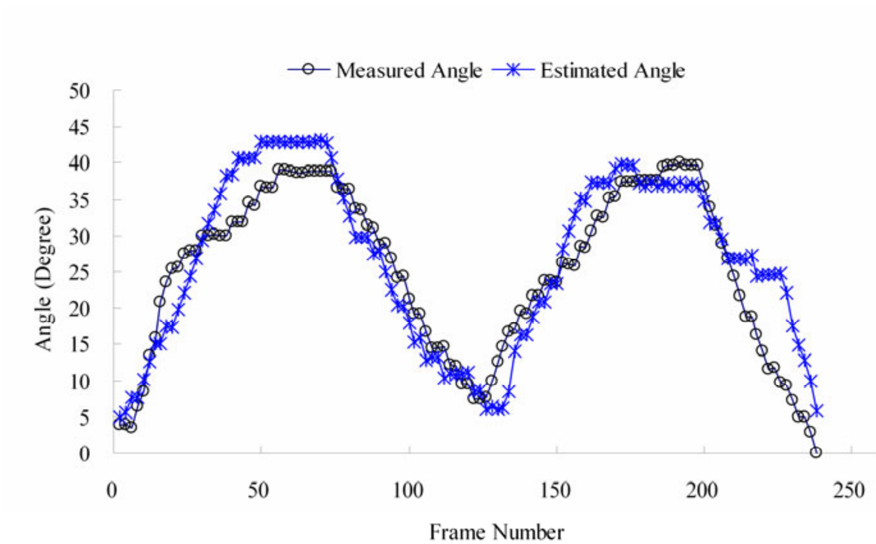

Fig. 3. Measured and estimated wrist angles calculated from the 2-channel ultrasound data in a typical trial

4 Discussion

In this study, the feasibility of using multidimensional ultrasound signal to control powered prosthesis was investigated. Based on the previous work that the morphological changes of forearm muscles extracted from one dimensional ultrasound can be used to control powered prosthesis, we custom-designed a system to synchronously collect multi-channel ultrasound, joint angle, and EMG signals of forearm muscles. Multivariable linear regression was used to estimate the wrist angle during flexion-extension movement. The estimated angle was further applied to control the opening-closure function of the prosthetic hand and the control performance was qualitative evaluated. The preliminary results indicated that the prosthetic hand could be well controlled by the proposed method. However further studies are required to quantitatively investigate the control performance and compare it with the traditional EMG control.

Acknowledgments. This work was supported by the National Natural Science Foundation of China (Grant No. 81000637), the State Key Program of National Natural Science of China (Grant No. 61031003), the National Basic Research Program 973 from Ministry of Science and Technology of China (Grant No. 2010CB732600).

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