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

A Linear Model for Simultaneously and Proportionally Estimating Wrist Kinematics from EMG during Mirrored Bilateral Movements*

Lizhi Pan, *Student Member, IEEE*, Xinjun Sheng, Dingguo Zhang and Xiangyang Zhu, *Member, IEEE*

Abstract— **This paper presents a linear model for simultaneous and proportional estimation of the two degree-of-freedoms (DOFs) wrist angle positions with surface electromyography (EMG). A 5th order state-space model was used to estimate wrist kinematics from 4-channel surface EMG signals of the contralateral forearm during mirrored bilateral movements without motion constraints. The EMG signal from each of the three limbed normal subjects was collected along with each angle position in two DOFs from both of the arms, with motion parameters tested including the radial/ulnar deviation and flexion/extension of the wrist. The estimation performance was in the range 0.787-0.885 (R^2 index) for the two DOFs in three limbed normal subjects. The results show that wrist kinematics can be estimated in 2 DOFs by state-space models with relative high accuracy compared with the results reported previously. The method proposed, as requiring only kinematics measured from the contralateral wrist, is potentially available for a unilateral amputee in simultaneous and proportional control of DOFs in powered upper limb prostheses.**

I. INTRODUCTION

One of the greatest challenges in myoelectric control is to obtain the simultaneous and proportional control signal. Classification of myoelectric patterns has been an option which is significant in clinical application for upper limb amputees for about 30 years[1], [2]. The clinical applicability of powered upper limb prostheses using pattern recognition is still limited, although the classification of multiple motions could get an accuracy > 0.95 by using current techniques[3]. The main reasons are the relative fewer functions that can be classified with acceptable accuracy and the inherent sequential and ON/OFF control of the intended class selection[4].

Simultaneous and proportional control signals for a multifunction powered upper limb prostheses is one of the most significant challenges in myoelectric control[5]. The simultaneous and proportional control of multiple degree-of-freedoms (DOFs) movements was analyzed by Muceli et al.[6], who proposed a control strategy that can be practically applied in unilateral transradial amputees for simultaneous and proportional control of multiple DOFs. Artificial neural network (ANN) was used to estimate the complex kinematics wrist and/or hand from high-density surface EMG signals of contralateral forearm during mirrored bilateral movements in free space. This work proved that mirrored bilateral training is feasible in estimation of kinematics from surface EMG signals of contralateral forearm. Mirrored bilateral training strategy is especially designed for the unilateral upper limb deficient individuals and has the excellent potential to be used by unilateral upper limb deficient individuals for simultaneous and proportional control of multiple DOFs in powered upper limb prostheses. However, this approach needed 102 electrodes and had very complex computation. Feature reduction has been done in their work, where the estimation performances of 7, 14, 12, PCA7 and PCA14 electrodes have been analyzed. The results showed that the estimation accuracy of all angles was decreased when the feature set dimensionality was reduced, especially for pronation/supination.

In this study, a linear estimation method of wrist kinematics in 2 DOFs from surface EMG was proposed. Both wrist angles and the surface EMG of wrist-related muscles were concurrently recorded. Mirrored bilateral training was adopted in this work for its potential to be used by unilateral upper limb amputees. And we estimated the angle positions of the contralateral wrist from the surface EMG using state-space models. Since the 2 DOFs, wrist radial/ulnar deviation and flexion/extension, are closely related to the four muscles of the forearm, namely, (1)extensor carpi radialis (ECR), (2) flexor carpi radialis (FCR), (3) flexor carpi ulnaris (FCU), (4) extensor carpi ulnaris (ECU), four-channel surface EMG signals from the above muscles were explored.

This paper presents a new linear state-space model to estimate the kinematics of the contralateral wrist from the surface EMG signals of wrist-related muscles during mirrored bilateral 2 DOFs wrist movements without motion constraints.

II. METHODOLOGY

A. Subjects

As a preliminary study, the proposed method in limbed normal subjects is analyzed, which is a necessary basis for future testing in disabled subjects. Three limbed normal (age, 25 ± 2) took part in the experiment. All the subjects participated in the experiment had signed the informed consent and the procedures accorded with declaration of Helsinki.

B. Procedure

As shown in Fig.1, a subject was asked to sit in the chair with his/her forearms along the body resting on the armrests. The subject was instructed to perform a series of mirrored, bilateral, dynamic contractions starting from the resting position. The experiment paradigm included four single DOF

*This work was supported by the National Basic Research Program (973 Program) of China (Grant No. 2011CB013305) and the Science and Technology Commission of Shanghai Municipality (No.11JC1406000).

Lizhi Pan, Xinjun Sheng, Dingguo Zhang and Xiangyang Zhu are with the State Key Laboratory of Mechanical System and Vibration, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai, 200240, China(email: melzpan@sjtu.edu.cn, xjsheng@sjtu.edu.cn, dgzhang@sjtu.edu.cn and mexyzhu@sjtu.edu.cn)

978-1-4577-0216-7/13/$26.00 ©2013 IEEE

movements: wrist flexion, wrist extension, radial deviation and ulnar deviation. The subject was instructed to perform a series of mirrored, bilateral, dynamic contractions starting from the resting position. Movements to be reproduced were displayed in advance on a computer screen located in front of the subject.

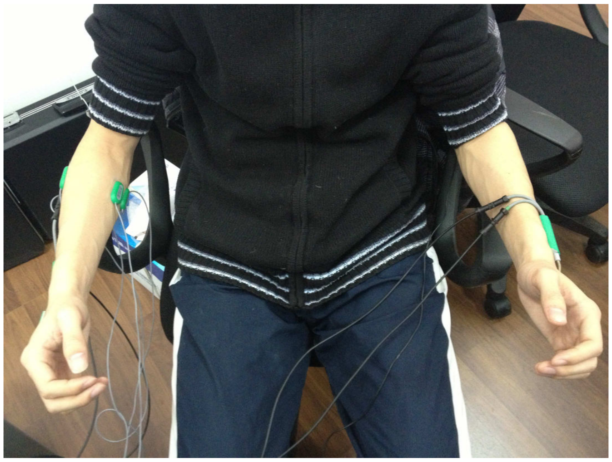

Fig. 1. Sitting position of a subject. Surface EMG was acquired from the right arm and wrist kinematics were recorded from both arms.

C. Data Acquisition

As shown in Fig.2, surface EMG was acquired from four wrist related muscles of the forearm: (1) ECR, (2) FCR, (3) FCU, (4) ECU. Bipolar, noninvasive surface electrodes (SX230 W4X8, Biometrics, UK) were placed over the target muscles using medical adhesive tape. The electrodes were connected to data acquisition Bluetooth DataLOG (DataLOG W4X8, Biometrics, UK), and the signals were sampled at 1000Hz.

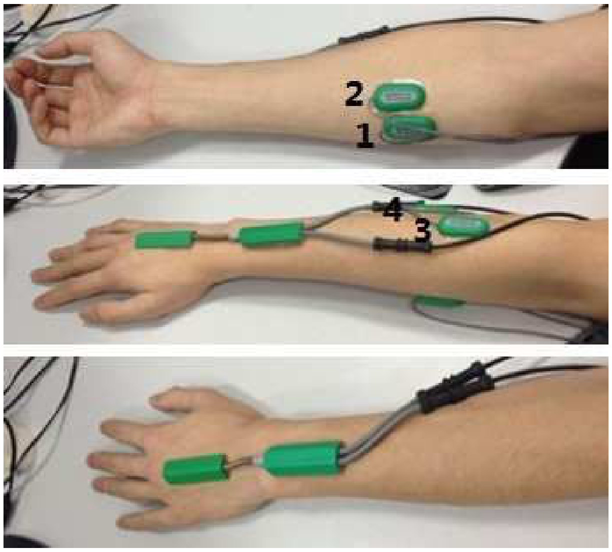

Fig. 2. Position of the surface EMG electrodes and goniometers.

As shown in Fig.2, two twin axis goniometers (SG110, Biometrics, UK), which can simultaneously measure angles in up to two planes of movement, were placed on the back of both arms to measure the angle positions in two DOFs. The goniometers were connected to the same data acquisition Bluetooth DataLOG, and the signals were sampled at 1000Hz as well.

D. Data Processing

A 4th order zero-lag Butterworth band-pass filter (pass band 20-400Hz) was adopted to attenuate DC offset, motion artifacts and high frequency noise in surface EMG signals[7]. The filtered EMG signals were full-waved rectified and low-pass filtered (5th order zero-lag Butterworth digital filter, cut-off frequency 10Hz) to obtain the muscle activity envelopes. And the wrist joint angle positions were low-pass filtered (5th order zero-lag Butterworth digital filter, cut-off frequency 10Hz) as well. Then the filtered EMG signals and the angle data were used as the input and reference for the ”EMG-angle” model identification.

E. Decoding Wrist Motion from EMG

To decode the EMG signal in real time, a function is identified to map surface EMG signal to wrist angle position as follows[8]:

$$Y = f(U) \tag{1}$$

where Y is human wrist angle position and U is surface EMG signal. ANN and Support Vector Machine(SVM) have been previously used for continuously estimating hand movements from surface EMG[9][10]. In this work, a state-space model was used to decode the relation between surface EMG and wrist angle positions.

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) \\ y(k) &= Cx(k) \end{aligned} \tag{2}$$

where x is the hidden state vector, y is the joint angle representation, u is the muscle activations, A is the system matrix that represents the dynamic behavior of the hidden state vector x, B is the matrix that maps the surface EMG signal u to the state vector x, and C is the matrix that represents the relationship between the wrist angle positions y and the state vector x. Four state-space models were used to estimate the radial/ulnar deviation and flexion/extension angle positions of the ipsi-lateral and contralateral wrist. We used different state-space models for different angle positions for the reason to obtain a better estimation performance for each DOF. Each state-space model had the surface EMG signals as input and one of the angle positions as reference. All state-space models were fifth order. The state-space models were identified using the ’n4sid’ algorithm[11], which is a subspace method for estimation of state-space models.

The performance of the state-space model was evaluated using a two-fold cross validation procedure. Each motion test was repeated twice. One of the repetitions was used for model training, where the second half for model validation. To estimate the performance of the state-space model in the estimation of each angle, the coefficient of determination R^2[12] was used. The index R^2 is defined as follows:

$$R^2 = 1 - \frac{\sum_{t=0}^{N}\left(\widehat{f(\mathrm{t})} - f(\mathrm{t})\right)^2}{\sum_{t=0}^{N}\left(f(\mathrm{t}) - \overline{f(\mathrm{t})}\right)^2} \tag{3}$$

where N is the number of data samples, $f(\mathrm{t})$ is angle position function, $\widehat{f(\mathrm{t})}$ is the corresponding estimated angle positions from the state-space model, and $\overline{f(\mathrm{t})}$ is the temporal average of $f(\mathrm{t})$.

The wrist angle positions could be recorded for identification from the forearms contralateral to the one used to acquire surface EMG signals for future applications in unilateral upper limb deficient individuals. Nevertheless, the wrist angle positions were acquired from both forearms to compare the estimation performances for ipsi-lateral and contralateral forearms in this work.

III. RESULT

It's well known that the number of orders in the state-space models influenced the performance. As we have done a series of system identifications on three subjects with these 4-channel EMG signals and the two DOFs angles of ipsi and contralateral wrist, five-order model fitted this problem well.

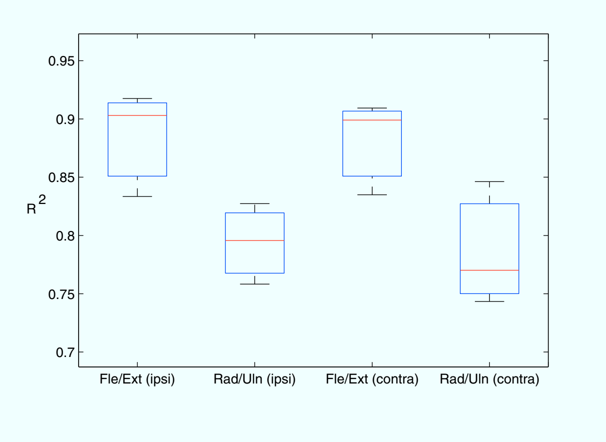

Fig. 3. Average R^2 value for ipsi-lateral and contralateral wrist.

The subjects performed symmetric movements in rhythm with both wrists. As shown in Fig.3, the average index R^2 between the real and the estimated angle positions was 0.794 ± 0.031 (0.787 ± 0.04) for radial/ulnar deviation, 0.885 ± 0.034 (0.881 ± 0.024) for flexion/extension for the ipsi-lateral(contralateral) wrist. The estimation performances for the ipsi-lateral and contralateral forearms were similar for 2 DOFs of the wrist.

Fig.4 and Fig.5 show representative results from one subject (ipsi-lateral and contralateral case) to show the performance of angle position estimation by the presented state-space model. The parameters of the state-space model for ipsi-lateral flexion/extension were listed in Table I.

TABLE I

PARAMETERS OF MATRIX A, B AND C

A	0.9899	-0.00394	-0.00561	0.001882	-0.00372
	0.003558	0.99904	-0.02553	-0.00163	-0.0006
	0.003555	0.031576	0.98573	-0.0426	-0.00115
	-0.00117	0.000926	0.005244	0.99666	0.032485
	0.003401	0.009355	-0.03091	-0.01921	0.97269
B	0.010557	-0.00269	-0.00062	-0.00317	
	0.037964	-0.00876	0.008872	-0.00998	
	0.016334	-0.00095	0.033315	0.002475	
	-0.08044	0.01915	-0.01108	0.019806	
	0.048529	-0.01063	0.019013	-0.00909	
C	5315.7	-55.805	213.49	610.14	-5.6389

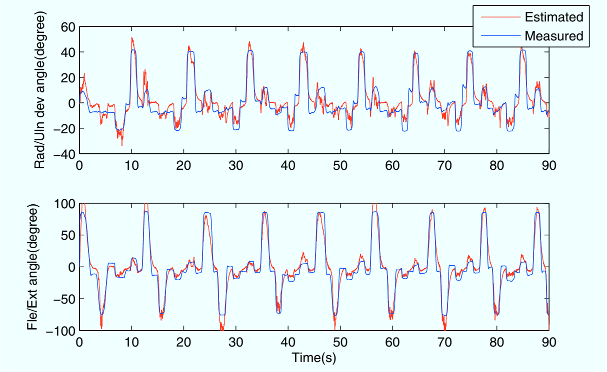

Fig. 4. Measured and estimated angle positions for a representative subject. In this example, the R^2 was 0.828 and 0.918 for radial/ulnar deviation and flexion/extension. Estimations are obtained for the ipsi-lateral hand.

IV. DISCUSSION

This paper proposed a state-space model estimating the contralateral wrist kinematics during movements in two DOFs from only 4-channel surface EMG signals. This study presents that it is feasible to use the state-space model to estimate the kinematics of the both wrists from the sEMG of the unilateral wrist-related muscles during mirrored bilateral movements in free space.

As shown in Fig. 3, the average R^2 indexes for radial/ulnar deviation and flexion/extension in this work were comparable with the results of Muceli et al.[6]. In addition, we used only 4 electrodes and they used 102 electrodes. And the average R^2 indexes were 0.1 higher than the results when they used 7 electrodes. The above comparisons show that a linear state-space model and a relatively small number of surface EMG signals could achieve a good estimation performance for wrist radial/ulnar deviation and flexion/extension. The average R^2 index for flexion/extension is higher than that for radial/ulnar deviation. It was a very common phenomena occurred in other studies[4][6]. The average R^2 indexes for ipsi-lateral wrist were a little higher than that for the contralateral wrist. We attributed it to the better synchronization characteristics between the surface EMG signals and the kinematics of the ipsi-lateral wrist.

Fig. 4 and Fig. 5 show that the angle traces estimated by the proposed state-space models fit the the measured angle traces well. Because of muscles control the wrist operation

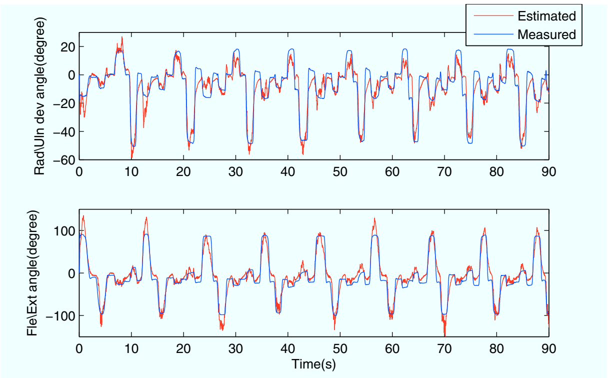

Fig. 5. Measured and estimated angle positions for a representative subject. In this example, the R^2 was 0.846, and 0.899 for radial/ulnar deviation and flexion/extension. Estimations are obtained for the contralateral hand.

in a synergistic fashion[13], the angle traces show that the movement that subjects were asked to reproduce brought the movement of the other DOF. Although it doesn't mean that the estimation had a good accuracy during the concurrent involvement of the 2 DOFs (Fig. 4 and Fig. 5), the results show that simultaneous and proportional wrist control of 2 DOFs is capable in the proposed method.

The advantage of state-space model is that it has less computation complexity compared with other nonlinear models, which could facilitate hands-on implementation in practice, although this state-space model is still like a black box model. As we found that the five-order state-space model fits this problem well by trial and error, we could assume that there maybe exist a five-order formulation which can express the relationship between wrist kinematics and these four-channel surface EMG signals well. In next step, we will do a large number of experiments to verify this assumption and attempt to find some inner mechanism about the form of this five-order formulation.

The limit position is a very important issue for myoelectric prosthesis control. The exceeded limit position estimation may damage hardware of the prosthesis and cause injury of the amputees. As shown in Fig. 4 and Fig. 5, there were some exceeded limit position estimations in the results. Actually, we are considering a classification method to detect the limit movement and then eliminate the error of exceeded limit position estimations.

V. CONCLUSIONS

According to the research in this paper, the wrist kinematics is capable of being estimated with state-space model, which formed by four-channel surface EMG signals from contralateral forearm during mirrored movements. Thus a potential solution is proposed to be practically applied in simultaneous and proportional wrist or hand control of multiple-DOF prosthesis for unilateral transradial amputees. For further study, extended experiments on the unilateral transradial amputees will be performed and the finger angles be estimated with the state-space model.

ACKNOWLEDGMENT

The authors want to thank Dr. Mitsuhiro Hayashibe for helpful instruction. And the authors also want to thank all the subjects for taking part in the experiment.

REFERENCES

[1] B. Hudgins, P. Parker, and R. Scott, "A new strategy for multifunction myoelectric control," *Biomedical Engineering, IEEE Transactions on*, vol. 40, no. 1, pp. 82–94, 1993.
[2] P. Parker, K. Englehart, and B. Hudgins, "Myoelectric signal processing for control of powered limb prostheses." *Journal of electromyography and kinesiology: official journal of the International Society of Electrophysiological Kinesiology*, vol. 16, no. 6, p. 541, 2006.
[3] R. Merletti and P. Parker, *Physiology, engineering, and noninvasive applications*. IEEE Press Series on Biomedical Engineering.-Wiley-IEEE Press, 2004.
[4] J. Nielsen, S. Holmgaard, N. Jiang, K. Englehart, D. Farina, and P. Parker, "Simultaneous and proportional force estimation for multifunction myoelectric prostheses using mirrored bilateral training," *Biomedical Engineering, IEEE Transactions on*, vol. 58, no. 3, pp. 681–688, 2011.
[5] A. Fougner, O. Stavdahl, P. Kyberd, Y. Losier, and P. Parker, "Control of upper limb prostheses: Terminology and proportional myoelectric control-a review," *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, vol. 20, no. 5, pp. 663–677, 2012.
[6] S. Muceli and D. Farina, "Simultaneous and proportional estimation of hand kinematics from emg during mirrored movements at multiple degrees-of-freedom," *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, vol. 20, no. 3, pp. 371–378, 2012.
[7] H. Hermens, B. Freriks, R. Merletti, D. Stegeman, J. Blok, G. Rau, C. Disselhorst-Klug, and G. Hägg, *European recommendations for surface electromyography*. Roessingh Research and Development The Netherlands, 1999.
[8] P. Artemiadis and K. Kyriakopoulos, "Emg-based teleoperation of a robot arm using low-dimensional representation," in *Intelligent Robots and Systems, 2007. IROS 2007. IEEE/RSJ International Conference on*. IEEE, 2007, pp. 489–495.
[9] C. Pulliam, J. Lambrecht, and R. Kirsch, "Electromyogram-based neural network control of transhumeral prostheses," *J Rehabil Res Dev*, vol. 48, pp. 739–753, 2011.
[10] J. Vogel, C. Castellini, and P. van der Smagt, "Emg-based teleoperation and manipulation with the dlr lwr-iii," in *Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on*. IEEE, 2011, pp. 672–678.
[11] L. Ljung, *System identification*. Wiley Online Library, 1999.
[12] N. R. Draper, H. Smith, and E. Pownell, *Applied regression analysis*. Wiley New York, 1966, vol. 3.
[13] N. Jiang, K. Englehart, and P. Parker, "Extracting simultaneous and proportional neural control information for multiple-dof prostheses from the surface electromyographic signal," *Biomedical Engineering, IEEE Transactions on*, vol. 56, no. 4, pp. 1070–1080, 2009.