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Use of Muscle Thickness Change to Control Powered Prosthesis: A Pilot Study

Jing-Yi Guo, Xin Chen, and Yong-Ping Zheng

Abstract—**Nowadays, most of the commercial upper-limb externally powered prosthetic devices are controlled by electromyography (EMG) signal. It is detected from the remaining muscles of amputated arms to control the prostheses. However, there are some inherent limitations of EMG control, such as muscle cross talk. On the other hand, it has been demonstrated that the muscle thickness change collected by ultrasound during contraction, namely sonomyography (SMG), could be used for muscle assessment and had the potential for prosthetic control. In this study, we investigated the feasibility of controlling a powered prosthesis by one-dimensional SMG (1-D SMG) signal and compared the performances of SMG and EMG control in tracking the guided patterns of wrist extension. SMG and EMG signals, collected from the extensor carpi radialis, were used to control the open-close motion of a powered prosthesis respectively. It was found that the mean RMS tracking errors of SMG control under different movement rates were 12.8±3.2% (mean±SD) and 14.8±4.6% for sinusoidal and square guiding waveforms, respectively, while the corresponding values of EMG control were 24.1±5.0% and 22.9±5.5%, respectively. Paired t-test showed that the RMS errors of SMG control were significantly smaller than those of EMG control. The results suggested that SMG signal, based on further improvement, may have great feasibility to be an alternative method to control prostheses.**

I. Introduction

Powered prostheses have been used for decades to provide an artificial extension for amputees [1]. They could be used to replace the missing parts of human body due to disability from birth, or injury and to supplement the defective body parts. A typical powered prosthesis, comprised of mechanical and electrical components, extracts features or patterns from the electrophysiological signal (such as signals from muscle and brain) and maps them into movement functions of the mechanical motor.

Electromyography (EMG) signal, recorded by electrodes on the skin surface, provides a noninvasive method of measuring muscle activity, and has been extensively investigated for controlling prosthetic devices [2]. However, there are still some inherent limitations of EMG control that have to be overcome. It is difficult to provide a natural control of multiple degree-of-freedoms (DOFs) prosthesis based on multi-channel EMG signals. Subjects need intensive conscious effort to control the prosthesis and most of them feel fatigue after using it for a long time [3].

Mechanical signal generated by muscle contraction could be also used as a control signal for powered prostheses. It is suggested that mechanomyography (MMG) signal has the potential to be an alternative control input for the powered prostheses [4], [5]. Another research group designed and implemented a novel self-contained MMG-driven prosthesis for below-elbow amputees [6]. The dynamic pressure and shape changes at specific sites on amputee residua were also introduced as control signal of multi-finger prostheses [7], [8].

On the other hand, due to its ability to reflect architectural change of muscle and tissue, ultrasonography is employed to estimate muscle function and activity [9] Simultaneous measurements of EMG and ultrasound image have been reported for monitoring the muscle activity in a quasi-static way [9], [10]. In these studies, the morphological changes of muscles measured by ultrasound image were traditionally used for diagnosis or assessment, but not targeting for control purposes. Zheng et al [11], [12], [13] suggested the continuous monitoring of muscle activity by real-time ultrasound image, and named the real-time changes of muscle architectures as sonomyography (SMG). Their study demonstrated that SMG signal could be potentially used for powered prosthetic control. However, the ultrasound image system is not suitable for control purpose, as the system is too expensive and the ultrasound probe is too large for practical use.

Recently, we developed a system to collect and analyze A-mode ultrasound, surface EMG and mechanical signal, such as force and joint angle simultaneously. This system has

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Jing-Yi Guo is with Department of Heath Technology and Informatics, The Hong Kong Polytechnic University, Kowloon, Hong Kong, China (e-mail: ejingyiguo@hotmail.com)

Xin-Chen was with Department of Heath Technology and Informatics, The Hong Kong Polytechnic University, Kowloon, Hong Kong, China (e-mail: gorilla_chenxin@hotmail.com)

Yong-Ping Zheng is with Department of Heath Technology and Informatics, and Research Institute of Innovative Products and Technologies, The Hong Kong Polytechnic University, Kowloon, Hong Kong, China. He is the corresponding author (phone: 852-27667664; Fax: 852-23624365; email: ypzheng@ieee.org).

been successfully used to detect the dynamic thickness change of skeletal muscles during contractions [14]. In the present study, SMG signal extracted from A-mode ultrasound signal was used to control the powered prosthesis in real-time. The control performance was evaluated and the advantages of SMG control and future development are discussed.

I. MATERIAL AND METHODS

A. Subjects

Nine healthy adults, including seven males and two females volunteered to participate in this study (mean ± SD age= 31 ± 4 years; body weight = 67.9 ± 16.7 kg; height =170.1 ± 9.4 cm). All participants were right-hand-dominant without any known neuromuscular disorders.The human subject ethical approval was obtained before carrying out the experiments.

B. Hardware setup

An ultrasound pulser/receiver (model 5052 UA, GE Panametrics, Inc. West Chester, OH, USA) was used to drive a 10 MHz single element ultrasound transducer (model V129, GE Panametrics, Inc., West Chester, OH, USA), and to amplify the received signals. The A-mode ultrasound signal was digitized by a high speed A/D converter card (Gage CS82G, Gage Applied Technologies, Inc, Canada) with a sampling rate of 100 MHz. The prosthesis was controlled to open and close by the analog pulse outputted from NI DAQ card (NI-DAQ 6024E, National Instruments Corporation, Austin, TX, USA). The prosthesis open-close level was measured by an electronic goniometer (model XM110, Penny & Giles Biometrics, Ltd; Gwent, United Kingdom) which was fixed on the back of the prosthesis (Fig. 2). The angle signal was digitized by the same NI DAQ card. The surface EMG signal, captured from the EMG bipolar Ag-AgCl electrodes (Axon System, Inc., NY, USA), was amplified by a custom-designed EMG amplifier with a gain of 1000 and filtered by a 10-300 Hz band-pass analog filter within the amplifier, and then digitized by same NI DAQ card with a sampling frequency of 1 KHz.

C. Software design

Signal acquisition, synchronization, analysis, display, as well as prosthesis control tasks were implemented by the custom-designed software of ultrasound measurement of motion and elasticity developed by Microsoft VC++6.0 platform. Fig. 1 shows the software interface to capture and process the ultrasound signals. When the muscle contracted, the dimensional change induced the variations of distance between the interface of fat-muscle and that of the muscle-bone, which would cause the A-mode ultrasound echoes to shift by a certain distance. The cross-correlation algorithm was utilized to estimate the distance change of ultrasound echoes in the following frames and was calculated as follow:

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

where $x(i)$ is the reference signal and $y(j)$ is the selected signal, $\bar{X}$ and $\bar{Y}$ are the means of $x(i)$ and $y(j)$, respectively. The metacarpophalangeal (MCP) joint angle of the middle finger was measured by the goniometer to evaluate the open-close level of the hand. Both the angle signal and a pre-designed guiding waveform were plotted in the same figure on the computer screen to give the subject a visual feedback. The software could also collect continuous EMG signal and control the prosthesis with similar interface as Fig. 1. The root mean square value (RMS) was extracted from the EMG signal to control the prosthesis in the same manner as SMG control.

D. Experiment protocol

The control performances of both SMG and EMG were tested for each subject. As shown in Fig. 2, the subject was seated in a comfortable chair with his/her forearms under rest

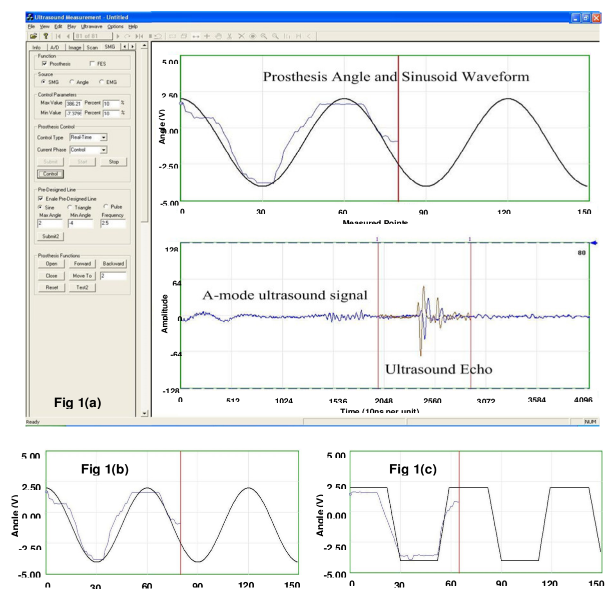

Fig.1. An illustration of the software interface used to simultaneously collect 1-D SMG and goniometer signal and to control prosthesis. (a) The top window illustrates the sinusoidal waveform used to guide the wrist extension and flexion movement along with the goniometer signal which represents the prosthesis open-close level. The bottom window shows the ultrasound signal with the selected reference echo used for tracking the muscle thickness change. (b) A typical sinusoid waveform with a rate of 10 cycles per minute. (c) A typical square waveform with a rate of 10 cycles per minute.

on the table. In SMG test, the 10 MHz single element ultrasound transducer (radius 3 mm) was inserted into a custom-designed holder of radius 10 mm made of silicone gel in order to attach the transducer to the skin. The transducer together with the holder was positioned on the belly of extensor carpi radialis. Double-sided adhesive tape was used to fix the holder, while ultrasound gel was applied between the transducer and skin. Before each experiment, the subjects

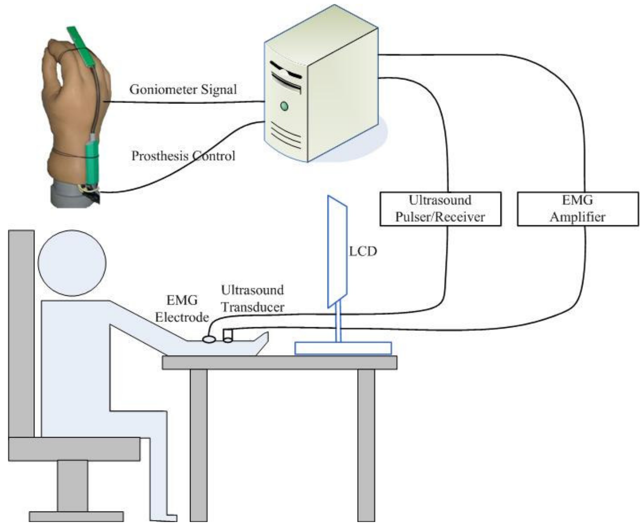

Fig.2. An illustration of the SMG and EMG prosthesis control experiment

were asked to produce several wrist extensions in order to determine the deformation range which was then mapped into the open-close range of the prosthesis for the following control. The subject was instructed to perform wrist extension while watching the pre-designed guiding waveform along with the prosthesis angle on the computer screen. The subject could adjust the degree of the movement to match the two waveforms. The amplitude of both sinusoid and square waveforms was linearly corresponded to the prosthesis angle. The sinusoid waveform investigated the subject's ability to continuously control the prosthesis while the square waveform demonstrated the subject's ability to maintain the prosthesis in two different stationary levels. The wrist extension movement rates were set to 4, 6, 10 cycles per minute for each guiding waveform. Therefore, each subject performed a total of six tasks of wrist extension. For each task, five repeated trials were performed, in which the first two were used for training, and data was recorded for the next three trials.

In EMG test, the bipolar Ag-AgCl electrodes were attached to the belly of extensor carpi radialis, and similar testing protocol was adopted to make the results comparable. The subjects were instructed to perform the wrist extension under the guidance of pre-designed waveform. A total of six tasks, under the three wrist extension rates for the two different waveforms, were performed by each subject.

The root mean square (RMS) tracking error between the guiding waveform and prosthesis angle was defined as:

$$RMSTE = \sqrt{\frac{\sum_{i=1}^{n}\left[\left(y_i - y_i^{'}\right)/\left(M_{\max} - M_{\min}\right)\right]^2}{n}} \qquad (2)$$

where y_i is the instant value of the guiding waveform, $y_i^{'}$ is the instant value of prosthesis angle, $M_{\max}$ and $M_{\min}$ are minimal and maximal values of the guiding waveform respectively. Since the amplitude range of the guiding waveform represented the motion range of the prosthesis, this RMS tracking error was essentially a normalized error with respect to the motion range.

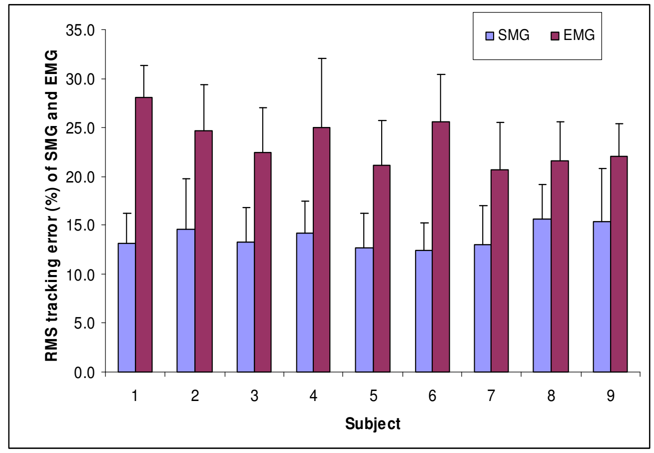

Fig.3. The overall mean RMS tracking error of each subject for all the movement rates. The error bar represents the standard deviation from the mean.

II. Results

The overall mean RMS tracking errors of SMG under the three movement rates were 12.8±3.2 % and 14.8±4.6 % for the sinusoid and square guiding waveforms, while the corresponding values for EMG were 24.1±4.9 % and 22.9±5.5 %, respectively. The overall mean RMS tracking errors of each subject for all the movement rates and waveform patterns are shown in Fig. 3. Paired t-test showed that the RMS errors of SMG control were significantly smaller than those of EMG control ($p < 0.05$). Two-way ANOVA was used to test the effects of both the movement rate and guiding waveform patterns on the RMS tracking error. For SMG control, it was observed that both factors had significant effects ($p = 2.0*10^{-6}$ for movement rate and $p = 0.007$ for guiding waveform pattern) and their interaction effect was also significant ($p = 0.02$). However, for EMG control, neither factors had significant effects ($p = 0.059$ and $p = 0.27$ respectively).

III. Discussion

In this study, we investigated the feasibility of controlling powered prosthesis by 1-D SMG signal and compared the performances of SMG and EMG in tracking the guided patterns of wrist extension. The statistical analysis showed that the RMS tracking error of SMG control was significant smaller than that of EMG control, indicating that SMG had better performance than EMG in prosthetic control. This result confirmed our previous hypothesis that SMG had the potential to be an alternative signal of EMG for control purpose. In previous studies, we have explored the feasibility of control powered prosthesis by SMG signal in a systematic way [14]. The current study was an extension of our previous work by using SMG and EMG to control a real powered prosthesis. The results suggested that performance of SMG control was better than EMG control which was consistent with the previous findings [14].

We used only one channel of SMG from the forearm extensor muscle to control the prosthesis. To control prosthesis in DoFs, multi-channel SMG signal from different groups of muscles are required to predict the motions of individual joint. One major advantage of multi-channel SMG control is that there is no cross talk between different channel SMG signals since ultrasound can individually detect morphological changes of muscle in neighboring locations. Thus, further experiments should be performed to explore the potential of controlling the multiple DoFs prosthesis by extracting information from multi-channel SMG signals. Moreover, as mentioned above, the performance of the prosthesis can affect the control accuracy to some degree. In future experiment we plan to use more dexterous prosthesis with higher motion speed and higher motion resolution.

In summary, we constructed the 1-D SMG prosthetic control system, and evaluated the performance of prosthetic control in tracking different given wrist extension patterns. The use of SMG control could provide an alternative method to EMG control. Further studies are required to explore the potential of multiple channels of SMG to achieve multiple DoFs control.

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REFERENCES

[1] A. Muzumdar. Powered Upper Limb Prostheses: Control, Implementation and Clinical Application. Berlin; New York: Springer, 2004.

[2] R. N. Scott, and P. A. Parker, "Myoelectric prostheses: state of the art," *J. Med. Eng. Technol.*, vol. 12, pp. 143-151, Jul-Aug 1988.

[3] C. Cipriani F. Zaccone S. Micera, and M. C. Carrozza, "On the shared control of an EMG-controlled prosthetic hand: Analysis of user-prosthesis interaction," *IEEE Trans. Robo.*, vol. 24, pp. 170-184, Feb 2008.

[4] D. T. Barry, J. A. Leonard, A. J. Gitter, and R. D. Ball, "Acoustic myography as a control signal for an externally powered prosthesis," *Arch. Phys. Med. Rehabil.*, vol. 67, pp. 267-269, Apr 1986.

[5] D. T. Barry, J. A. Leonard, A. Gitter, and R. D. Ball, "Acoustic myography as a prosthetic control signal," *Arch. Phys. Med. Rehabil.,* vol. 65, pp. 616-616, 1984.

[6] J. Silva, W. Heim, and T. Chau, "A self-contained, mechanomyography-driven externally powered prosthesis," A*rch. Phys. Med. Rehabil.*, vol. 86, pp. 2066-2070, Oct 2005.

[7] R. L. Abboudi, C. A. Glass, N. A. Newby, J. A. Flint, and W. Craelius, "A biomimetic controller for a multifinger prosthesis," *IEEE Trans. Rehabil. Eng.*, vol. 7, pp. 121-129, Jun 1999.

[8] D. J. Curcie, J. A. Flint, and W. Craelius, "Biomimetic finger control by filtering of distributed forelimb pressures," *IEEE Trans. Neural. Syst. Rehabil. Eng.*, vol. 9, pp. 69-75, Mar 2001,

[9] P. W. Hodges L. H. M. Pengel R. D. Herbert, and S. C. Gandevia, "Measurement of muscle contraction with ultrasound imaging," *Muscle Nerve*, vol. 27, pp. 682-692, Jun 2003.

[10] J. M. McMeeken I. D. Beith D. J. Newham P. Milligan, and D. J. Critchley, "The relationship between EMG and change in thickness of transversus abdominis," *Clin. Biomech.*, vol. 19, pp. 337-342, May 2004.

[11] J. Shi, Y.-P. Zheng, X. Chen, and Q.-H. Huang, "Assessment of muscle fatigue using sonomyography: Muscle thickness change detected from ultrasound images," *Med. Eng. Phys.*, vol. 29, pp. 472-479, May 2007.

[12] J. Shi , Y.- P. Zheng, Q.- H. Huang, and X. Chen, "Continuous monitoring of sonomyography, electromyography and torque generated by normal upper arm muscles during isometric contraction: Sonomyography assessment for arm muscles," *IEEE T. Bio-Eng.,* vol. 55, pp. 1191-1198, Mar 2008.

[13] Y.-P. Zheng, M. M. F. Chan, J. Shi, X. Chen, and Q.-H. Huang, "Sonomyography: Monitoring morphological changes of forearm muscles in actions with the feasibility for the control of powered prosthesis," *Med. Eng. Phys.*, vol. 28, pp. 405-415, Jun 2006.

[14] J.-Y. Guo, Y.-P. Zheng, Q.-H. Huang, and X. Chen, "Dynamic monitoring of forearm muscles using one-dimensional sonomyography system," *J. Rehabil. Res. Dev.*, vol. 45, pp. 187-195, 2008.