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Evaluation of Sonomyography (SMG) for Control Compared with Electromyography (EMG) in a Discrete Target Tracking Task

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Abstract—**Most of the commercial upper-limb externally powered prosthetic devices are controlled by electromyography (EMG) signals. We previously proposed using the real-time change of muscle thickness detected using ultrasound, namely sonomyography (SMG), for the control of prostheses. In this study, we compared the performance of subjects using 1-D SMG signal and surface EMG signal, using a discrete target tracking protocol involving a series of letter cancellation tasks. Each task involved using grip force, EMG or SMG from a wrist extensor muscle to move a cursor to one of 5 locations on a computer screen, at the first four of which were located a letter and last of which was a word of "NEXT". The target was defined by the location showing the letter "E" and, once the subject reached this target, they were instructed to "cancel" the E from the screen, using a button operated by the contralateral hand. A paired t-test revealed that the percentage of letters correctly cancelled with force/angle and SMG signal in isometric force control, and with SMG in wrist extension were significantly higher than with EMG ($P<0.05$) for both isometric control and wrist extension. The results suggest that SMG signal has great potential as an alternative to EMG for prosthetic control.**

I. INTRODUCTION

MOST commercial upper-limb externally powered prosthetic devices are controlled by electromyography (EMG) signals. The EMG signal detected from musculature on the residual limb is processed to derive either threshold or continuous control signals.

An effective and reliable prosthesis should have multiple degrees of freedom (DOF), be highly accurate, intuitive to control [1], and provide feedback to the user [2]. Various researchers are focusing efforts on achieving these goals. However, despite its wide application in prosthetic control, EMG is limited by its inherent properties. It is sensitive to external electromagnetic fields and other perturbations. Further, with standard surface electrodes, it is difficult to detect individual deep muscle EMG and this limits its potential for multi DOF control.

Ultrasonography is another widely used method to measure muscle morphological changes in both static and dynamic conditions. Since skeletal muscle architecture is closely correlated with its function [3], various ultrasound-measured parameters have been employed to characterize muscle activities [4], [5], [6]. We previously proposed using the real-time change of muscle thickness detected using ultrasound, namely sonomyography (SMG), for the control of prostheses [6]. Compared with SMG using 2-dimensional (2-D) ultrasound images [6], SMG based on small, lightweight A-mode ultrasound [7] so-called one-dimensional SMG (1-D SMG) potentially provides a more portable, compact, inexpensive, and practical solution.

It is possible that SMG and EMG, both of which represent muscle activity, but each of which has its own characteristic relationships with resultant force and movement, may vary in ease of control. One approach to quantifying "ease of control" is the use of the dual task paradigm, in which a secondary cognitively demanding task is carried out in parallel with a motor task. A previous pilot study used a dual task paradigm to compare the EMG and so-called myokinemetric signals [8]. However, problems with the transduction of the myokinemetric signals led to inconclusive results. In this preliminary study investigating SMG, we compared the performance of subjects in the discrete target tracking (motor) task subset of the experiment reported in [8] using a 1-D SMG signal and surface EMG signal. We hypothesized that the 1-D SMG signal could provide the user with improved performance on a 1D discrete target tracking task compared with EMG, thus may have potential as a non-invasive method to detect skeletal muscle activities for control purposes.

II. METHODS

A. Subjects

Ten healthy adults, including five males (mean ± SD age= 30.8 ± 4.8 years; body weight = 71.8 ± 15.2 kg; height =171.0 ± 7.3 cm) and five females (age =28.2 ± 6.1 years; body weight = 49.4 ± 3.8 kg; height = 162.2 ± 5.3 cm), volunteered to participate in this study. The human subject

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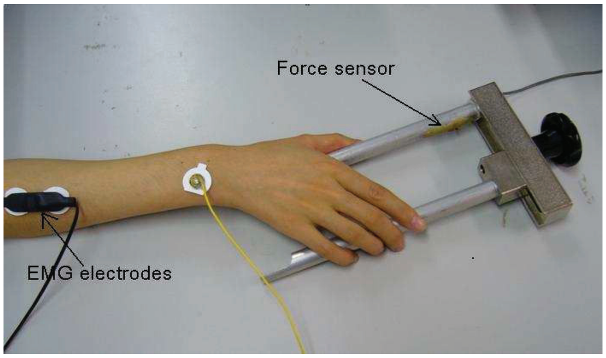

Fig. 2. EMG electrodes were placed on the belly of the extensor carpi radialis muscle when subject performed force control task. The force of the hand was detected using a custom-made force sensor.

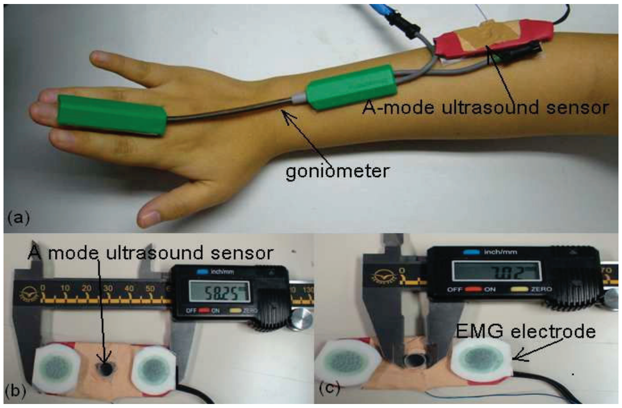

Fig. 1. (a) Placement of the 1D ultrasound transducer, EMG electrodes and goniometer on the extensor carpi radialis muscle when subject was doing wrist extension. Ultrasound gel applied between the ultrasound transducer and skin to aid acoustic coupling. (b) The length of the three sensors was 5.8 cm. (c) The diameter of A-mode ultrasound sensor was 0.7 cm

ethical approval was obtained from the relevant committee in the lead author's institution and informed consents were obtained from all subjects prior to the experiment.

A. *Experiment protocol*

The protocol used in this study is similar to the motor task subset of the experiment reported in [8]. The subject was asked to perform wrist extension movements (Fig. 1) and isometric force control (Fig. 2) respectively. The extensor carpi radialis muscle was chosen as it contributes to both wrist extension and isometric grip force, and is easily accessible for surface EMG and 1-D SMG measurement. The task was to control the cursor to cancel the letter "E", whenever it appears in the screen. As an example， when the subject performed wrist extension, angle, EMG and 1-D SMG signals were generated and the amplitude of these signals were linearly used, as appropriate, to control the cursor's position. The subject was provided with a set of 4 letters (Fig 3) and asked to move the cursor on the position of letter "E". The subject was instructed to press a button using the other hand when the cursor was positioned over the letter "E". If the subject achieved this, the letter "E" was successfully cancelled. After all the "E"s in the set of 4 were cancelled, the cursor was moved to "NEXT" as shown in Fig 3 and a new set of letters appeared on the computer screen. The angle change of wrist, force, EMG and 1-D SMG collected from the extensor carpi radialis muscle were separately used to control the cursor to cancel the letter "E", whenever it appeared on the screen within 90 seconds.

Each task was divided into three parts, which are calibration, practice and a test. During the calibration, the system recorded the maximal and minimal values when subject doing the isometric contraction and wrist extension. The minimum value corresponded to the lowest icon ("NEXT" in Fig. 3) and 90% of maximum corresponded to the highest icon ("E" in Fig. 3). The reason for using 90% of maximal value rather than maximal was to reduce the effort required to reach the top icon and therefore avoid muscle fatigue during the 90 second test. After calibration, the subject could enter the practice part to examine the results of calibration. If they were satisfied with the result of calibration, they could proceed to the test part to begin real testing. Alternatively, they could reenter the calibration part to reset the maximal and minimal values.

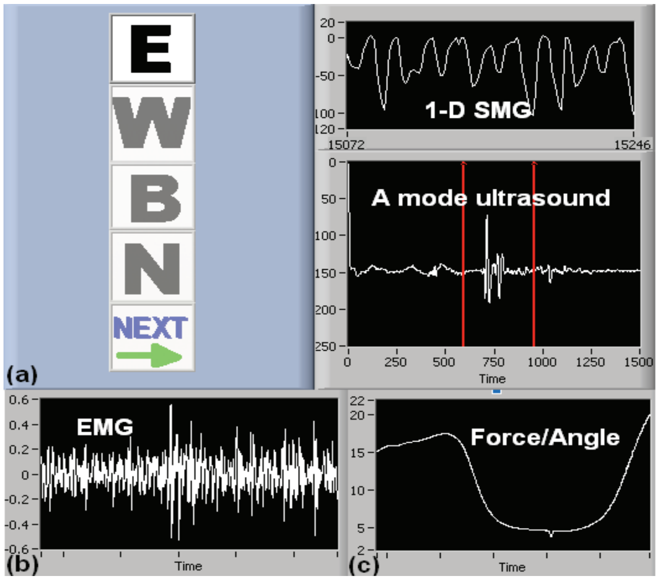

Fig. 3. (a) The software interface used to collect 1-D SMG signals. The muscle deformation signal (i.e. SMG) extracted from A-mode ultrasound was displayed for controlling the cursor to cancel the letters. The muscle deformation was measured according to the echo movement reflected from the muscle-bone interfaces. Window was selected to include the ultrasound echoes. (b) The EMG signals were collected from the extensor carpi radialis muscle and EMG RMS was used to control the cursor. (c) The force collected from force sensor or angle detected by electrical goniometer was used to control the cursor.

B. *Data acquisition*

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 10C6SJ, Shantou Institute of Ultrasonic Instruments Ltd., Shantou, Guangdong, China), and to amplify the received signals. The A-mode ultrasound signal was digitized by a high speed A/D converter card with a sampling rate of 150 MHz (Gage CS82G, Gage Applied Technologies, Inc, Canada). 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 2000 and filtered by a 10-400 Hz band-pass analog filter within the amplifier. An electrical goniometer (model XM110, Penny & Giles Biometrics, Ltd., Gwent, United Kingdom) was used to collect the wrist angle signal. The isometric force was detected by a custom-made force sensor with a strain gauge (model KFG-6-120-C1-11, Kyowa Electronic Instruments Co., Ltd., Japan) on one of its arms (Fig. 2). EMG, angle and force signals were digitized by a 12-bits data acquisition card (NI-DAQ 6024E, National Instruments Corporation, Austin, TX, USA) with a sampling rate of 1 KHz in a PC with two 2.33 GHz Intel quad-core and 3.25 GB RAM. The frame rate of A-mode ultrasound was approximately 10 Hz, which was also applied to the data rates of 1-D SMG, EMG RMS, force and angle signals.

During the each test, the number of correctly cancelled letters (N_c), mistakenly cancelled letters (N_m) and skipped letters (N_s) were recorded automatically by the software.

C. Data analysis

1-D SMG was extracted from the position change of the A-mode ultrasound echo reflected from the interface between muscle and bone. A cross-correlation algorithm was employed to track the displacements of ultrasound echo during the movement. The equation used to calculate the normalized one-dimensional cross-correlation is 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 ultrasound signal from the initial frame and $y(j)$ is the selected signal in the updated frame. $\bar{X}$ and $\bar{Y}$ are the means of $x(i)$ and $y(j)$, respectively. It requires a reference signal from an initial frame and would search for the signal most similar to the reference signal for estimating the object position in the updated frame. The A-mode ultrasound echo reflected from muscle-bone interface was selected by a tracking window in the first frame (Fig. 3, a). When the muscle was contracting, its dimensional changes caused variation in distance between the interface of fat-muscle and that of muscle-bone, which would cause the A-mode ultrasound echoes to shift a certain distance. However, the echo reflected from the interface of fat-muscle is weak and its position during movement almost did not change, so in the current study, the displacement of the echo from muscle-bone interface was calculated and was regarded as the muscle thickness change. The percentage deformation of the muscle is defined as

$$D = \frac{(d - d_0)}{d_0} \times 100\% \tag{2}$$

where d_0 is the initial position of the echo reflected from interface of muscle-bone and d is the position of the echo when the muscle is contracting.

The percentage of correctly cancelled letters (P_c) and skipped letters (P_s) were calculated as the following

$$P_c = \frac{N_c}{N_c + N_s + N_m} \times 100\% \tag{3}$$

$$P_s = \frac{N_s}{N_c + N_s + N_m} \times 100\% \tag{4}$$

A paired t-test was used to compare the difference among four signals during both of isometric force control and wrist extension. One-Way ANOVA was also used to determine whether there were any differences in the performances of each signal in the two different strategies. All the data were calculated using SPSS (SPSS Inc. Chicago, IL, USA) and statistical significance was set at 5% probability level.

III. RESULTS

In the isometric force control condition, the overall mean (N=10) number of "E" correctly cancelled, mistakenly cancelled letters and "E" skipped were 48±7, 6±4,1±1 for force signal, for SMG were 35±10 , 7±5 , 1±1, and for EMG were 29±13 , 15±7 , 3±3. In the wrist extension, the corresponding value were 44±10, 7±4,1±1 for angle signal, for SMG were 34±9 , 4±4, 3±3, and for EMG were 30±13 , 19±12 , 4±3. A paired t-test revealed that the percentage of the number of "E" correctly cancelled with force/angle (86.8±5.5%/85.2±7.1%) and SMG signal (82.8 ±13.2% in isometric force control, 82.2±10.9 in wrist extension) was significantly higher than that with EMG (59.0 ±16.3% in isometric force control, 57.1±18.9% in wrist extension) (P<0.05) for both isometric control and wrist extension. There were no significant decreases in the percentage of "E" correctly cancelled between SMG and force/angle for isometric control and wrist extension (Fig. 4). The paired t-test also showed that the number of "E" skipped

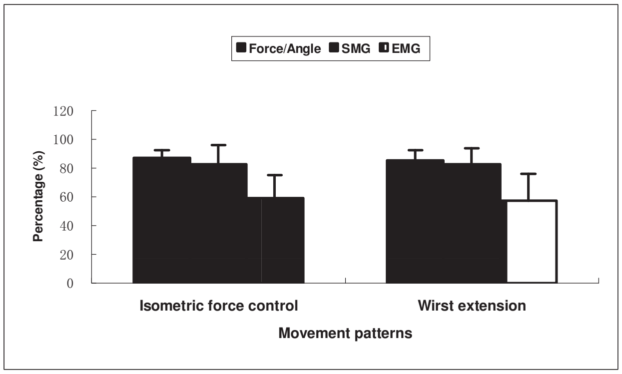

Fig. 4. The percentage of the number of "E" correctly cancelled of each signal (force/angle, SMG and EMG) during the movement of isometric force control and wrist extension.

was not significantly different among all the three signals during the isometric force control. During the wrist extension, the number of “E” skipped of angle signal (1.3±1.6%) was significantly smaller than that of SMG (7.3±8.9%) and EMG (9.3±8.1%) (P=0.015, 0.039) (Fig. 5). There was no significantly difference between EMG and SMG. One-Way ANOVA revealed that there were no significant differences in the performances of each signal under two different strategies (isometric force control or wrist flexion-extension).

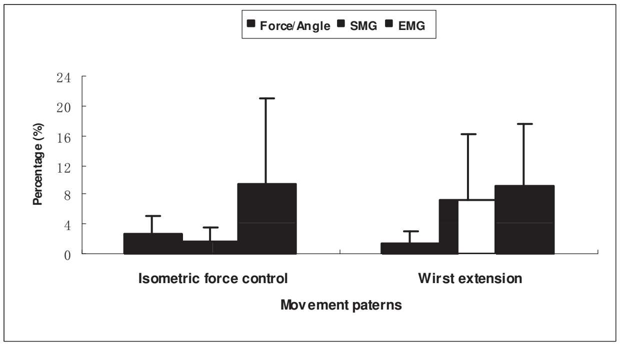

Fig. 5. The percentage of the number of “E” skipped of each signal (force/angle, SMG and EMG) during the movement of isometric force control and wrist extension.

IV. DISCUSSION

In this study, the control performance of force/angle signal, 1D SMG, i.e. real-time muscle thickness change detected using A-mode ultrasound, and EMG was compared during isometric force contraction and wrist extension. The number of “E” correctly cancelled, mistakenly cancelled letters and “E” skipped were recorded to quantitatively estimate the performance among the signals in terms of accuracy. It was found that the percentage of the number of “E” correctly cancelled with force/angle (86.8±5.5%/85.2±7.1%) and SMG signal (82.8±13.2% in isometric force control, 82.2±10.9 in wrist extension) was significantly higher than that with EMG (59.0±16.3% in isometric force control, 57.1±18.9% in wrist extension) (P<0.05) for both isometric control and wrist extension. This may indicate that SMG could perform significantly better than EMG in terms of accuracy both in isometric control and dynamic control (wrist extension). On the other hand, there was no significant difference in the percentage of the number of “E” correctly cancelled between SMG and force/angle for the isometric control and wrist extension. The results suggest that 1-D SMG signal may have potential to be an alternative signal for prosthetic control, and may even offer better control performance.

For the amputee subject, the force or angle signal used in this study could not be used. It has been reported that there is an exponential relationship between EMG magnitudes and the strengths generated by different skeletal muscles [6], [9].Compared with surface EMG, it is found that SMG signals of a skeletal muscle have approximately linear relationships with their corresponding resultant isometric torques [10] or joint angles for isotonic contractions [6]. The result of the present study strongly support that the control test either a isometric or dynamic task could be performed better when the control signal has a linear relationship with the external physiological signal, which is the force signal in the isometric control and wrist angle in wrist extension. The use of 1D SMG may therefore reduce the training efforts when it is used for the control of prostheses. However, the current study only tested on the extensor carpi radialis muscle of able-bodied subjects, the performance of the subjects using SMG from other skeletal muscle is still unknown, and only very limited number of movements were examined. Further studies with both amputee and healthy subjects with various movements are required to examine whether or not this is the case. Furthermore, it is a challenge to firmly attach the A-mode ultrasound transducer to the interesting position.

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