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Comparison of Complexity of EMG Signals Between a Normal Subject and a Patient after Stroke -a Case Study

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Abstract—**An innovative method to quantitatively assess the motor function of upper extremities for post-stroke patients is proposed. A post-stroke patient and a normal subject were recruited to conduct a special performance of voluntary elbow flexion and extension by following a sinusoidal trajectory from 30° to 90° at 6 different peak angular velocities in a horizontal plane. During the tests, the elbow angle and subject's electromyographic (EMG) signal (biceps brachii and triceps brachii) were recorded simultaneously. Fuzzy approximate entropy (fApEn) was applied to analyze the EMG signals. The results showed observable differences in fApEn when the control and the patient (unaffected and affected arms) were compared, and an uptrend of fApEn was detected with the increase in the tracking velocities in both the normal individual and patient (unaffected and affected arm). The fApEn values, which are a measure of complexity of EMG, could be used for the quantitative evaluation of the deficiencies of motor control induced by stroke.**

I. INTRODUCTION

In many countries, stroke is a major cause of death and disability. It has been reported nearly 800,000 Americans experience a stroke each year [1], and the number is over 7 million in China[2]. Intensive therapeutic interventions have been shown to have a positive effect on neurological recovery of limb motor functions [3]. During the process of therapy and rehabilitation，a method of evaluation is needed to help designing more appropriate treatment strategies. As yet, clinical scales are widely applied to clinical evaluation. However, the clinical scales are semi-quantitative evaluation method, which is not sensitive enough to reflect local change. To assess the motor units deficiency of affected muscles extremities quantitatively, some methods to quantify the deficit for passive mechanical properties of the affected joints in subjects after stroke have sought to been presented such as: haptic robot-based writing task [4], jagged trajectory tracking movement [5], and target point reaching test [6].

The Electromyography (EMG) signal is currently widely used in several fields such as physiological muscle assessment, muscle metabolic activity, functional electrical stimulation and so on [7]. As a kind of physiological signals, the EMG signal is a complicated signal that measures electrical currents generated in muscles during its contraction representing neuromuscular activities [8]. Furthermore, the EMG signal is nonlinear and even chaotic which is more suitable to be analyzed by nonlinear method, Gupta et al. used the fractal dimension characterize the EMG signal of flexion-extension with load [9], and Dingwell and Cusumano used Lyapunov index to analyze the EMG of lower extremes during walking [10]. Though these nonlinear measures have achieved some success in quantifying EMG signals, a very large dataset is usually necessary in order to attain reliable and convergent values in calculation. In comparison with them, fApEn (fuzzy approximate entropy), which is a measure of time series complexity first presented by Chen et al. in 2007 [11] combining the concept of "fuzzy sets" introduced by Zadeh [12] and approximate entropy developed by Pincus [13], were more robustness to noise when characterizing signals with different values, and it had achieved many merits in recognizing different motions [11] and detecting muscle fatigue [14]. By importing the concept of fuzzy sets, the fApEn shows less dependence on the data length , stronger relative consistency and more robustness to the noise. Futhermore, the fApEn can achieve better estimation on the short experimental data [11].

In this study, we designed a velocity-dependent elbow target tracking experiment, aiming to compare the fApEn of EMG signals of muscles in upper arm during voluntary elbow flexion and extension between the dominant side of a normal subject, the affected arm and unaffected arm of the patient following a stroke.

II. METHOD

A. Subjects

A healthy volunteer (male, 19 yrs, dominant side: right) without known neurological or orthopedic deficiencies and a patient with chronic stroke (male, 57 yrs, affected side: right) were recruited in the study. The subject selection criteria for patient were as follows: (1) hemiparesis resulting from a single unilateral lesion of the brain with onset at least 6 months before data collection; (2) the subject must be able to generate voluntary contraction, biceps and triceps muscles of affected side should have measurable EMG; (3) the subject's residual active elbow range of motion must be meet the experimental requirement (30° -90°); (4) the subject should not have visual, cognitive, or attention deficit, which would prevent them from following the experimental procedures.

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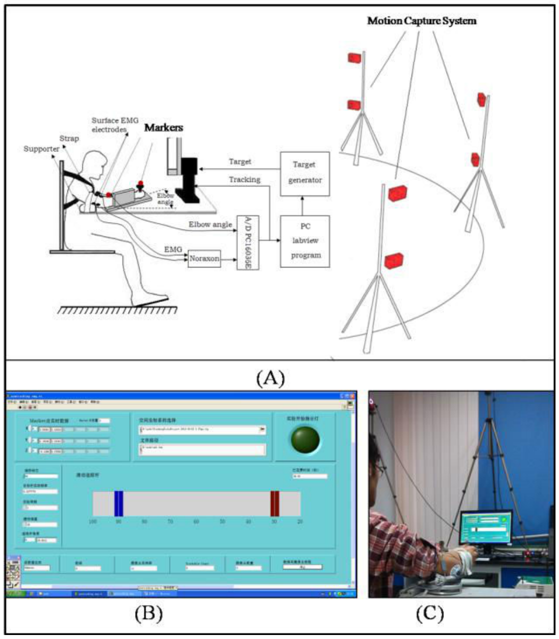

Fig. 1 (A) Schematic diagram of the experiment setup; (B)the interface of feedback; (C) the normal subject under test.

B. Experiment setup

The experiment setup was shown in Fig.1. During the experiment, the subjects were instructed to sit beside the table with a manipulandum, which was suitable for the subject to rest the arm in the horizontal plane with the same height as that of the shoulder, and the shoulder was in 90° of abduction and 45° of horizontal flexion. The upper arm was fixed to the supporter on the table, while the forearm was attached to a manipulandum with the axis of rotation in line with the elbow joint. In front of the subjects, there is a computer screen was settled to display both the target and the actual elbow angle by the Labview software.

The coordinates of the makers attached to the manipulandum was captured by a motion capture system (OptiTrack, NaturalPoint, USA), and the angular displacement of the elbow joint of the normal subject can be calculated by the coordinates of the makers, which were attached to the elbow joint and the end of the manipulandum respectively (a flexible electrogoniometer (Penny & Giles, UK) was used for the measurement of actual elbow angle for the patient). A tele-EMG system (MyoSystem1400, Noraxon, USA) with a bandwidth of 10-500 Hz per channel was used to capture and amplify the surface EMG signals from two selected upper-arm muscles: biceps brachii and medial triceps brachii. The surface EMG signals were captured with Ag/AgCl surface electrodes (Noraxon, USA), which were placed in bipolar configuration with a 2 cm space between the centers of the electrodes. The angle signal and EMG signals from biceps brachii and medial triceps brachii were recorded simultaneously and were stored in a PC via a 16-channel A-D converter for off-line analysis (PCI 6036E, National instrument, Texas, USA).

C. Procedure

Before the test, the subjects were introduced to the experimental protocol. Then, the subjects were instructed to sustain the elbow at 30 deg flexion (elbow angle was defined as 0°when the elbow is in full extension), After a random delay generated by the software with the range of 2 to 8 sec, the indicator light on the screen turned green and the target pointer began to move along the horizontal line in a sinusoidal trajectory between 30 deg and 90 deg at the same time, and each trial lasts 36 seconds. The subjects were told to try their best to follow the moving target pointer by flexing or extending their elbow joint. The actual elbow angle was also displayed in another pointer as the real-time feedback. Then, each subject was administered 18 trials structured in three blocks. Each block consisted of six trials with different velocities, which were arranged in a random sequence. In each trial, subjects were ask to complete different number of cycles (3, 6, 8, 12, 15 and 18 cycles) of sinusoidal trajectory of flexion and extension movements in 36 seconds resulting in six different peak velocities (15.7, 31.4, 47.1, 62.8, 78.5, and 94.2 deg/s, respectively). The main goal is to track the target as close as possible to minimize the error. The subjects had a 30-second and 5-minute rest time between each trial and block respectively. For the patient the task was performed on both the affected and unaffected arms and for the normal subject, the task was performed on his dominant side.

D. Fuzzy Approximate Entropy

Based on the approximate entropy [11], the algorithm of fApEn was developed by importing the concept of 'fuzzy sets'. The most significant purpose of fApEn was to assess the complexity of signals. Here, we used it on the sEMG signals aiming to detect the different complexity of EMG between the normal and post-stroke subjects.

The processed raw EMG signals of both biceps brachii and triceps brachii were reconstructed to high-dimensional vectors and analyzed by the algorithm of fApEn as follows:

Given an N samples time series $\{u(i):1\le i\le N\}$, a new vector sequences can be formed:

$$X_i^m = \{u(i),\cdots,u(i+m-1)\} - \frac{1}{m}\sum_{j=0}^{m-1}u(i+j) \tag{1}$$

In which X_i^m represents m consecutive u values, commencing with the ith point.

Then, the definition of distance between X_i^m and X_j^m is:

$$d_{ij}^m = \max_{k\in(0,m-1)} \left|u(i+k)-u_0(i)-u(j+k)+u_0(j)\right| \tag{2}$$

The similarity of the two vectors is defined through a fuzzy function:

$$D_{ij}^m(n,r) = \exp(-(d_{ij}^m / r)^n) \tag{3}$$

Then the function ϕ^m aggregated the similarity from any vectors in the time series to another:

$$\varphi^m(n,r) = \frac{1}{N-m}\sum_{i=1}^{N-m}\left(\frac{1}{N-m-1}\sum_{j=1,j\ne i}^{N-m} D_{ij}^m\right) \tag{4}$$

Finally, fApEn (m, n, r) is estimated by the algorithm of the difference between the function of length m+1 and m.

$$fApEn(m,n,r,N)=\ln\varphi^{m}(n,r)-\ln\varphi^{m+1}(n,r) \qquad (5)$$

The related parameters in the estimation of fApEn such as the number of data point in selected window- N, the length of sequences to be compared- m, and the tolerance window r determine the final value of fApEn.

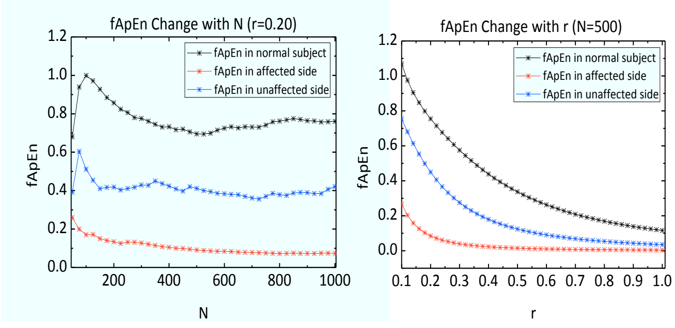

Fig.2 The performance of triceps EMG ApEn during elbow extension in the velocity of 31.4deg/s for the subjects with N and r increased.

In this study, we chose N=500, r=0.2*SD and m=2 which coincide with other studies [14] and determined by the test result in fig. 2 as well.

III. RESULT

Fig. 3 showed the actual trajectory from the healthy subject and the patient of both unaffected and affected sides. It is obvious that the one from the control was the smoothest of the three, and the one from the affected side held the worst tracking result. Furthermore, the amplitude of triceps EMG from the both sides of patient was larger than that from the healthy subject. After an amplification of 8000 times, the amplitude of triceps EMG kept in a high level at nearly 0.1V (unaffected side) and 0.15V (affected side), while the level from the normal subject was much smaller at 0.035V during elbow extension.

As Fig. 4 shown, the fApEn of both biceps EMG during flexion period and triceps EMG during extension period between the control, affected arm and unaffected arm were observably different in all six angular velocities. The fApEn values from the healthy individual were higher than it from the patient of both sides, and the fApEn of EMG from affected side were the lowest in blue. What is more, there was a rising trend of fApEn with increasing tracking velocity in three groups (the normal subject, the affected and unaffected arms)

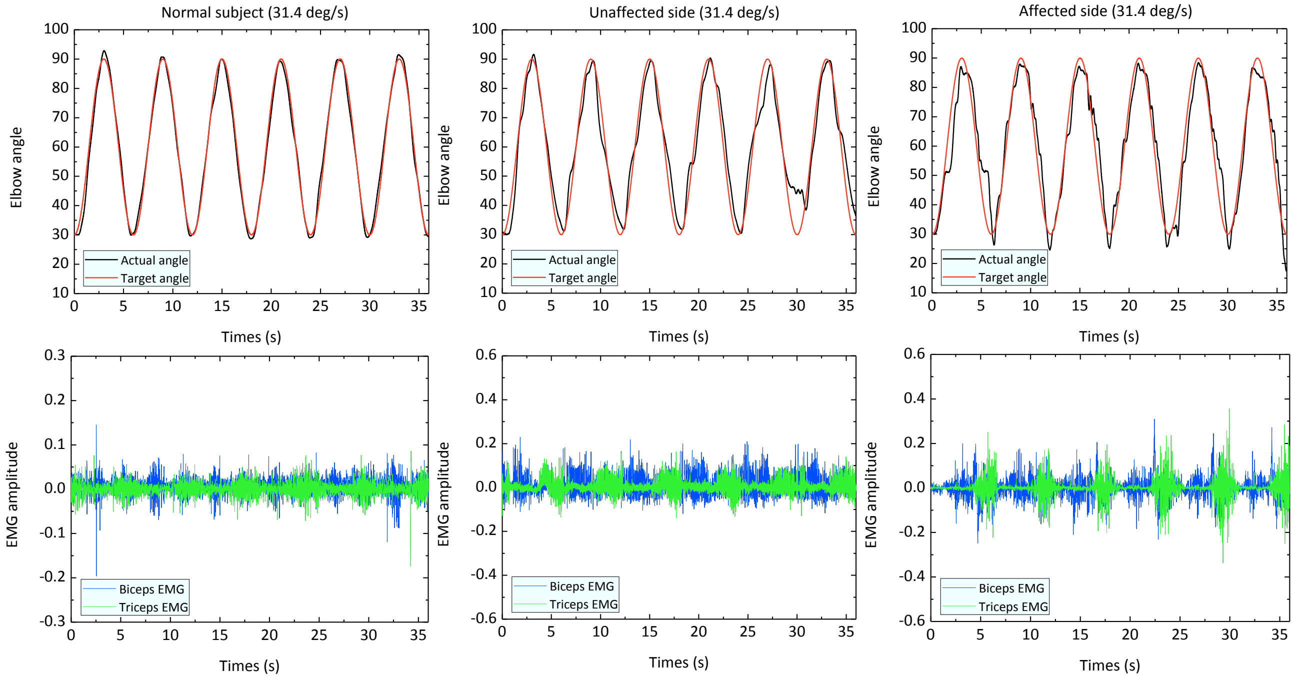

Fig.3 The target angle and the actual angle (above), the biceps EMG and triceps EMG (below) of the normal subject and patient in both unaffected side and affected side at a velocity of 31.4 deg/s.

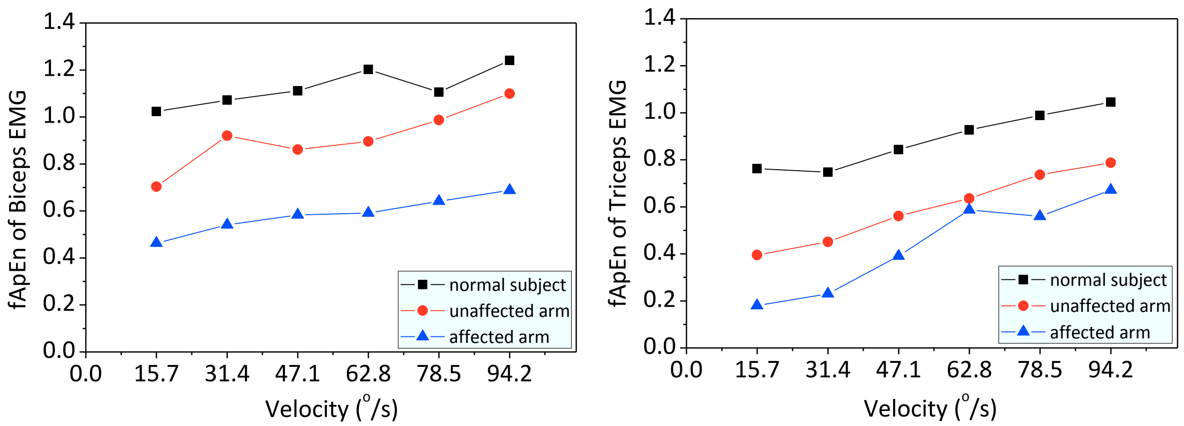

Fig.4 The fApEn of biceps EMG during flexion (left) and triceps EMG during extension (right) in the normal subject and the patient of both affected and unaffected arms at different angular velocities.

IV. DISCUSSION

The difference of fApEn values between the normal individuals and the patients after a stroke may result from the damage in the motor cortex. Rosenfalck et al. reported that the number of motor units activated and the firing rate of motor units decreased in patients after stroke [15], which may cause the decrease of EMG complexity. Thus, further investigation is needed to detect the mechanisms underlying the reduction of complexity in EMG of muscles from the individuals with stroke. The findings in this study has potential clinical value for evaluating the motor units' characteristic of paretic muscles during the process of rehabilitation after stroke, in addition, the difference of fApEn values between the healthy subject and the patient could be applied to assist the establishment of evaluation criterion clinically.

In this paper, a comparative case study has been reported to put forward a new measurement to understand the stroke -induced neurological change. Future work is desired to prove the stability of it on a larger number of subjects.

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