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Surface electromyography analysis of blepharoptosis correction by transconjunctival incisions

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ABSTRACT

Upper eyelid movement depends on the antagonistic actions of orbicularis oculi muscle and levator aponeurosis. Blepharoptosis is an abnormal drooping of upper eyelid margin with the eye in primary position of gaze. Transconjunctival incisions for upper eyelid ptosis correction have been a well-developed technique. Conventional prognosis however depends on clinical observations and lacks of quantitatively analysis for the eyelid muscle controlling. This study examines the possibility of using the assessments of temporal correlation in surface electromyography (SEMG) as a quantitative description for the change of muscle controlling after operation. Eyelid SEMG was measured from patients with blepharoptosis preoperatively and postoperatively, as well as, for comparative study, from young and aged normal subjects. The data were analyzed using the detrended fluctuation analysis method. The results show that the temporal correlation of the SEMG signals can be characterized by two indices associated with the correlation properties in short and long time scales demarcated at 3 ms, corresponding to the time scale of neural response. Aging causes degradation of the correlation properties at both time scales, and patient group likely possess more serious correlation degradation in long-time regime which was improved moderately by the ptosis corrections. We propose that the temporal correlation in SEMG signals may be regarded as an indicator for evaluating the performance of eyelid muscle controlling in postoperative recovery.

1. Introduction

Blepharoptosis or ptosis, which is a congenital, acquired, or age-related drooping of the upper eyelid, results from dysfunction of the levator aponeurosis. For healthy individuals, the upper eyelid covers around 1.0–1.5 mm of the superior part of the cornea when the eye is open. For patients with blepharoptosis, the amount of cornea covered by the upper eyelid varies, resulting in visual disturbances and cosmetic problems. Surgery to correct the ptosis, which is one of the most common facial rejuvenation procedures (Sakol et al., 1999), is the most effective treatment for blepharoptosis (Lai et al., 2013; Smith et al., 1969).

Transcutaneous (Waqar et al., 2010) and transconjunctival (Patel and Malhotra, 2009) incisions are two methods that are used in blepharoptosis correction surgeries. The main difference between the two methods is that the orbicularis muscle is disrupted with the transcutaneous incision. The basic concept of the correction is to strengthen the levator aponeurosis by shortening Müller's muscle and advancing and fixing the levator aponeurosis to the tarsal plate (Ichinose and Leibovitch, 2010; Patel et al., 2010). Normally, the closure and elevation of the upper eyelid automatically maintains the balance. However, if the levator aponeurosis is strengthened by shortening it with the transcutaneous procedure, the orbicularis is weakened, and the balance is

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disrupted, which may result in lagophthalmos. In contrast, if the levator aponeurosis is strengthened with the transconjunctival procedure, the orbicularis muscle is kept intact and unaltered. Hence, the transconjunctival approach has the advantages of shorter recovery time, less postoperative swelling, and nearly no or faster-recovering lagophthalmos immediately after the surgery (Ichinose and Tahara, 2007). Because we were familiar with ptosis correcting surgeries that involve the transconjunctival approach, this study was conducted with the transconjunctival approach.

Although surgical corrections of upper eyelid ptosis have been common and effective since 1806 (Beard, 1986; Servat and Mantilla, 1986), the prognoses of the patients generally rely upon clinical observations and lack definite and quantitative preoperative and postoperative descriptions of the eyelid muscles and their postoperative recoveries. The electrooculography (EOG) is used in recording of eye movements, which involve most of the muscles around the eyeball (Fuchs and Luschei, 1970). It is not designated for specified muscles related to eyelid closure and opening. For the evaluation of blepharoptosis correction that involves the orbicularis oculi muscle and the levator aponeurosis with the Muller's muscle, it is ideal to use surface electromyography (SEMG) (Ban et al., 2010; Gorkovenko et al., 2012) rather than EOG. Therefore, we performed a SEMG data analysis of upper eyelid ptosis corrections that involved transconjunctival incisions in order to objectively and quantitatively assess the improvements in eyelid muscle control. Eyelid SEMG signals are recordings of the electrical signals on the eyelid surface that measure the activities of Müller's and the orbicularis muscles. These signals result from the many action potentials that are involved in muscle force generation. The electrical activity of a muscle starts before the generation of force occurs and can be detected by SEMG recordings before the onset of the movement (Evinger et al., 1991; Holobar et al., 2014; Yun et al., 2014). Because the frequency distribution of the eyelid SEMG signals are not as simple as a special class of noise like $1/f$ (see Section 3), a time series analysis approach beyond a Fourier spectrum analysis was needed for this study. Based on the assumption that effective and efficient muscle control of eyelid closure and opening involves specific intrinsic properties in the SEMG signals, muscle functionality was evaluated in this study by analyzing the temporal correlations in the recorded time series with the detrended fluctuation analysis (DFA) (Peng et al., 1994).

DFA is a method that was developed for analyzing complex time series data and that is especially useful for data representing the dynamics of complex systems. Biomedical systems are complex dynamical systems that consist of a group of constituents (subsystems) that usually interact among one another through feedback. The DFA method detects intrinsic correlations in a signal by measuring the fluctuations of the signals with respect to local trends in a scale window. Because this method is free of models and easy to implement, it has been successfully applied to data analysis in a wide variety of problems in physical, engineering, medical, and social sciences and has specifically examined a number of biomedical signals, such as heartbeats (Peng et al., 1995) and sleep electroencephalography (D'Rozario et al., 2013); biological data, such as DNA sequences (Peng et al., 1994); and financial data, such as stock market indices (Wu, 2012). Thus, the use of DFA was suitable to examine our hypothesis that young and aged normal subjects and patients have distinct temporal correlations in their eyelid SEMG recordings.

2. Patients and methods

This study, which was a retrospective study that was based on clinical data on upper eyelid ptosis corrections, was approved by the Mackey Memorial Hospital Institutional Review Board (IRB No. 13MMHIS262).

2.1. Test protocols

The SEMG examination was standardized and performed by one technician. The procedure was explained to the subjects before the test started. The patients were selected as candidates for the SEMG examination before the surgery if they did not have the following conditions: previous eyelid surgery, myasthenia gravis, HIV (+), pregnancy, or age less than 18 years. A patient with blepharoptosis was examined if 2–5 mm of his/her upper limbus was covered by the lid margin. A normal subject had less than 1.5 mm of his/her limbus covered by the lid margin. The SEMG measurements were actively recorded by two channels with two electrode tapes (0.5 cm × 0.5 cm) that were placed beneath the surfaces of each subject's left and right lateral eyebrows (Bailey et al., 2009; Schumann et al., 2010; Tassinary and Cacioppo, 2000), two electrode tapes that were placed on the ipsilateral cheek for reference recording, and one electrode tape that was placed on the chin as a ground (see Fig. 1). The cables were immobilized with tape. The subjects lay in a supine position during the SEMG. Test signals were collected by the technician to confirm that the electrodes were adhered correctly, and then the examination was performed normally. Next, each subject was asked to close his/her eyelids three times for 15 s each and then open his/her eyelids three times for 15 s each while gazing frontally. The same procedures were applied to all of the subjects.

2.2. Subjects

Thirteen patients who underwent surgery for blepharoplasty between November 2011 and December 2014 were involved in the study. Four of the 13 patients agreed to be in the study, while the other nine patients did not desire to undergo the examinations or the rehabilitation facility was not available during those periods. Eyelid SEMG (Fig. 1) recordings were performed with the eyes open and closed in the four patients with blepharoptosis and in six young and six aged normal subjects without ptosis. A transconjunctival

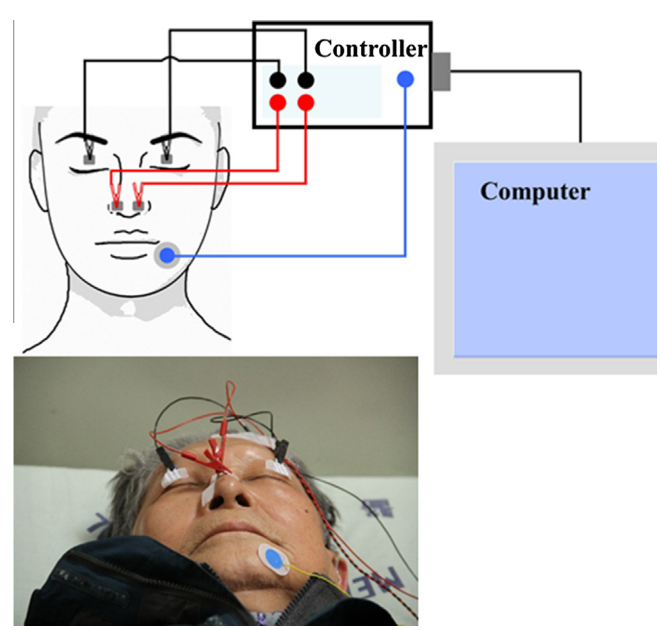

Fig. 1. Experimental setup for the eyelid surface electromyography (SEMG) recordings. Black: point of active recording. Red: point of reference recording. Blue: point of ground. The recording was implemented with an EMG recorder with a sampling frequency of 31.95 kHz for two channels with 16-bit precision and noise level <6 μV. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

approach through Müller's muscle was performed on six eyelids of four patients with upper eyelid ptosis (one female and three males; 35–79 years old; mean age, 57 years). Patient 1 (56 years old) and patient 2 (79 years old) had ptosis corrections only on their right eyes, and patient 3 (39 years old) and patient 4 (52 years old) had operations on two eyes. The 12 eyelids of the young normal subjects (three females and three males; 26–33 years old; mean age, 30 years) and the 12 eyelids of the aged normal subjects (four females and two males; 52–86 years old; mean age, 73 years) were considered the control group.

2.3. Surgical procedures

The patients was placed in a supine position and locally anesthetized with 1% xylocaine and 1:200,000 epinephrine. The solution was injected subcutaneously with a 27-gauge needle in the eyelid and conjunctiva along the superior region of the tarsal plate. Gentle diathermy was applied first above the superior border of the tarsus. Müller's muscle and conjunctiva were dissected off as a composite flap with one-third of the lateral part left intact. The levator aponeurosis was dissected upward, and adequate length of the aponeurosis was excised according to the degree of ptosis and function of the levator. The levator was advanced downward and fixed to the superior margin of the tarsus with a continuous suture with 6-0 polydioxanone. Double-eyelid blepharoplasties were done before the conjunctiva was repaired with a 7-0 Vicryl (polyglactin 910) buried suture (Ichinose and Tahara, 2007). Lagophthalmos was not immediately observed or was only temporarily found in the patients after the operations, and the patients were followed for 2 months.

2.4. SEMG recordings

The SEMG data were recorded as a time series with an EMG recorder (Sierra Wave, Cadwell, Kennewick, WA, USA; max sampling frequency, 78.6 kHz) with a sampling frequency of 31.95 kHz per channel with 16-bit precision for a 200-ms period. The experimental setup and the parameter settings of the EMG recorder are shown in Fig. 1. Among the four patients, patients 1 and 3 were examined with SEMG once before and after the operation, and patients 2 and 4 were examined once preoperatively and twice postoperatively. Each young normal subject was examined once, while each aged normal subject was examined three times and then averaged. Thus, there were 34 recordings; each had 2×2 data per time point (left and right eyes, eye open and closed) and 6400 time points. The raw data of the SEMG signals consisted of the potential difference between the active electrode and the reference electrode. Due to the transmission of electric potential through the skin surface and the effects of the dynamic relationships among the muscles, the reference recording might not have been zero or symmetric to zero. Thus, the baseline SEMG signals might have drifted during the measurements. Such drifting was irrelevant and had no effects on our DFA analysis. Besides, conscious movements of the subjects have been excluded by the technician, and unconscious movement artefacts (if there were) in SEMG signals were not pre-processed, since unorganized movement artefacts have no effects on our DFA analysis and organized movement artefacts cause a trackable plateau in our DFA plot (see next subsection) and we have never seen it in our analysis. Typical raw SEMG signals for the young and aged normal subjects and a patient's left eye are shown in Fig. 2. Note that noises in these data are indefinite but essentially exist in low frequency regime. Using the empirical mode decomposition (Huang et al., 1998; Wu and Hu, 2006) to adaptively separate signal and noise, the signal to noise ratio (SNR) of the data estimated through the standard algorithm based on signal power is larger than 25 dB.

2.5. DFA analysis of the SEMG data

The SEMG data were analyzed with the DFA (Peng et al., 1994) method. In brief, muscle contractions are functionally oriented, and the SEMG signals contain intrinsic correlations that can be assessed with the DFA. The DFA calculates the fluctuations f of a time series $x(t)$ in different scales according to the method described by Peng et al. (1994):

$$f(n) = \sqrt{\frac{1}{T}\sum_{t=1}^{T}[x(t) - x_n(t)]^2} \sim n^{\alpha},$$

where n is a scale factor for resampling $x(t)$, T is the data length, and $x_n(t)$ is the best fit of the data of $x(t)$ in a moving window of size n. The slopes of the linear regimes in the plot of f vs. n on a log–log scale are characterized by the index α. Basically, the α values of 0.5, 1.0, and 1.5, respectively, correspond to random walk, $1/f$ noise, and Brownian motion. The $0.5 < \alpha < 1.0$ values represent persistent behavior, while the $1.0 < \alpha < 1.5$ values indicate negative correlations in the signal.

In this study, we noted that, by definition, the time series $x(t)$ is a fractional Brownian motion that consisted of a sequence of walks or steps. Such a situation is generally valid for its primary application on tick-like data, such as DNA sequences (Peng et al., 1994) and heartbeats (Peng et al., 1995). For SEMG data, there is no such tick that is to be defined through the system. Instead, it is recorded in a fixed sampling time interval. From the viewpoint of the overall electric potential, its properties are more similar to motion than to walks. Thus, in this study, the raw data were used as the input $x(t)$.

Muscle control is a process that consists of motor neuron stimulation and muscle contraction, which is generally characterized by excitation of an action potential for force generation, which is followed by subsequent repetitive excitations for force sustainability. The waiting time for a subsequent excitation is a function of the duration of an action potential and the excitability of the muscle fibrils to which the branches of the motor neuron are attached. These set a characteristic time scale in the DFA plot of eyelid SEMG recordings. Below this time scale, effective and efficient muscle control is expected to manifest negative correlations in SEMG recordings, which depict the coordinated responses of sequential neural firings and feedbacks. Above this time scale, the temporal correlations reflect the properties of sequential action potentials that are relevant to muscle force substantiality. Accordingly, we assumed that changes in the properties of temporal correlations suggest a correlation degradation that gradually formed in the eyelid muscle control of the aged normal group and that became a serious degradation that corresponded to control failure in the patient group. Thus, measuring the DFA index of an eyelid SEMG time series was a way to evaluate the cooperative performances of associated muscles.

2.6. Statistical analysis

The statistical analyses were performed with the basic functions of Excel for Windows. The statistical averages of the DFA α index values of the subjects in a particular group were calculated relative to the sample size of the group. Student's t-tests were used to calculate the p values of the group differences when using a particular group distribution as a reference. P values less than 0.05 were considered significant.

2.7. Repeatability of the measurements

The SEMG examinations can be performed with any standard EMG recorder with a sufficiently high sampling frequency (e.g., 31.95 kHz in this study). The DFA analysis can be conducted with

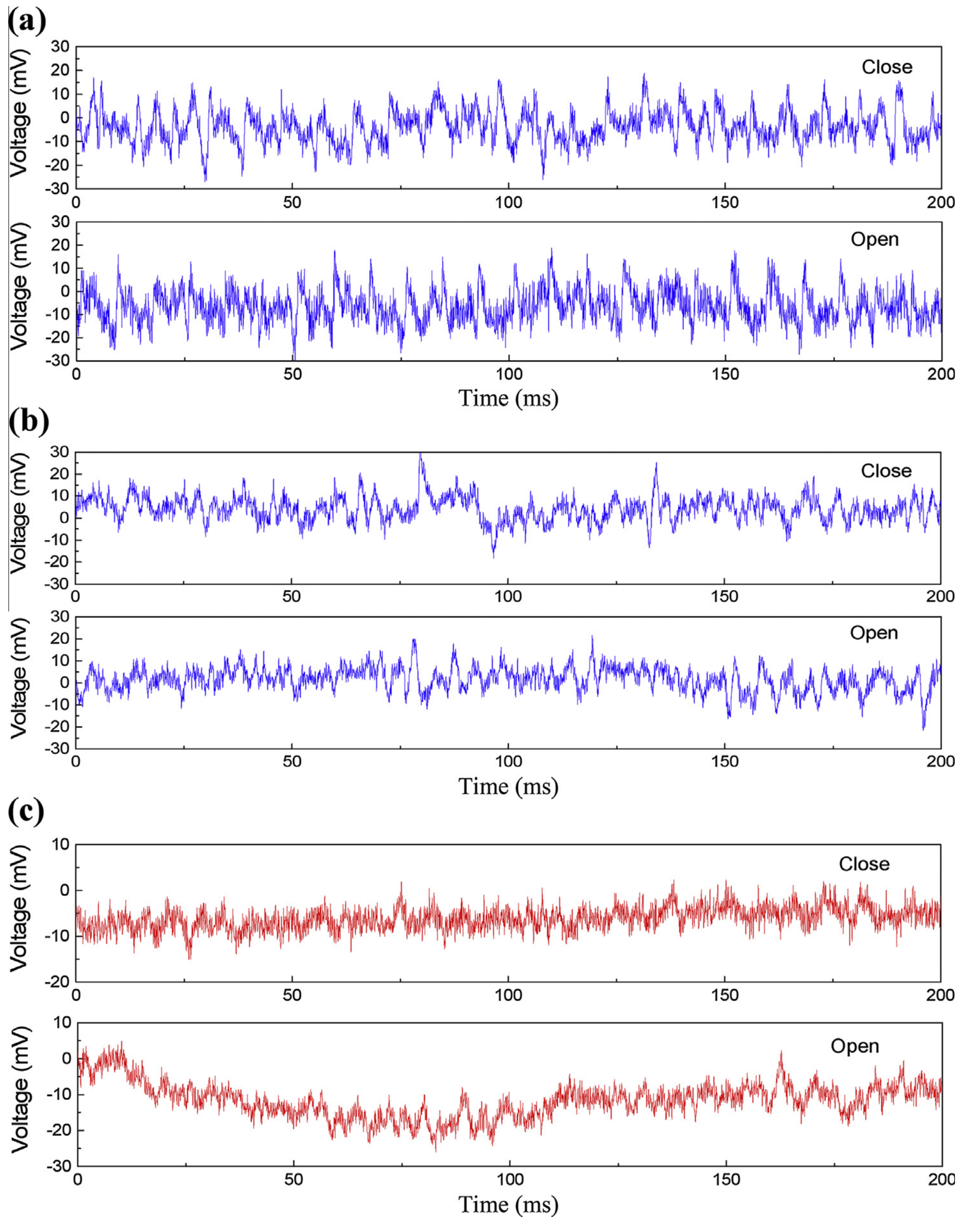

Fig. 2. Typical raw SEMG signals of open and closed left eyes of (a) a young normal subject (SNR, 28 dB), (b) an aged normal subject (SNR, 27 dB), and (c) a patient (SNR, 28 dB).

a program with dfa.c source code, which is available to the public at PhysioNet (http://physionet.org/). The repeatability of the average DFA α index values was associated with the distribution of the index values of a particular group. For sample sizes of no more than 12 eyes, a moderate standard deviation (see Table 1) appeared to be acceptable.

3. Results and discussion

Before the DFA analysis, we performed a Fourier power spectrum analysis on the eyelid SEMG data to explore the frequencies and general properties of the signals, and the results for a young normal subject, an aged normal subject, and a patient are shown in Fig. 3. These results confirmed that the eyelid SEMG signals did not belong to a simple signal class, such as $1/f$ noise. A more sophisticated analysis method, such as the DFA, was needed in this study.

The DFA for a typical young normal subject is shown in Fig. 4. In Fig. 4(a) for the closed left eye, the log–log curve of $f(n)$ vs. n was described by two slopes: $\alpha_1(=1.27)$ for the scale less than 3 ms (about 100 data points) and $\alpha_2(=0.65)$ for the scale longer than 6 ms (about 200 data points). For the open eye, the analysis showed $\alpha_1 = 1.33$ and $\alpha_2 = 0.52$). Similar results for the right eye are shown in Fig. 4(b). All of the cases showed the same inflection point at 3 ms.

The same analysis was applied to the aged normal subjects, and the same inflection point at 3 ms was observed on the log–log plot of $f(n)$ vs. n (see Fig. 5). The α_2 value was relatively larger in this case with respect to no substantial difference in α_1 between the aged and young normal subjects.

A patient's results are shown in Fig. 6. Similarly, the log–log plot of $f(n)$ vs. n had an inflection at 3 ms, thus defining the α_1 and α_2 indices. The α_2 value was larger than those of the young normal subjects for both the left and right eyes and especially for the open eye, and these results were similar to those of the aged normal

Table 1
The average preoperative and postoperative α index values of the normal subjects and patients in the detrended fluctuation analysis (DFA). Student's *t*-tests show that young normal, aged normal, and preoperative and postoperative patients were generally distinguishable by using a DFA α index value of a particular group as a reference (R). *P* values less than 0.05 were considered significant and are indicated with an asterisk (*). See main text for details.

		Normal		Patients	
		Young	Aged	Before operation	After operation
Closed-eye	$\langle\alpha_1\rangle$	1.34(±0.14)	1.17(±0.21)	1.36(±0.12)	1.21(±0.17)
	p value	R	0.012*	0.758	0.494
		0.758	0.022*	R	0.841
	$\langle\alpha_2\rangle$	0.55(±0.09)	0.66(±0.16)	0.85(±0.13)	0.82(±0.19)
	p value	R	0.021*	0.031*	0.066
		0.031*	0.395	R	0.464
Open-eye	$\langle\alpha_1\rangle$	1.37(±0.11)	1.12(±0.19)	1.35(±0.13)	1.31(±0.21)
	p value	R	0.042*	0.772	0.028*
		0.772	0.161	R	0.049*
	$\langle\alpha_2\rangle$	0.52(±0.12)	0.67(±0.20)	0.76(±0.19)	0.65(±0.22)
	p value	R	0.076	0.013*	0.011*
		0.013*	0.090	R	0.362

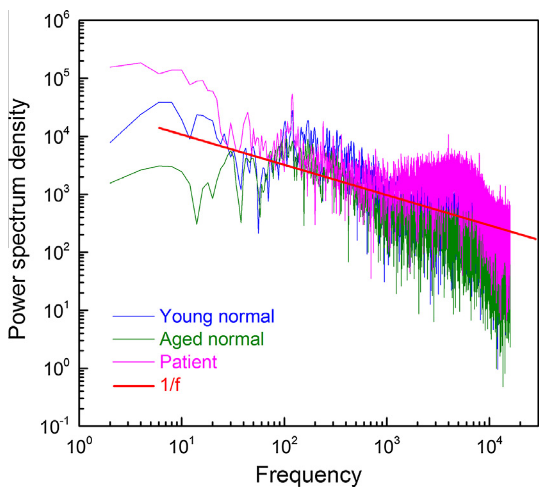

Fig. 3. Log–log plot for the Fourier power spectrum density analysis of typical SEMG signals of open right eyes of a young normal subject, an aged normal subject, and a patient. A 1/*f* noise case is shown for reference.

subjects. Note that $\alpha_2 \approx 0.5$ for the young normal subjects indicated random-like control behavior on scales longer than 6 ms. Because the shortest neuron response time is about 3–4 ms, this feature implied that the control of muscle activity through the neural system functioned well at this time scale in young normal subjects such that the corresponding SEMG signals were unorganized ($\alpha_2 \approx 0.5$) and relatively less energy was consumed. This suggested that if an eyelid is opened or closed with effective muscle force, then the eyelid at the correct position does not need to have a persistent force for support. Instead, a random-like control behavior that is due to detection-associated activity can be observed. Thus, this case was expected to consume less energy than those with persistent force signals. In contrast, persistence in the SEMG recordings for long time scales in the patients ($0.5 < \alpha_2 < 1$) indicated that the sustainability of the muscles was lost and that more energy was needed for controlling the correlated excitation of action potentials. In order to determine whether the index values were specific for distinct groups, we determined the statistical average of the DFA α index values of the subjects in a group with respect to the sample size of the group. The average DFA α index values for all of the eyes from the young and aged normal groups and the patient group from before and after the operations are summarized in Table 1 and plotted in Fig. 7. For the closed eye, the short time-scale temporal correlation, which was represented by $\langle\alpha_1\rangle$ from 1.34 ± 0.14 in the young normal group (sample size: 2 × 6 eyes) to 1.17 ± 0.21 in the aged normal group (2 × 6 eyes), and the long time-scale temporal correlation, which was represented by $\langle\alpha_2\rangle$ from 0.55 ± 0.09 to 0.66 ± 0.16, were significantly degraded. Although the preoperative patients had an $\langle\alpha_1\rangle$ value (1.36 ± 0.12) that was compatible to the young normal group (2 × 4 eyes), their $\langle\alpha_2\rangle$ value (0.85 ± 0.13) was larger than that of the aged normal group and much larger than that of the young normal group. The same situation was observed in the open-eye cases. Remarkably, the ptosis corrections did not significantly change the individual α_1 and α_2 values but substantially decreased the $\langle\alpha_1\rangle$ and $\langle\alpha_2\rangle$ values in the postoperative SEMG recordings (see Table 1).

In summary, we observed in the eyelid SEMG analysis that (a) aging caused degradation of the temporal correlations in both short and long time-scales, (b) patients with blepharoptosis mainly suffered from degradation of the temporal correlations in the long-time scale, and (c) ptosis correction improved the temporal correlation degradations in the long time-scale. These results showed that the degradation of the correlations in the long time-scale that was represented by $\langle\alpha_2\rangle$ was more relevant to blepharoptosis, implying that the properties of the sequential action potentials after force generation, which are responsible for the muscle sustainability for a particular eyelid state, were a key feature. More specifically, the $\langle\alpha_2\rangle$ values around 0.5 in the young normal group were assumed to represent no degradation, while the values around 0.85 in the patient group were considered pathological. The in-between $\langle\alpha_2\rangle$ value in the aged normal group represented some degradation. Because the $\langle\alpha_2\rangle$ values were statistical results, we cannot explicitly define a precise range of $\langle\alpha_2\rangle$ for each group at this time because of the limited number of subjects in each group. Remarkably, because the eyelid elevation muscles are not effective in patients with blepharoptosis, their eyelid closure muscles might also not be effective. We therefore propose that ptosis corrections modify the eyelid elevation mechanical properties of the levator aponeurosis and Müller muscles, which is similar to changing the spring constant of a stretched spring, such that the eyelid movements are more effective and efficient. In addition, ptosis corrections do not substantially change the properties of the orbicularis oculi muscles that are associated with eyelid closure but rather improve their effectiveness by changing the amount of effective movements. These features were reflected by the significant changes in $\langle\alpha_2\rangle$ that occurred as a result of the ptosis corrections.

Accordingly, the DFA assessments of the temporal correlations were able to significantly differentiate the young and aged normal groups and the patient groups by properly choosing a DFA α index of a particular group as a reference in the Student's *t*-test (see Table 1). Specifically, the four groups of young normal, aged

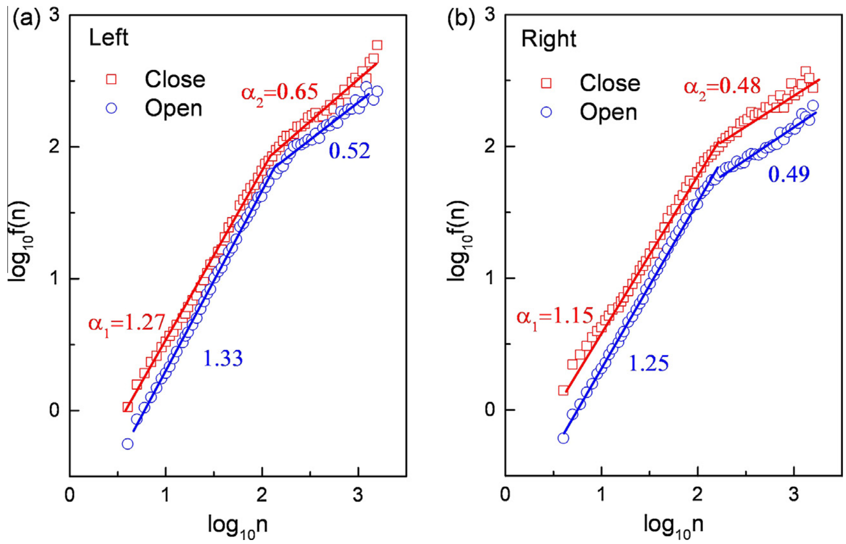

Fig. 4. The detrended fluctuation analysis (DFA) of a typical young normal subject. (a) Left eye. (b) Right eye. The α values were determined by linear fitting.

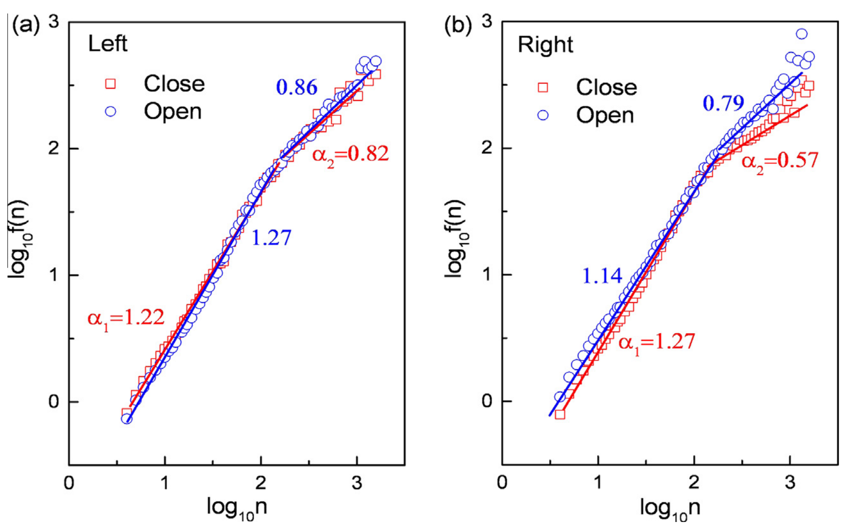

Fig. 5. DFA of a typical aged normal subject. (a) Left eye. (b) Right eye.

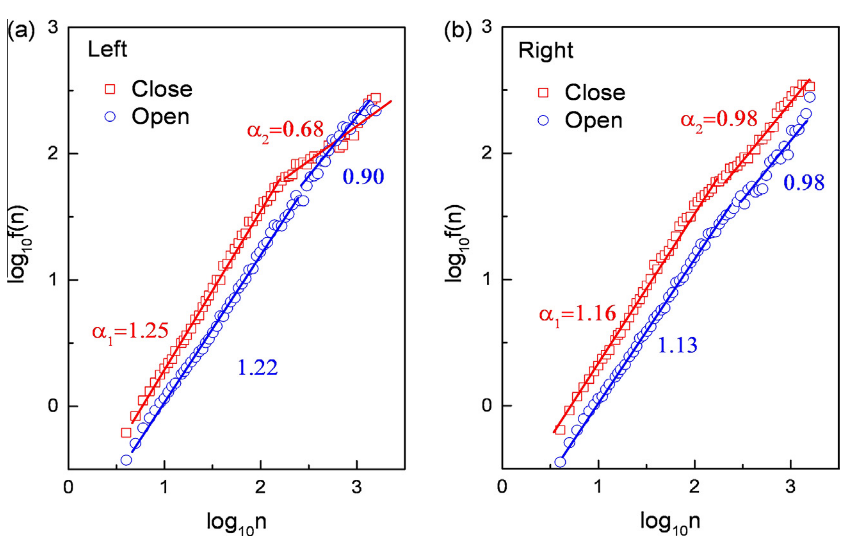

Fig. 6. DFA of a typical patient. (a) Left eye. (b) Right eye.

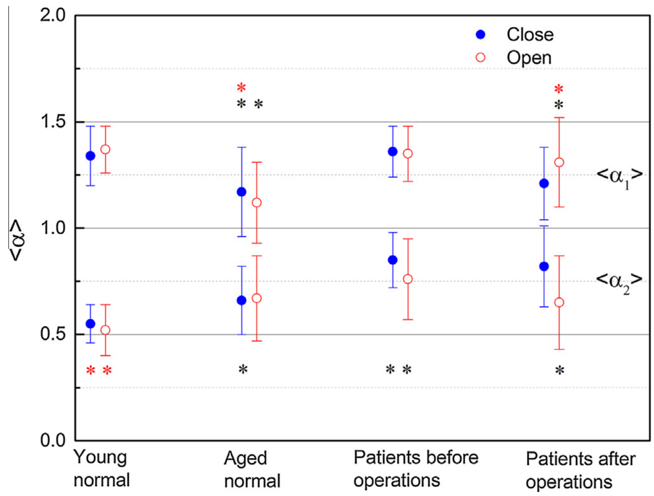

Fig. 7. Distributions of the average preoperative and postoperative DFA α index values of young and aged normal subjects and patients. Star: $p < 0.05$. Black star: indicating use of the DFA α index value of the young normal group as a reference to calculate the p value. Red star: indicating use of the preoperative DFA α index value of the patient group as a reference to calculate the p value. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

normal, patients before operation, and patients after operation have been used for differentiation with respect to young normal group and preoperative patient group respectively using their open-eye or closed-eye DFA α index values. For example, both the preoperative and postoperative patient groups were distinguishable from the young normal group when the open-eye α_2 value of the young normal group was used as a reference. In addition, the aged normal group was distinguishable from the young normal group if the closed-eye α_2 value of the young normal group was used as a reference.

In brief, muscle control dysfunction in the patient group resulted in temporal correlation degradations that were similar to those in the aged normal group, which occurred as a result of aging. Because the aged normal group did not have dysfunctional muscle control, the temporal correlation degradation was only one of the characteristics in the blepharoptosis eyelid SEMG recordings. The changes in the correlation properties in the long time-scale that occurred as a result of successful operations implied that both the levator aponeurosis and orbicularis oculi muscles remained functional, and overall muscle control improved.

4. Conclusions

We studied the SEMG signals of eyes with upper eyelid ptosis that were corrected by the transconjunctival procedure, which reserves the orbicularis muscle and prevents postoperative lagophthalmos. We found that DFA assessments of the temporal correlations in eyelid SEMG recording differentiated the signals of the young and aged normal groups and the patient group by properly choosing a DFA index of a particular group as a reference in the statistical tests. The correlation properties in the postoperative SEMG recordings in the patient group were closer to the regime of the normal group, showing that muscle control became effective after ptosis correction. Thus, the DFA index can be considered an indicator of muscle functionality.

Neural networks and their associated muscle control are an example of a so-called complex system. A single measure is therefore, in principle, insufficient for assessing a complex system with unknown and usually large degrees of freedom. This study, however, provided a unique analysis of eyelid SEMG signals with very high sampling frequency, thus indirectly demonstrating the signal temporal correlations that were relevant to muscle control from the aspect of the neuronal responses. These findings contribute to a better understanding of muscle control through EMG and kinesiology, which is of interest to the related research community as well as clinical doctors.

While we focused on upper eyelid ptosis corrections by transconjunctival incisions in the present study, our analysis was generally applicable to a number of treatments. The potential application of the analysis to other biomechanical systems, such as the activity and mobility of patients in rehabilitation programs, which can also be characterized by SEMG, is well worth exploring.

Conflict of Interest

The authors declare that they have no conflict of interest.

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