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Analysis of Sustained Maximal Grip Contractions Using Emperical Mode Decomposition

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Abstract-Muscle fatigue and physiological tremor during a Sustained Maximal Grip Contraction (SMGC) were analyzed using Empirical Mode Decomposition (EMD) in this study. Thirty-nine healthy subjects volunteered for the experiment and performed a 25-s SMGC. Fatigue parameters such as the relative power output (RPO) were calculated from the residual of SMGC after applying EMD. Using the energy spectrum of the intrinsic mode functions (IMF) obtained using Hilbert-Huang Transform (HHT), physiological tremor was identified from the 4-12 Hz region in IMF3 and IMF4. Data were analyzed for five consecutive 5-s epochs to identify changes in fatigue and tremor over time. The EMD method was able to identify a greater resistance to fatigue in women compared to men (p<0.05) and in non-dominant hands compared to dominant hands (p<0.05). Consistent with the results for fatigue, women had less tremor than men (p<0.05), while non-dominant hands trembled less than did dominant hands (p<0.05). Higher levels of tremor were observed for non-fatigue-resistant subjects for both 10-15 s and 15-20 s epochs (p<0.05). The EMD is an appropriate method to indentify both fatigue and tremor during SMGC.

Keywords-Sustained Maximal Grip Contraction; Fatigue; Physiological Tremor; Empirical Mode Decomposition

I. INTRODUCTION

The Maximal Grip Strength (MGS) provides a good assessment of overall muscle strength, particularly in elderly subjects [1], as well as being linked to a range of other conditions. In addition to MGS, the control and response strategy of the neuromuscular system such as fatigue and steadiness of contractions can be found by analyzing Sustained Maximal Grip Contractions (SMGC) [2]. Analysis of this physiological force tremor is of interest both in exploring the neural mechanisms during sustained contractions and in investigating effects of aging or neuromuscular diseases [3].

In order to evaluate fatigue and tremor during prolonged grip-strength contractions, a signal-processing method that can deal with the non-stationary nature of the signal and its short duration, as well as the low frequency content is needed. One method that is well-suited to such an application is the Empirical Mode Decomposition (EMD) followed by the Hilbert transform [4]. The advantage of EMD and the Hilbert-Huang Transform (HHT) is that the energy in the signal is more concentrated, resulting in less leakage than for traditional methods such as the Fast Fourier Transform (FFT) or wavelets [5]. In addition to the information obtained from the HHT, EMD provides a residual component that could be used as an indication of fatigue development during SMGC. The aim of this paper was to apply the EMD method to analyze fatigue and tremor during a SMGC.

II. METHODS

A. Subjects

Twenty-four men and 15 women were tested, with their characteristics shown in Table I. No subjects reported any history of fractures or injuries in their forearms or hands. All subjects gave their informed consent prior to being tested.

B. Data Collection

In order to precisely record the grip strength, a high-sensitive dynamometer Myogrip was designed by the Institute of Myology, Paris, France [6] (Fig. 1). The Myogrip dynamometer is built around a precision force sensor (SML-200, Interface, Scottsdale, AZ) and measures force in decaNewtons (daN), with a sensitivity of 0.01 daN (i.e. approximately 10 g) and an accuracy of 0.05 % of the full scale (89 daN). This dynamometer can work according to four modes. In Mode I, the Myogrip displays force locally and instantaneously on a digital display; in Mode II, only the maximal force value is recorded and displayed; in Mode III, force is transmitted wirelessly in radio frequency; in Mode IV, force is transmitted via RS-232 connection. In this study, data were collected at 250 Hz using an RS232 connection, with a calibration performed before and after each recording period.

C. Experimental Protocol

Subjects were seated on a chair facing the evaluator, with their shoulders adducted and their testing arm close to their body, with 180° of elbow extension and a slight wrist extension [6]. Each subject was tested for both dominant and non-dominant hands in a randomized order to account for any learning or fatigue effects.

	Men (n=24)		Women (n=15)	
	Mean (SD)	Range	Mean (SD)	Range
Age (y)*	20.4 (0.9)	19.4-22.7	20.0 (0.7)	18.9-21.2
Height (cm)*	179.8 (6.3)	169-192	167.5 (4.2)	160-176
Weight (kg)*	73.2 (8.9)	58-90	58.1 (9.1)	44-81
Right handed**	22 (91.7%)		14 93.3%)	
Left handed**	2 (8.3%)		1 (6.7%)	

TABLE I. SUBJECT CHARACTERISTICS

* Data are expressed as means (SD).

** Data are expressed as number (percentage)



Figure 1. The Myogrip dynamometer.

Maximal grip strength (MGS) values were measured twice for each hand for three seconds, alternating between hands, with 30 s between trials. If two trials for a given hand differed by more than 10%, a third trial was performed, with the MGS taken as the largest force from the two closest values [6]. After the MGS trials, subjects were given a five-minute rest before performing a SMGC for 30 s. Each hand was tested only once, with 5 minutes between SMGC tests. Subjects were given continuous verbal encouragements before and during all trials in order to motivate them to exert their true MGS and to sustain the highest possible force during the SMGC. All subjects were retested following the same experimental protocol two weeks later. The first 25 s of the SMGC signal after the maximal value was chosen for all subsequent analysis in order to ensure all signals were of equal length, and did not include a relaxation period that was sometimes observed in the final second.

D. Empirical Mode Decomposition

Empirical Mode Decomposition (EMD) decomposes signals into waveforms that are modulated in both amplitude and frequency by extracting the oscillatory modes embedded in the signal. The waveforms thus extracted are the Intrinsic Mode Functions (IMF), with each IMF yielding a meaningful local frequency.

The decomposition is based on the following assumptions: (i) the signal has at least two extrema - one maximum and one minimum; (ii) the characteristic time scale is defined by the time lapse between the extrema; and (iii) if the data were totally devoid of extrema but contained only inflection points, then it can be differentiated once or more times to reveal the extrema. Final results can be obtained by integrations of the components. The EMD algorithm is as follows: (a) The envelopes defined by the local maxima and minima for the data x(t) to be decomposed are formed using a cubic-spline interpolation. (b) The upper and lower envelopes are averaged to obtain the mean values $m_1(t)$, with this signal then subtracted from the original signal, thus creating the first component

$$h_1(t) = x(t) - m_1(t)$$
(1)

(c)If the first component is not an IMF, $h_i(t)$ is taken as the new signal and steps (a) and (b) are repeated until the first component is an IMF. (d) When the first IMF component $c_i(t)$ has been identified it is subtracted from the original signal,

leaving a residual $r_1(t) = x(t) - c_1(t)$. Steps (a) to (c) are repeated with r(t) taking the place of x(t) until $r_n(t)$ is smaller than a predetermined value or becomes a monotonic function such that no more IMF can be extracted.

$$x(t) = \sum_{i=1}^{n} c_i + r_n$$
(2)

The data has thus been decomposed into n empirical modes and a residual r_n , which is either the mean trend or a constant. The first component has the smallest time scale, which corresponds to the highest frequency component of the original signal.

E. Hilbert Transform

For an arbitrary time series, x(t) it is possible to represent its Hilbert Transform, y(t), as:

$$y(t) = \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{x(t')}{t-t'} dt'$$
(3)

where P indicates the Cauchy principal value. With this definition, an analytic signal z(t) can be represented as:

$$z(t) = x(t) + iy(t) = a(t)e^{i\theta(t)}$$
(4)

in which

$$a(t) = [x^{2}(t) + y^{2}(t)]^{1/2}$$
(5)

$$\theta(t) = \arctan(\frac{y(t)}{x(t)}) \tag{6}$$

Therefore x(t) can be expressed as:

$$x(t) = real \sum_{i=1}^{n} a_i(t) \exp(i \int \omega_i(t) dt)$$
(7)

where

$$\omega(t) = \frac{d\theta(t)}{dt} \tag{8}$$

The Hilbert Spectrum $H(\omega,t)$ can then be calculated, with the Hilbert energy spectrum defined as:

$$ES(t) = \int H^2(\omega, t)dt$$
(9)

The EMD and HHT algorithms were performed using Matlab 7.0.1 (The MathWork, Inc., Natick, MA, USA).

F. Fatigue Parameters

In order to quantify fatigue, three parameters were used. The initial force proportion (IFP) was defined as the F_{max} which is the initial force value of the residual, divided by the MGS.

$$IFP = F \max/MGS \tag{10}$$

The power output (PO) was defined as the integral of the tendency over time (N.s):

$$PO = \int_0^{25} residual(t)dt \tag{11}$$

The *PO* can be used as a measure of the power generated over the 25-s trial. The relative power output (RPO) was

defined as the ratio of PO (the surface below the force tendency) to the surface below the line of F_{max} :

$$RPO = PO/(F_{\max} \times t) \tag{12}$$

The RPO quantifies the global decrease in force during the 25-s trial.

G. Tremor Parameters

In order to identify physiological tremor, analyses of the Hilbert spectrum and of the Hilbert energy spectrum were performed for all signals. The high-frequency components, including noise, were concentrated in IMF1 and IMF2, while the low-frequency components were located in IMF5, and all subsequent IMFs. Physiological tremor is known to occur within the frequency band of 4-12 Hz; this frequency band was always contained within IMF3 and IMF4 for all subjects. Therefore, all calculations of tremor parameters were performed on IMF3 and IMF4. The energy of IMF3 and IMF4 for each 5-s epoch was calculated using (9), and was taken to represent the level of tremor in the force signal. These energy values were normalized using the energy present in the corresponding residual. In order to assess the effects of fatigue on tremor, subjects were classified as fatigue-resistant or non-fatigue resistant if their RPO was one of the highest or lowest third of the total range. This grouping was performed for each epoch, as calculated in section F above.

H. Statistical Analysis

The nonstationarity of the grip-strength signals was verified by the run test [7]. All parameters were assessed for normality using the Kolmogorov-Smirnov test. All variables were normally distributed, with the exception of the level of tremor, which became normally distributed after log transformation. Accordingly, the log-transformed version of tremor was used for all subsequent statistical analyses.

Independent t-tests were used to compare MGS, fatigue, and tremor levels between genders. Paired t-tests were used to analyze the influence of hand dominance and the retest effect for both fatigue and tremor levels. Repeated measures ANOVA was used to test for an effect of time on the amount of tremor in IMF3 and IMF4, as well as an effect of time on fatigue, with gender as a covariate. The effect of fatigue on the amount of tremor was assessed using ANOVA for each of the five epochs. All statistical analyses were performed using the Statistical Package for Social Sciences (SPSS Inc., Chicago, IL, USA). P values less than 0.05 were considered to be statistically significant.

III. RESULTS

A. Data Description and HHT Application

Examples of SMGC signals for two contrasting subjects, as well as their EMD decompositions are shown in Fig 2. The left-hand column of the figure (2a, 2c and 2e) is for a typical non fatigue-resistant subject with marked fluctuations in grip strength (age 19.9 y, male, MGS 326.9 N), whereas the right-hand column (2b, 2d and 2f) is for a typical fatigue-resistant subject with limited fluctuations in grip strength (age 20.1 y, female, MGS 260.7 N). After analyzing the Hilbert spectra for these two subjects, we found that the

majority of the signal component is in the frequency region below 20 Hz (98%) When the 0-20 Hz region is examined in detail, the majority of the energy (94%) of all IMFs can be seen to be below 3 Hz, irrespective of the magnitude of the fluctuations in grip strength observed. The Hilbert energy spectra show that the region of physiological interest (4-12 Hz) is mainly contributed by the IMF3 and IMF4. Therefore the summations of these two components (4-12 Hz) for the same two subjects are shown in Fig. 2c and Fig. 2d; and the summations of other fluctuations (IMF5-IMF9) are shown in Fig. 2e and Fig. 2f respectively.

B. Fatigue effect

The parameters used to quantify maximum force (MGS, IFP) and fatigue (PO and RPO) are shown in Table II for both test and retest data. The MGS for women was on average



Figure 2. (a) Typical force signal during a 25-s SMGC for a subject with marked fluctuations in force level; (b) Typical force signal during a 25-s SMGC for a subject with limited fluctuations in force; (c) Summation of IMF3 and IMF4 (4-12 Hz) for the subject shown in (a); (d) Summation IMF3 and IMF4 (4-12 Hz) for the subject shown in (b); (e) Summation of IMF5-9 (< 4 Hz) for the subject shown in (a); (f) Smmation of IMF5-9 (< 4 Hz) for the subject shown in (b).

63.4% of that of men, while MGS for non-dominant hands averaged 91.2% of that of the dominant hands. The IFP for women was 5% higher than that observed for men, while the IFP for non-dominant hands was 4% higher than that of dominant hands. For PO, results for the non-dominant and dominant hands were highly correlated (r=0.942), with the dominant hand 7% stronger than the non-dominant hand. The test-retest reliability for PO was particularly high (r=0.972). In respect to the RPO, non-dominant and dominant hands were correlated (r=0.646;), with no significant difference between the dominant and the non-dominant hand. Test-retest reliability for RPO was high (r=0.756). There was a significant effect of gender on RPO and PO, with women having significantly higher values for RPO, but significantly lower values for PO. The MGS was strongly correlated with PO (r=0.92). In contrast, MGS was not significantly correlated with RPO (r=0.08; p>0.05). In respect to the effect of time on fatigue, repeated measures ANOVA showed that fatigue increased significantly throughout the trial (Fig. 3).

C. Tremor effect

Men had significantly more tremor than women for IMF3 (difference of 0.56 for the log-transformed variable; p<0.05). However, there was no significant difference in tremor between men and women for IMF4. Across all subjects, the dominant hand trembled more than the non-dominant hand for both IMF3 and IMF4 (0.45 and 0.72 for IMF3 and IMF4 respectively; p<0.05). In respect to the effect of time on tremor, repeated measures ANOVA showed that tremor of dominant hand increased significantly from epoch 5-10 s to epoch 10-15 s for both IMF3 and IMF4 (Fig. 4 p<0.05).

D. Relationship between fatigue resistance and tremor

The relationship between resistance to fatigue and the amount of tremor was assessed using ANOVA for each of the five epochs (Fig 3 and Fig 4). Fatigue-resistant subjects were classified as the 33% of subjects with the lowest RPO values, while non fatigue-resistant subjects were classified as the 33% of subjects with the highest RPO values. There was no effect of the level of fatigue resistance for the 0-5 s and 5-10 s epochs. In contrast, significantly higher levels of tremor were observed

TABLE II: FATIGUE EFFECT OF A SUSTAINED 2:	5S SUB-MAXIMAL GRIP TEST
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	Men		Women		
	Test 1	Test 2	Test 1	Test 2	
MGS (N) for DH	430.2	421.1	274.7	275.2	
	(70.0)	(76.3)	(60.8)	(64.9)	
MGS (N) for NDH	403.0	382.3	254.3	233.8	
	(71.1)	(87.1)	(63.6)	(60.0)	
IFP for DH	0.84	0.84	0.89	0.84	
	(0.10)	(0.09)	(0.10)	(0.13)	
IFP for NDH	0.84	0.88	0.93	0.89	
	(0.10)	(0.08)	(0.10)	(0.11)	
RPO for DH	0.68	0.69	0.74	0.71	
	(0.10)	(0.09)	(0.06)	(0.11)	
RPO for NDH	0.68	0.72	0.76	0.75	
	(0.09)	(0.08)	(0.07)	(0.09)	
PO (106 N.s) for DH	1.84	1.82	1.28	1.22	
	(0.43)	(0.42)	(0.32)	(0.38)	
PO (106 N.s) for NDH	1.72	1.71	1.21	1.11	
	(0.40)	(0.43)	(0.32)	(0.33)	
Data are expressed as means (SD)					



Figure 3. Fatigue of dominant and non-dominant hands during SMGC over time. Fatigue is shown as 1 - RPO, while time is represented as 5-s epochs (0-25 s). *Significantly different from the previous epoch for the dominant hand; † Significantly different from the previous epoch for the non-dominant hand



Figure 4. Tremor of dominant and non-dominant hands during SMGC over time in (a) IMF3 and (b) IMF4. Temor is shown as the log-transformed value of the energy of the Hilbert Spectrum as calculated by (9). Time is represented as 5-s epochs (0-25 s).* Significantly different between the dominant and non-dominant hands during the same epoch. † Significantly different from the previous epoch.

for non-fatigue-resistant subjects for both 10-15 s and 15-20 s epochs (p<0.05). There was no effect of fatigue resistance on tremor levels for the 20-25 s epochs.

VI DISCUSSION

In respect to fatigue, force decreased throughout the SMGC by between 26 and 32 % (RPO from 0.68-0.74). This finding was in keeping with previous results in which a 50% reduction

in force was reported for a 60-s maximal voluntary contraction [8]. Such a decrease in force over time has been shown to be related to peripheral factors such as metabolic function and muscle fiber types [9]. The decline in muscle force observed occurs irregularly, enabling muscle tremor to be identified. Such physiological tremor is present in all muscular contractions, with the frequency of tremor ranging from 4Hz to 12Hz [10]. The underlying mechanisms behind such differences in the frequency of tremor include changes in muscle contraction dynamics, proprioception, muscle receptor properties, as well as purely central factors [11].

Both IMF3 and IMF4 contain those components of the original force signal that are between 4 and 12Hz, the range in which involuntary physiological tremor is located. Such tremor has been thought to be a reflection of changes in the firing rates of slow and fast twitch motor units during strong isometric contraction [12]. In addition to the variations shown in IMF3 and IMF4, marked variations in force levels of the lower-frequency IMFs were also present, as seen in the examples presented in Fig. 2. The fluctuations in force output at low frequency could be due to both voluntary and involuntary reasons such as intermuscular changes in order to maintain grip strength at the desired level or changes in blood pressure and pH levels [13].

Women were less powerful but began their contractions at higher relative levels of initial force (IFP) in comparison to men. Despite their higher IFP, women were more fatigue resistant than men, as shown by the higher RPO values. This finding is in agreement with the work of Shih, who also observed greater fatigue resistance in women [14]. The reason for such fatigue resistance in women is thought to be due to gender differences in muscle mass [15]. Since women have proportionally less muscle mass than men, women will generate lower absolute muscle forces when performing the same relative work, if a similar specific tension is assumed [15]. However, even when men and women are matched for strength, women still exhibit a fatigue resistance advantage, indicating that other mechanisms are involved [16].

Non-dominant hands were more fatigue resistant than were dominant hands. This finding could be related to differences in metabolic economy during SMGC and fiber-type distributions [9] and possibly to functional divergences. while subjects with low resistance to fatigue trembled more than subjects with high fatigue resistance. The results of the present study also showed that although dominant and non-dominant sides have the same levels of fatigue (Fig. 3), the dominant hand has more tremor than the non-dominant side (Fig. 4). Similar findings in relation to tremor between dominant and non-dominant hands have been previously reported for sub-maximal contractions [17]. The explanation for the differences observed was attributed to the contribution of newly-recruited motor units to force tremor, which are primarily fast twitch as part of the orderly recruitment process.

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V CONCLUSION

EMD is an appropriate analytical method for use with SMGC. The level of fatigue present can be accurately identified using the residual obtained from this method, while physiological tremor can be identified using the selection of appropriate IMFs. It would be of interest to test the EMD method in tandem with EMG recordings in order to identify the relationship between inter- and intra-muscular changes in terms of the force able to be sustained. Finally, the application of the method using other protocols, such as sub-maximal contractions would be of interest.

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