Mean and Median Frequency of EMG Signal to Determine Muscle Force based on Time-dependent Power Spectrum

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Abstract—The analysis of EMG signals can be generally divided into three main issues, i.e., muscle force, muscle geometry and muscle fatigue. Recently, there are no universal indices that can be applied for all issues. In this paper, we modify the global fatigue indices, namely mean frequency (MNF) and median frequency (MDF), to be used as a muscle force and fatigue index. Due to a drawback of MNF and MDF that it has a non-linear relationship between muscle force and feature value, especially in large muscles and in cyclic dynamic contractions. A time-dependence of MNF and MDF (TD-MNF and TD-MDF) is computed for dynamic contractions. Subsequently, a slope of the regression line that fits maximum values of MDF (and MNF) during a number of cyclic contractions is used as a fatigue index. To be additionally used as a muscle force index, some suitable ranges of TD-MNF and TD-MDF should be selected and five effective statistical parameters including mean, median, variance, root mean square and kurtosis, were applied to the selected range. From the experiments, the performance of TD-MNF is definitely better than that of TD-MDF. The results showed that mean and median features of the selected TD-MNF series have a better linear relationship with muscle force (load level) compared to the traditional methods and have a significant difference (p<0.001) between feature values for different loading conditions. Moreover, there is a certain pattern of TD-MNF for all trials and subjects that has not been found in traditional MNF. TD-MNF is optimized when an overlapping consecutive window method is performed with a 384-sample window-size and a 192-sample window-increment. In total, mean and median features of the selected TD-MNF series can be used as a muscle force and fatigue index. In future works, the proposed method can be used instead of using multiple features for the EMG signal analysis.

Index Terms—Electromyography signal, median frequency, mean frequency, feature extraction, muscle contraction.

I. INTRODUCTION

In recent, many potential applications, both medical and engineering, based on an analysis of electromyography (EMG) signals have been established [1], [2]. Usually, an analysis and detection of EMG signals can be divided into three main issues, i.e., muscle force, muscle geometry (joint

angle) and muscle fatigue [3]. A combination of muscle force and joint angle detection, for instance, is used to decide an output class for controlling a prosthetic leg [4]. Throughout this procedure, a feature extraction is one of the most important steps [2]. Because of the hidden information in a noisy EMG data, features that maintain useful EMG information and discard unwanted EMG part and interference should be more carefully considered [5].

Generally, features-based on time-domain and frequency-domain are two important feature ones [6]. Integrated EMG, mean absolute value, root mean square, and zero crossing per second are commonly used features in time-domain analysis [6]. Time-domain features are frequently used as a muscle force detection tool, whereas their performance in the detection of muscle fatigue is a major drawback for these features [7]. On the other hand, an effective domain of EMG feature analysis for the muscle fatigue detection is based on frequency information [7]. In frequency domain, several variables of EMG power spectrum are deployed as features. Two ordinarily and frequently examined features are median frequency (MDF) and mean frequency (MNF).

On the contrary, a usage of MDF and MNF in determining muscle force illustrates the contradictory findings [8]–[17]. A number of literatures [8]–[11] showed a continuous increase of MDF and MNF as levels of muscle force increase. In contrast, MDF and MNF decrease with increasing force levels in a number of studies [12]–[14]. Moreover, in some researches, values of MDF and MNF are unaffected by change in muscle force (independent of the contraction levels) [15]–[17].

To confirm the conflicting results mentioned above, the experiments are re-tested in this study; moreover, several possible reasons for the conflicting results are discussed. To modify these frequency-domain features to be the universal indices that can detect both muscle force and muscle fatigue, a modification of traditional MDF and MNF is proposed. Further, all literatures presented above were analyzed with EMG signal recorded from the biceps brachii during a static contraction. A non-linear relationship with muscle force of MDF and MNF are also investigated in a dynamic contraction [18] and in a large muscle [19].

In this study modified MDF and MNF are proposed based

on EMG signals recorded from a biceps brachii muscle during dynamic contractions. As an indicator of muscle fatigue during cyclic dynamic contractions, instead of using a whole signal fast Fourier transform (FFT) in the standard features, a concept of using consecutive FFT has been proposed. A slope of the regression line that fits maximum values of MDF (and MNF) during a number of cyclic contractions was used as a fatigue index [20]. From our recent preliminary studies [21-22], to solve the non-linear relationships between feature values and muscle loads, some ranges of MDF and MNF extracted from the consecutive FFTs showed a linear relationship of feature and muscle force level. In this study, evaluations of time-dependent FFT parameters are proposed including FFT window length and increment. In addition, to easily observe and deploy in real-world application, some useful statistical parameters are applied with a selected efficient range. As a result, the optimal range and parameter have been established that it can be used to detect both muscle force and muscle fatigue. Additionally, it can be used instead of using the multiple features [23].

II. EXPERIMENTAL PROTOCOL AND EMG DATA COLLECTION

In experiments, four healthy male subjects were asked to perform the exercises during the repetitive elbow flexion-extension tasks. A range of the dynamic contraction was from a full extension (0º, forearm vertical) to a full flexion (approximately 150º) with 3 s in duration. Four different loads, consisting of 2, 4, 6 and 8 kg, were proposed. For the first three subjects, there are 20 trials in each load; except for a last subject, there are 40 trials in each load. The experimental setup is shown in Fig. 1(a).

EMG data were recorded by two surface electrodes on the biceps brachii and a reference electrode was placed on the wrist, as shown in Fig. 1(b). All EMG data recordings were carried out using a Mobi-6b (TMS International BV, Netherlands). EMG signals were sampled at a rate of 1024Hz with a 24-bit analog-to-digital resolution. In addition, a band-pass filter of 20-500Hz and an amplifier with 19.5 times were set.
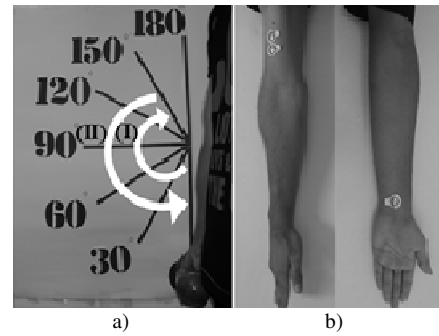

Fig. 1. a) – apparatus used to apply constant force at various joint angles (I) flexion (II) extension; b) – electrode locations: (left) Biceps brachii muscle and (right) a common ground [21].
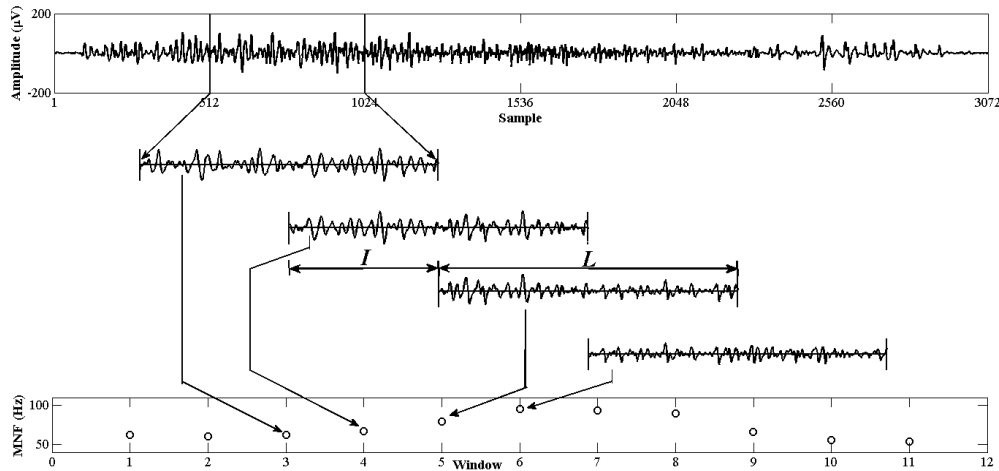

Fig. 2. A concept of consecutive overlapping FFTs with a window size (L) and a window increment (I) for the identification of muscle force during cyclic dynamic contractions.

III. TIME-DEPENDENT MDF AND MNF METHODS

In order to analyze the EMG power spectrum in both of muscle force and fatigue indices, we investigate a time dependence of the MDF and the MNF of a time-sequential data, which are called "Time-dependent MDF and MNF (TD-MDF and TD-MNF)" [21-22]. It is one of the time-frequency analysis methods that can be referred to as a short-time Fourier transform (STFT), i.e., spectrogram [20], with a rectangular window. In the beginning, definitions of traditional MDF and MNF of EMG power spectrum are described as follows:

MDF is a frequency value at which the EMG power spectrum is divided into two regions with an equal integrated power. It can be expressed as

$$\sum_{j=1}^{\text{MDF}} P_j = \sum_{j=\text{MDF}}^{M} P_j = \frac{1}{2}\sum_{j=1}^{M} P_j , \qquad (1)$$

where P_j is the EMG power spectrum at a frequency bin j and M is the length of frequency bin.

MNF is an average frequency value that is computed as a sum of product of the EMG power spectrum and frequency, divided by a total sum of spectrum intensity. It can be expressed as

$$\text{MNF} = \sum_{j=1}^{M} f_j P_j \bigg/ \sum_{j=1}^{M} P_j , \qquad (2)$$

where f_j is a frequency value at a frequency bin j.

The proposed TD-MDF and TD-MNF methods used a sliding window technique for extracted features instead of using the whole data. This technique showed the usefulness for non-stationary EMG signals that are recorded from the cyclic dynamic contractions as a fatigue index [20]. A concept of TD-MDF and TD-MNF techniques is shown in Fig. 2. In the figure, a window size in length L was used with a window increment by length I. A series of MDF and MNF can be derived from the successive FFTs for the whole length of EMG data. A total of n segment FFTs per trial was obtained, which can be calculated by

$$n = \left((N - L)/I \right) + 1 , \qquad (3)$$

where N is the length of EMG signal for a trial ($N = 3072$).

To yield an optimal performance of the TD-MDF and TD-MNF methods to determine muscle force and muscle fatigue, four significant parameters need to be evaluated and selected consisting of (1) the FFT window size, (2) the window increment of time-dependent procedure, (3) the suitable range of TD-MDF (and TD-MNF), and (4) the optimal feature extracted from the suitable range.

Firstly, effects of window size and increment functions were optimized. Six window size functions were tested ($L = 64, 128, 256, 384, 512, 768$ and 1024 samples); and possible window inclement functions based on eight types ($I = 1.5625\%, 3.125\%, 6.25\%, 12.5\%, 25\%, 50\%, 75\%$ and 100% of L) were also investigated. Note that small L cannot get eight possible windows. All possible combinations can be seen in Table I in the Experimental Results and Discussion Section. The observation and selection of the suitable range of TD-MDF and TD-MNF were proposed.

Subsequently, five statistical features were extracted from the selected range of TD-MDF and TD-MNF, including mean (average), median, variance, root mean square (RMS) and kurtosis, as can be assumed as a dimensionality reduction (DR) method. As a result, only one value is obtained from TD-MDF and TD-MNF series for using as a force index. Analysis of variance (ANOVA) was performed on such parameters to measure the relationship between parameter value and muscle load, and to appraise the significant difference in loading conditions.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

It is distinctly presented in the Introduction Section that traditional MDF and MNF illustrated the contradicting findings for a relationship between the MDF (and MNF) features and the levels of muscle load. This contradicting finding was confirmed respectively in our experimental results, as shown in Fig. 3(a) and 3(b). Average of MDF and MNF values from 20 trials per load were shown. Their relationships are different for each subject. For instance, in Fig. 3(b), MNF becomes independent of the contraction levels in subject 1. Subsequently, in subject 2, MNF increases together with the contraction levels, and decreases with the contraction levels in subjects 3 and 4. MDF also illustrate the similar findings as can be observed in Fig. 3(a).

There are several possible reasons for the conflicting

results found in the literature and in our results. A gender of the subjects is the first one. The differences in subject's gender can cause the differences in the fiber types and diameters [24]. In our study, all subjects are male but the contradiction is also found. An interesting issue, however, can be mentioned that the muscle strength testing (using Jackson Strength Evaluation System, model 32628, Lafayette Instrument) of subjects 3 and 4 has a higher value than that of subjects 1 and 2. The characteristic frequencies of subjects 3 and 4 have the similar trend (MDF and MNF decrease as force levels increase). This finding, moreover, is also true for TD-MDF and TD-MNF features as can be observed from Fig. 4 within the dashed line boxes. On the contrary, the findings of MDF and MNF for the subjects 1 and 2 are not consistent and also occurring in TD-MDF and TD-MNF features.
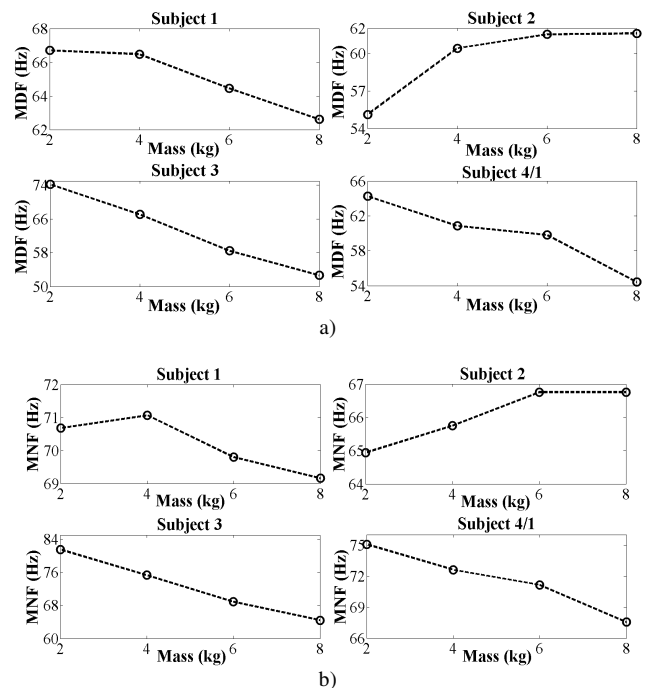

Fig. 3. a) – average of the traditional MDF of the EMG signals for different loads from four subjects; b) – average of the traditional MNF of the EMG signals for different loads from four subjects.

However, some ranges of TD-MDF and TD-MNF features, particularly for the central positions, have a better linear relationship with muscle load for all subjects. As shown in the Fig. 4, a certain linear relationship pattern of MDF and MNF is found for all subjects at the seventh and the eighth positions (as presented in the solid line boxes). Its relation is a decrease of the feature values with an increase of the force levels. Note that the results in the Fig. 4 are obtained from a condition with a 384-sample window size and a 192-sample window increment.

From the experiments, the performance of TD-MNF is definitely better than that of TD-MDF. In the rest of this paper, only the results of TD-MNF are discussed. A summary of all possible combinations of the window size and window increment is presented in Table I, with a suitable range of TD-MNF. From the experimental results, TD-MNF of EMG data with cyclic dynamic contractions showed a dynamical change with respect to time. In addition, there are certain patterns of TD-MNFs for each trial for all

subjects. The selection of a suitable range will offer a better separation performance between muscle force levels. These findings, moreover, have not been found from traditional MDF and MNF, as presented in Fig. 3.

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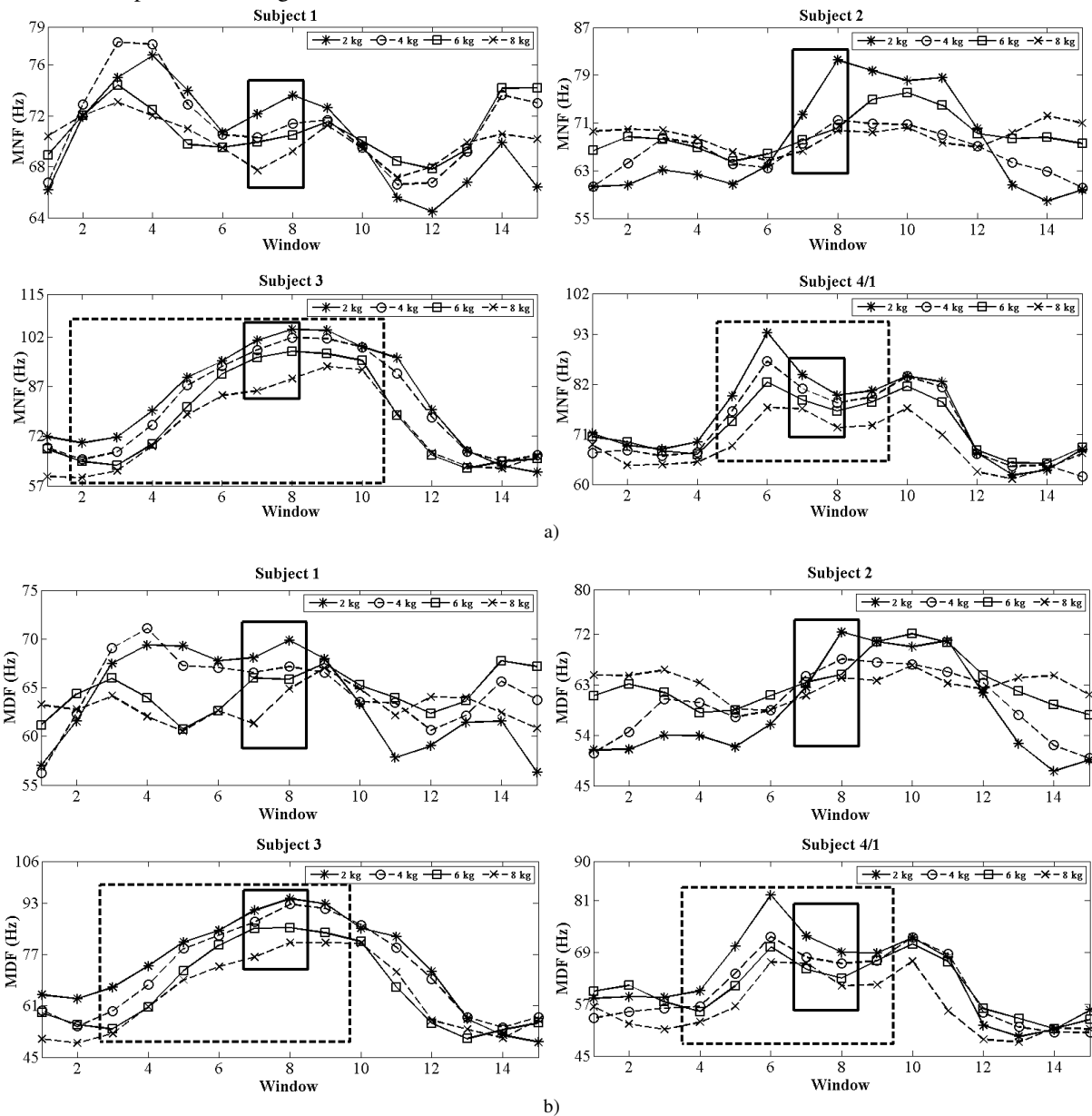

Fig. 4. a) – TD-MDF; b) – TD-MNF of the biceps brachii muscle during cyclic dynamic contraction with a 384-sample window size and a 192-sample window increment for different loads.

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To appraise the significant difference in loading conditions of all feature parameters, the results of p-value obtained from ANOVA analysis are used to confirm the statistical different significance as presented in Table II. The statistical feature parameters in this study can be seen as DR method in order to easily use in the applications. To automatically assess, we used the same range of TD-MNF for every subject that is reported in Table I.

For the first and the second optimized issues, the FFT window size and window increment, the results showed that the method of a 384-sample window size function with a 192-sample window increment function provided the best in separation ability than the other window conditions. It was found that there are the significant differences ($p<0.001$) between feature values (mean, median and RMS) for different loading conditions. However, mean and median

show a better performance in separation and computational complexity than the other four parameters including RMS. Window size and increment conditions of 384/96 and

768/96 are the better ones, however the computational time of a 384/192 window condition is lower than that of 384/96 and 768/96 as shown in Fig. 5.

TABLE I. A SUMMARY OF ALL POSSIBLE COMBINATIONS OF FFT WINDOW SIZE AND INCREMENT FUNCTIONS WITH A SUITABLE RANGE OF TD-MNF.

L	*I*	*n*	Selected range positions	Number of selected positions	% of whole length
128	32	93	-	-	-
	64	47	23-24	2	4.26%
	96	31	14, 16	2	6.45%
	128	17	-	-	-
256	16	177	70-90	21	11.86%
	32	89	36-48	13	14.61%
	64	45	19-24	6	13.33%
	128	23	10-13	4	17.39%
	192	15	-	-	-
	256	12	6-7	2	16.67%
384	24	113	49-63	15	13.27%
	48	57	25-32	8	14.04%
	96	29	12-16	5	17.24%
	192	15	7-8	2	13.33%
	288	10	-	-	-
	384	8	-	-	-
512	16	161	68-90	23	14.29%
	32	81	36-47	12	14.81%
	64	41	17-23	7	17.07%
	128	21	10-12	3	14.29%
	256	11	6	1	9.09%
	384	7	-	-	-
	512	6	-	-	-
768	12	193	103-109	7	3.63%
	24	97	52-55	4	4.12%
	48	49	27-28	2	4.08%
	96	25	10, 14	2	8.00%
	192	13	-	-	-
	384	7	-	-	-
	576	5	-	-	-
	768	4	-	-	-
1024	16	129	47-56	10	7.75%
	32	65	24-28	5	7.69%
	64	33	13-14	2	6.06%
	128	17	7, 11	2	11.76%
	256	9	4, 6	2	22.22%
	512	5	-	-	-
	768	3	2	1	33.33%
	1024	3	-	-	-

TABLE II. ANOVA ANALYSIS (AVERAGE *P*-VALUE FROM 4 SUBJECTS) OF FIVE STATISTICAL PARAMETERS EXTRACTED FROM SELECTED TD-MNF.

L / I	*p*-value				
	Mean	Median	Variance	RMS	Kurtosis
128/64	0.0943	0.0943	0.5897	0.0942	0.4720
128/96	0.0394	0.0394	0.4027	0.0436	0.7080
256/16	0.0015	0.0088	0.1963	0.0015	0.3954
256/32	0.0017	0.0161	0.3185	0.0017	0.6210
256/64	0.0019	0.0099	0.3527	0.0020	0.5274
256/128	0.0040	0.0116	0.2409	0.0044	0.5584
256/256	0.0308	0.0308	0.5044	0.0289	0.5269
384/24	0.0048	0.0060	0.3312	0.0046	0.6126
384/48	0.0037	0.0052	0.3214	0.0036	0.4952
384/96	0.0008	0.0009	0.2329	0.0009	0.3481
384/192	0.0005	0.0005	0.2518	0.0006	0.5491
512/16	0.0021	0.0034	0.1188	0.0020	0.3953
512/32	0.0041	0.0109	0.3902	0.0039	0.5537
512/64	0.0017	0.0010	0.1384	0.0017	0.2724
512/128	0.0049	0.0103	0.3099	0.0048	0.2225
768/12	0.0108	0.0106	0.2945	0.0109	0.4975
768/24	0.0086	0.0083	0.3057	0.0087	0.6390
768/48	0.0062	0.0062	0.2895	0.0063	0.5539
768/96	0.0008	0.0008	0.0913	0.0008	0.6826

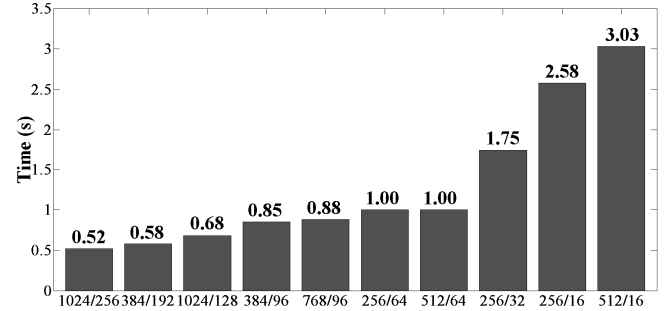| *L / I*	*p*-value				
	Mean	Median	Variance	RMS	Kurtosis
1024/16	0.0499	0.0545	0.1485	0.0496	0.3838
1024/32	0.0572	0.0572	0.1346	0.0568	0.4259
1024/64	0.0615	0.0615	0.2249	0.0613	0.2833
1024/128	0.0012	0.0012	0.1362	0.0012	0.4219
1024/256	0.0012	0.0012	0.1362	0.0012	0.4219

Fig. 5. The total computation time of the proposed algorithms for all trials in seconds.
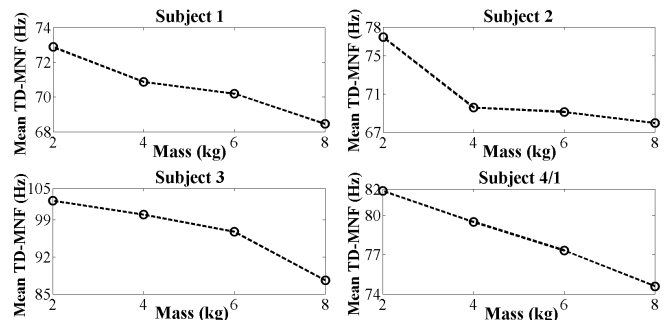

Fig. 6. Mean of the selected TD-MNF of the biceps brachii muscle during cyclic dynamic contraction with a 384-sample window size and a 192-sample window increment.
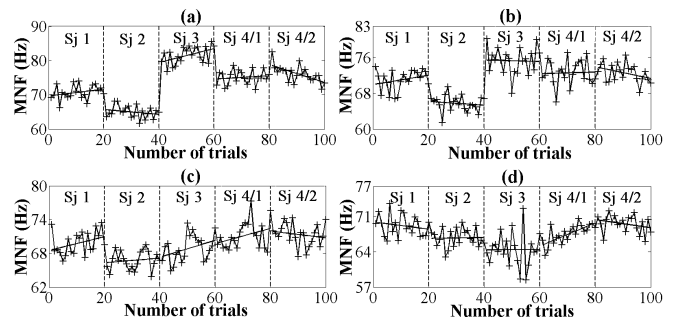

Fig. 7. The series of MNF feature of all subjects at different loading conditions: (a) 2 kg, (b) 4 kg, (c) 6 kg, and (d) 8 kg, for proving an un-fatiguing of the muscle.

In Fig. 6, a relationship between the mean feature of the selected TD-MNF and the muscle loading level is shown. There is a certain relationship of mean feature of the selected TD-MNF for all trials and all subjects that was not found in the traditional method. In order to confirm the discovery that it is not occurring from the effect of muscle fatigue. The linear regression analysis is employed to observe the behavior of the muscle fatigue. The series of the MNF values from all subjects with different loading levels, for instance, are shown in Fig. 7. It confirms that decreased MNF values are not affected from the muscle fatigue. Hence, we can conclude that the proposed method can be

used as a useful index to detect both muscle force and muscle fatigue.

V. CONCLUSIONS

A concept of using consecutive FFTs to extract the MNF feature (TD-MNF) has been proposed for yielding the analysis of EMG signal with a time-frequency domain. It can be used to detect muscle fatigue from the literature; moreover, in our study, the proposed modification of TD-MNF can be used to determine both muscle force and fatigue. Its better separation and reliability performance of the proposed method is shown through the experiments. An increasing of the processing cost in the method does not require any additional hardware. In total, four optimal parameters can be concluded: (1) the FFT window size is 384 samples; (2) the window increment of time-dependent procedure is 192 samples; (3) the suitable range of TD-MNF is from the seventh position to the eighth position; and (4) the optimal features extracted from the suitable range are mean and median parameters.

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