

Study of the Electrically Evoked EMG and Torque Output During the Muscle Fatigue Process in FES-Induced Static and Dynamic Contractions

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Abstract

This study compared the different fatigue processes of electrically elicited static and dynamic muscle contractions of quadriceps in five paraplegic subjects. An electrodynamicometer was utilized for recording the generated torque output and controlling the isokinetic dynamic movements. Stimulus-evoked electromyography (EMG), after artifact suppression, was used to observe the fatigue process. Besides torque output, the measured EMG features included peak to peak amplitude, rise time to peak and peak to peak duration. The measurements were modeled by a hyperbolic tangent function, which allowed observation of their time constants, inflection times and relative residual levels during the fatigue process. The time constants as well as the inflection time of torque output and EMG features were compared between static and dynamic contractions. The inflection times of torque output and all EMG features measured during static contraction were found larger than those of dynamic contraction. In EMG temporal features, the inflection times of rise time to peak and peak to peak duration in static contractions were also found significantly larger than those of dynamic contractions. These conditions indicated that, from either contractile (torque curves) or excitation (EMG features) aspects, the electrically elicited muscle contraction in dynamic movement is prone to fatigue earlier and faster.

Key words: electromyography, functional electrical stimulation, muscle fatigue, paraplegia.

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Irrespective of the stimulation modes or control schemes applied, muscle fatigue always interferes with the application of functional electrical stimulation (FES) in subjects with spinal cord injury. This is because the simultaneous contractions of paralyzed muscles elicited by externally applied stimulation are quite different from the graded recruitment characteristics of normal voluntary contractions [13, 24]. In addition, emaciation of the paralyzed muscle, due to the lack of conditioning and exercise after injury and other hemodynamic factors, further deteriorates the capability in a sustained contraction [9, 27]. Although many approaches have been proposed to alleviate the influence of muscle fatigue in FES studies, the characteristics and mechanism of muscle fatigue deserve deliberate studies [2, 12, 14].

Many researchers have studied muscle fatigue from the biomechanical, metabolic and neurophysiological aspects [3, 9, 15-19, 27]. The decline of torque values during static contraction is usually observed and modeled by ei-

ther an exponential or a hyperbolic equation [2, 16, 26-28]. Study of muscle fatigue from the metabolic aspect of muscle contraction by recording phosphorous metabolites from ³¹P magnetic resonance spectroscopy has been reported [15]. Through incorporating the metabolic process with a mechanical musculotendon model, the fatigue processes of the paralyzed quadriceps muscle subjected to intermittent stimulation can be predicted [8, 9]. From the neurophysiological aspect, studies have investigated the stimulus-evoked EMG (M-wave) or compound muscle action potential (CMAP) of stimulated muscle during the fatiguing process. The close correlation between muscle force and stimulus-evoked EMG peak to peak (PTP) amplitude indicates the possibility that the EMG signal can directly provide information for monitoring FES-induced muscle activity [5, 10, 22, 23].

In addition to the amplitude, other characteristics of CMAP, such as temporal features including latency, rise time to peak (RTP) and PTP duration, and frequency

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features including median or mean frequency, have also been used to quantify the muscle fatigue process [4, 6, 18, 26, 30]. The temporal and frequency features were utilized to investigate the propagation velocity of motor unit action potential in muscle fibers. Most of the studies found that the muscle fiber conduction velocity showed a decreased trend during the muscle fatigue process such that the spectral variables shifted to the left side, i.e., lower frequency component became more evident [7, 11, 18].

Most of the FES fatigue studies were conducted in the static condition, whereas the muscle force in many practical FES applications is usually generated at different muscle lengths or from dynamic movements. Researches reported that dynamic muscle force is related to contraction velocity [31, 32]. Our previous study on the velocity effect of stimulated muscle indicates that the amplitudes of the evoked EMG of the quadriceps muscle in lower contraction speeds are significantly larger than those of higher contraction speeds [3].

Although the contraction velocity effect of stimulated muscles has been discussed, the fatigue characteristics (particularly in the neural excitation aspect) of dynamic muscle contraction are still unclear. The issue of muscle fatigue during electrically elicited dynamic contractions is of paramount importance for external control of paralyzed extremities via FES, e.g. for optimizing the stimulation parameters and for better control of FES-walking. Our approach is to compare the changes of amplitude and temporal features of stimulus-evoked EMG during fatigue process of static and dynamic contractions. To characterize the fatigue process, a hyperbolic tangent equation, generally used for describing empirical data with a sigmoid-like curve, was adopted to fit the measurements derived from the torque output and the evoked EMG [16, 27]. The hyperbolic parameters of torque output, EMG PTP, RTP, and PTP duration obtained from static and dynamic contractions were compared in terms of the inflection time, time constant, and relative asymptotic value.

Materials and Methods

Experimental protocol

Five spinal cord injured subjects with neurological injury between C7 and T11, with no or only mild spas-

ticity, were recruited for this experiment. The detailed conditions of the subjects are listed in Table 1. The subjects had no musculoskeletal problems in their lower extremities. All subjects signed an informed consent form approved by National Cheng Kung University Hospital, Tainan, Taiwan.

During muscle fatigue study, the subject was seated in the chair of an electrodyamometer (Cybex 6000, Lumex, Inc., NY, USA) with the hip joint fixed in 80° flexion. The quadriceps muscle group was stimulated by a constant current stimulator with a monophasic waveform of 20 Hz with a pulse duration of 300 msec at a maximal current of 120 mA. The stimulation electrodes were placed on the distal and proximal ends of the quadriceps muscle bellies. The anode was placed 5 cm above the upper border of the patella. The cathode was placed 20 cm proximal to the placement of anode. In this arrangement, only the quadriceps muscle can be stimulated during the tests. This avoided the problem of measuring cross talk from other stimulated muscles. To detect the stimulus-evoked EMG, active electrodes with preamplifiers (Motion Control Co., Salt Lake City, Utah, USA) were applied on the stimulated muscles. The recording electrodes were placed mid-way between the anterior superior iliac spine and the upper border of the patella [25]. The interelectrode distance was 20 mm and the electrode position was maintained in each subject throughout the experiments. Before the application of measurement electrodes, the skin was abraded carefully to reduce the skin-electrode impedance. To suppress the stimulus artifact, the output stage of the stimulator was grounded immediately after the stimulus pulse was generated [20]. After artifact suppression and amplification, the stimulus evoked EMG was sampled through an analogue-to-digital converter with 5000 Hz sampling rate. The measured data were directly saved to a hard disk for later analysis using Matlab (Mathwork Co., Natick, Mass., USA) signal processing software.

Two types of contraction, both in static and dynamic conditions, were performed to induce fatigue. In dynamic isokinetic testing, the contraction velocity was controlled at 30°/sec with an excursion range from 30° to 110° of knee flexion. The choice of excursion range is based on the maximal knee flexion angle in the Cybex 6000 and the effect of passive stretch from the ham-

Table 1. Description of spinal cord injured patients participating in this study.

	Age (years)/Gender	Months post injury	Level of injury	Height (cm)	Weight (kg)
S1	52/M	30	T9	158	52
S2	22/M	13	T6	173	58
S3	44/F	27	C7	156	54
S4	42/M	88	T3	169	71
S5	43/M	100	T11	162	73

S = subject, C = cervical, T = thoracic.

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string muscle group. This is because the lengthened hamstrings will counteract the contraction of quadriceps muscle. According to the excursion range in dynamic contractions, the muscle fatigue study in static contraction was performed when the knee angle was maintained at the two different angles of 30° and 110°. For a single day, only one session of static or dynamic testing was performed with each leg. Adequate rest was required to avoid possible carry-over effect due to the long recovery time after muscle fatigue [9, 21].

Two types of features, amplitude and temporal features, were commonly used to characterize the waveform of the stimulus-evoked EMG. The PTP amplitude of the CMAP was highly correlated with declining torque output [5, 23]. The temporal features included RTP and PTP duration, which are believed to be related to muscle fiber conduction velocity [26].

Usually, the amplitude parameter of paralyzed muscle possesses nonlinear properties, which can be divided into the first plateau, a decaying slope, and the residual asymptotic level. In contrast, the change in the temporal parameters with inverted manifestation to the frequency parameter can be divided into an initial lower plateau, a rising slope, and the maximal asymptotic level. Our interest is in observing the rising and decaying processes of the evoked EMG parameters and the torque output during the fatigue process, rather than making a direct comparison of their values.

Data analysis

The hyperbolic tangent equation adopted to fit both the parameters of the evoked EMG and the torque output is

$$Y = a * \tanh(b * t - c) + d$$

where Y is the measured parameter of the evoked EMG or the generated torque as a function of time, t . The parameters a , b , c and d are estimated by using the least-square error method [27]. The inflection time and time constant, representing the time to reach 50% the change range and its changing rate, can be obtained from c/b and $1/b$, respectively. Derived from the four parameters, $d-a$ and $d+a$ represent the initial plateau and the asymptotic values, respectively. The total change of the parameter (the difference between maximum and minimum values) is $2a$. The value of $(d+a)/(d-a)$ represents the relative asymptotic value. Three tests, two static and one isokinetic, were performed on all subjects in each of the lower limbs. In total, there are 30 experimental specimens of the quadriceps muscle groups in the five subjects. For testing the differences in the fatigue process between static and dynamic contractions, the paired t tests were performed on each of the four measurements (torque output, EMG PTP, RTP, and PTP duration). The significant level was set at $p < 0.05$ for indicating the different fatigue rates in static and dynamic contractions.

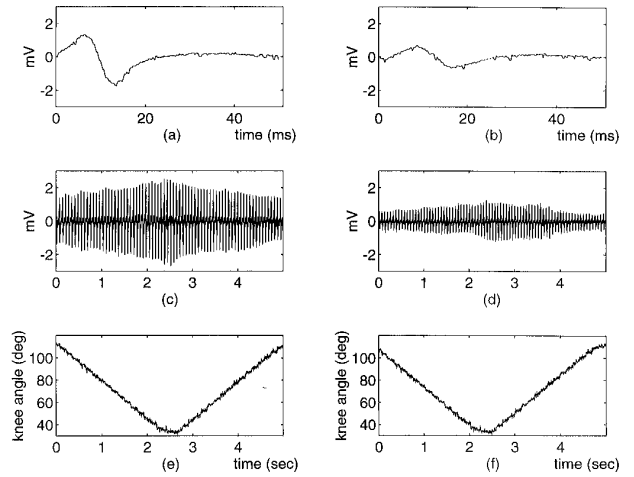


Figure 1. Sampled waves of stimulus-evoked EMG in dynamic contractions before (a and c) and after (b and d) muscle fatigue. The evoked EMG with larger amplitude and shorter duration was measured at the beginning of stimulation (a), in comparison with muscle fatigue (b) in the end of stimulation. The EMG amplitude varied with the change of joint angle can be observed before (c) and after (d) muscle fatigue during dynamic contractions, with the corresponding knee angles plotted on (e) and (f).

Results

Characteristics of amplitude and temporal features during muscle fatigue

Fig. 1 presents typical segments of stimulus-evoked EMG signals from subject 2 before and after muscle fatigue during dynamic muscle contraction. Compared to

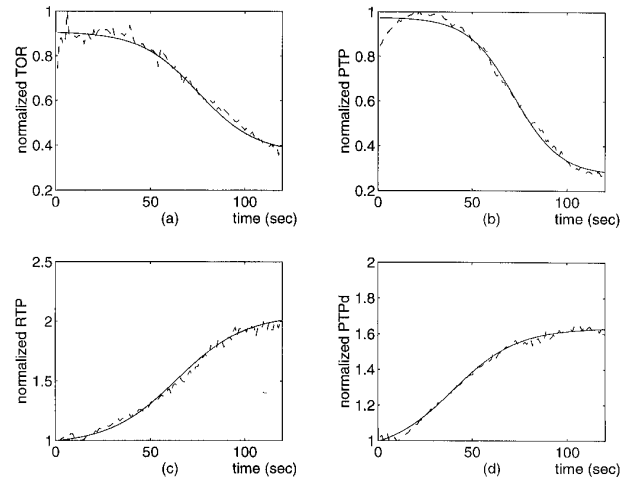


Figure 2. Typical examples of hyperbolic curve fits (solid line) for the measurements (dashed line) of (a) torque output and EMG features in static contractions, including (b) peak to peak (PTP) amplitude, (c) rise time to peak (RTP) and (d) PTP duration.

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the EMG before muscle fatigue in Fig. 1a, the stimulus-evoked EMG after muscle fatigue in Fig. 1b exhibits lower amplitude and broader waveform duration. The two plots on Figs. 1a and 1b were CMAP's sampled from the two segments showed on Figs. 1c and 1d which were plotted with respect to the knee flexion angles in Figs. 1e and 1f. Furthermore, the EMG amplitudes vary with the change of knee flexion angle, i.e. at varied muscle lengths, in dynamic contractions. In general, the stimulus-evoked EMG shows larger amplitude when the knee joint is at a less flexed position. From the corresponding knee flexion angles in Figs. 1e and 1f, the maximum EMG amplitudes for both before and after muscle fatigues cases can be observed at about 30° of flexion. Because of the oscillating features of stimulus-evoked EMG during dynamic contractions, the amplitude and temporal features of stimulus-evoked EMG from every repetition of dynamic movement were averaged for further comparison.

By taking the torque and stimulus-evoked EMG of static contractions as examples, the data collected from the same subject were normalized to his/her initial value and then fitted using the hyperbolic function. The solid lines shown in Fig. 2 are typical examples demonstrating the well fitting hyperbolic functions for torque output and EMG features in static contractions. As the muscle fatigued, the torque output decreased to about 38% of its maximum value, as shown in Fig. 2a. Similarly, the EMG PTP showed a decaying trend, as illustrated in Fig. 2b. This was positively correlated with the torque output ($r = 0.85$, $p < 0.05$). For the temporal features of stimulus-evoked EMG, both RTP (Fig. 2c) and PTP duration (2d) show a short initial flatness and then increase monotonically to a higher plateau. In contrast

to the positive correlation for EMG PTP amplitude, the two temporal features are negatively correlated with the torque output ($r = -0.74$ and -0.73 for RTP and PTP duration respectively, $p < 0.05$).

Comparisons between static and dynamic contractions

To illustrate the changes of features in dynamic contraction for entire fatigue process, Fig. 3 shows typical examples of torque output and EMG features measured during knee flexion back and forth from 30° to 110° under continuous stimulation. During dynamic contraction, Figs. 3a and 3b show the oscillations of torque output and EMG PTP amplitude as well as their hyperbolic best fit curves in a decreasing trend. In contrast, RTP and PTP duration fluctuate at a lower level first, then increase continuously to a higher level, which can also be fitted with rising hyperbolic curves (Figs. 3c and 3d). The corresponding knee angle in Fig. 3e shows that the EMG PTP amplitude peaks occur at about the same time with the knee flexion angle. This indicates that the PTP amplitude measured in the shortened position is larger than those obtained from lengthened positions. In addition, the oscillation of EMG PTP amplitude in accordance with flexion angle is more evident at the beginning of stimulation and diminishes over time (100 sec) (Fig. 3b). The peaks of RTP and PTP duration also occur at about the same time with the knee flexion angle. But different to EMG PTP amplitude, EMG temporal features have smaller values in shortened muscles than those from lengthened muscles. In contrast to the diminished oscillatory phenomenon in EMG PTP amplitudes, the RTP and PTP duration become increased as muscle fatigue progresses.

Table 2. Summary of hyperbolic fit parameters for the fatigue process during static and dynamic contractions

	Time constant (1/b) (sec)	Inflection time (c/b) (sec)	Asymptotic value (d+a)/(d-a)
Torque _{st}	26.99(5.25)	54.92(8.05)	0.40(0.06)
Torque _{dy}	19.70(5.63)	33.31(7.23)	0.52(0.21)
	<i>Torque_{st} > Torque_{dy}</i>	<i>Torque_{st} > Torque_{dy}</i>	
PTP _{st}	15.74(6.37)	52.30(4.76)	0.42(0.11)
PTP _{dy}	19.38(10.45)	40.34(7.18)	0.44(0.15)
	<i>PTP_{st} > PTP_{dy}</i>	<i>PTP_{st} > PTP_{dy}</i>	
RTP _{st}	32.84(7.29)	41.93(7.78)	1.70(0.48)
RTP _{dy}	24.41(3.33)	29.70(5.0)	1.80(0.68)
	<i>RTP_{st} > RTP_{dy}</i>	<i>RTP_{st} > RTP_{dy}</i>	
PTPd _{st}	29.84(7.29)	40.94(9.93)	2.06(0.59)
PTPd _{dy}	21.38(6.23)	30.53(11.09)	1.69(0.53)
	<i>PTPd_{st} > PTPd_{dy}</i>	<i>PTPd_{st} > PTPd_{dy}</i>	

PTP = peak to peak amplitude, RTP = rise time to peak, PTPd = peak to peak duration. The subscripts 'st' and 'dy' represents the measurements obtained from static and dynamic contractions, respectively. The values in the brackets are the standard deviations. The symbol '>' denotes the difference between static and dynamic contractions ($p < 0.05$).

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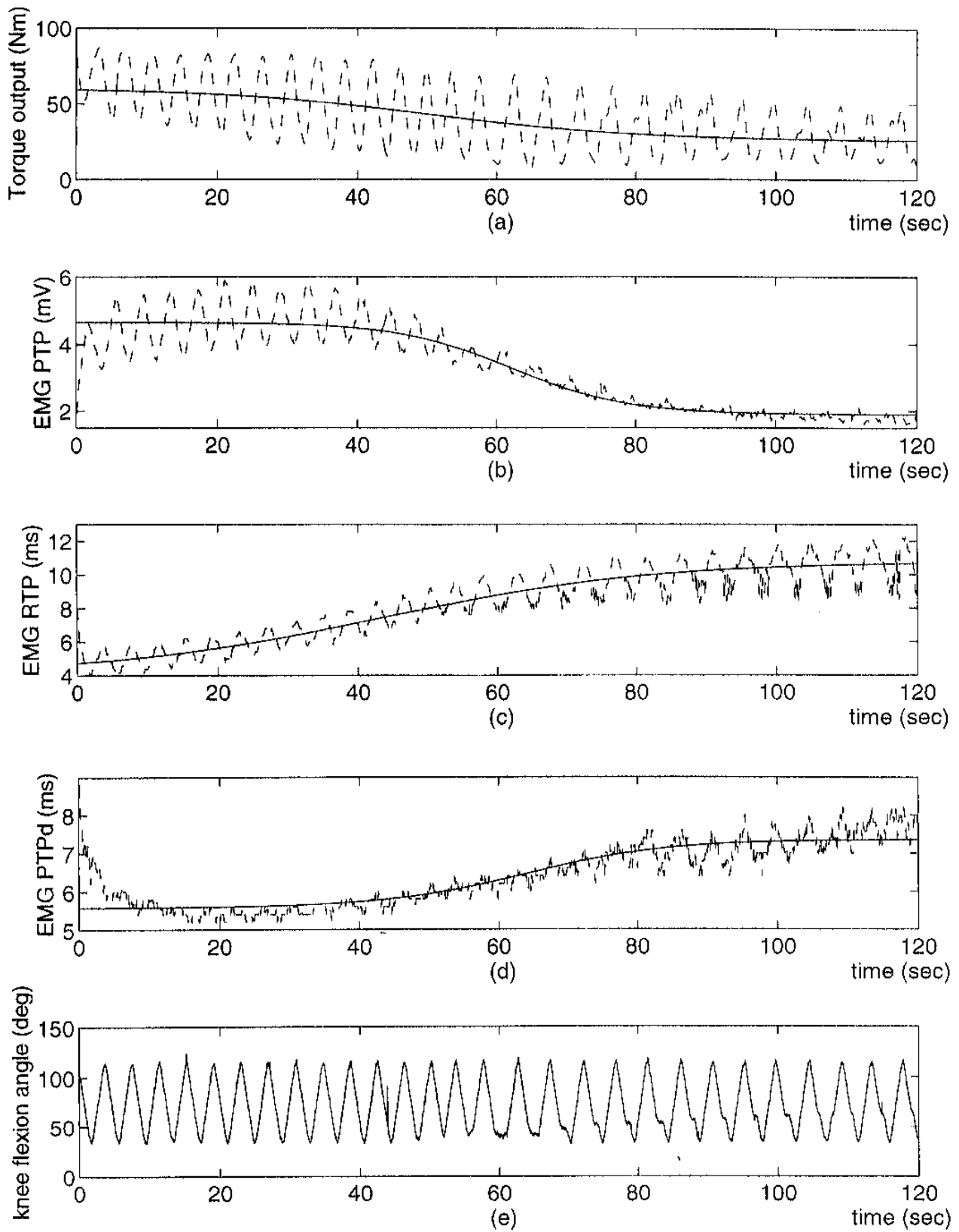


Figure 3. During dynamic contraction, the torque output (Nm: newton*meter) (a), EMG PTP amplitude (b), EMG RTP (ms: milli-second) (c) and EMG PTP duration (d) exhibit varied oscillatory behaviours with corresponding knee flexion angles plotted in (e). Both the torque output and EMG features are fitted to the hyperbolic functions (solid lines).

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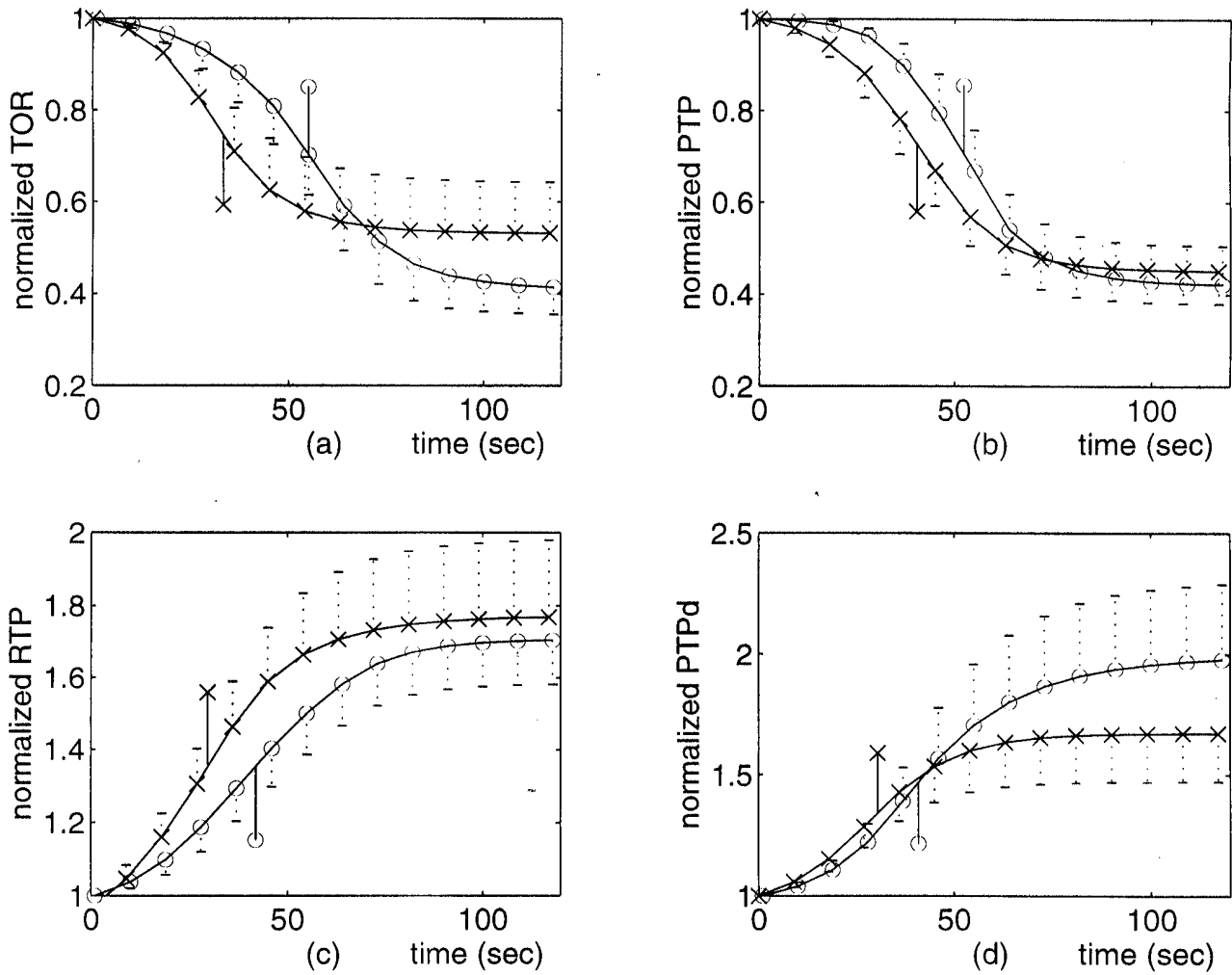


Figure 4. The averaged hyperbolic curves of torque output and EMG features of dynamic contractions (-x-) are compared with those derived from the averages of static contractions (-o-). The error bars on the figure denote the standard deviation of the averaged data. The inflection time of each curve was denoted by a vertically solid line (static -o- & dynamic -x-). The torque output (a) of static contraction has a slower decaying rate than in dynamic contractions. Among the EMG features, PTP amplitude (b) exhibits a similar declining rate, while the RTP (c) and PTP duration (d) of static contractions show slower rising rates than those of dynamic contractions. The extracted hyperbolic parameters are summarized in Table 2.

For comparing the fatigue process between static and dynamic contractions, the hyperbolic curve fit for torque output and EMG features extracted from the average of static contractions and dynamic contractions were summed and plotted in Fig. 4. The corresponding hyperbolic function parameters and further statistic analysis (paired *t* test) are summarized in Table 2. Slower declining rate in the torque output of static contractions, 26.99 ± 5.25 compared with 19.7 ± 5.63 in dynamic contractions, was observed (Fig. 4a). With the exception of EMG PTP amplitude (Fig. 4b), the EMG temporal features of RTP and PTP duration (Figs. 4c and 4d, respectively) show significantly larger time constants in static contraction. Significant differences for both torque output and EMG features between dynamic and static contractions were found for inflection time (Table

2). The inflection times of torque output (54.92 ± 8.05) and EMG PTP (52.30 ± 4.76) measured during static contractions were found significantly larger than those of dynamic contractions (33.31 ± 7.23 and 40.34 ± 7.18 , respectively). In EMG temporal features, the inflection times of RTP (41.93 ± 7.78) and PTP duration (40.94 ± 9.93) in static contractions were also found significantly larger than those of dynamic contractions (29.70 ± 5.0 and 30.53 ± 11.09 , respectively). Larger inflection times in static contraction imply that the changes of torque output and EMG features, either decreasing or increasing, are delayed in comparison with dynamic contractions. No significant differences in relative asymptotic values were found between static and dynamic contractions.

Discussion

Under continuous stimulation, either in static or dynamic contraction, the torque output and the EMG PTP amplitude exhibit decreasing trends and the temporal features of RTP and PTP duration show increasing trends during muscle fatigue. The reduction of EMG PTP amplitude during continuous stimulation could result from a reduction in the number of contributing motor units (MUs) or a reduction in the amplitude of the MUAP [26]. Concurrently with the reduction in EMG PTP amplitude, the increase in RTP and PTP duration denotes a broadening in the CMAP, which is commonly explained by the reduction of the muscle fiber conduction velocity [26].

In dynamic contractions, both of the amplitude and temporal features oscillated concurrently with the changes in muscle length. This phenomenon matched those observed from static contractions where muscle length had an obvious effect on the values of the EMG features [3]. In the fatigue process, when muscle force decayed intensely, the EMG PTP amplitude decreased to a low level, such that the intensity of oscillation was also lessened. On the other hand, the oscillations of temporal features became much larger as fatigue progressed. The larger oscillations of temporal features indicate that the difference of temporal features between lengthened and shortened muscles become more apparent. As muscle was fatigued, the temporal features on a lengthened muscle exhibited a slower propagation velocity, but it was less relevant to a shortened muscle. It seems that the effect of muscle length on the propagation time of the MUAP is more evident in the fatigued muscle.

Compared with static contractions, dynamic contractions showed more rapid change of the EMG features. The torque output was also found to be sustained for a shorter period than in static contractions. In both voluntary or electrically elicited muscle activities, the force-velocity relationship has been studied and analyzed. The results show that muscle fibers in high-speed contractions are less efficient in building contraction force [29, 31, 32]. The reason for the reduced force in high speed contractions is explained by poor excitation-contraction coupling (ECC) forming more cross bridges in a very short period. Furthermore, the fluid viscosity of the muscle, which causes viscous friction to impede muscle shortening also explains the earlier fatigue in dynamic contractions [32]. Our previous study on the comparison between dynamic and static contractions also revealed smaller EMG PTP amplitudes in dynamic contractions [3].

The mechanism of earlier fatigue in dynamic contractions might be explained from a mechanical point of view. In the beginning of stimulation, the muscles in static contractions are used to tighten the muscle fibers [1]. After that, the previously potentiated energy will be released successively. In static stimulation, there is

enough time to let the stimulation synchronize the motor units to contribute the long sustained torque output. This mechanism may explain the postponed muscle fatigue in static contractions.

In summary, the hyperbolic curve fit of torque and EMG features are used in this study to observe the muscle fatigue induced by continuous electrical stimulation at two different contraction types. Comparing the static and dynamic contractions, the decaying rate of force output and rising rate of EMG temporal features are slower in static contractions. These experimental results imply that electrically-elicited dynamic contraction is prone to fatigue earlier and faster as compared to static contraction.

Less fluctuation in PTP amplitude and larger oscillations in temporal features can be observed in the fatigue process of dynamic contraction. An abundance of physiological information can be inferred from the oscillatory phenomena of the hyperbolic parameters of EMG features. Our ongoing research is to compare the time constant and inflection time of temporal features between normal and chronic spinal cord injured subjects in an attempt to estimate the changes in muscle fiber composition after deprivation of supraspinal control.

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