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Electromyographical assessment on muscular fatigue—an elaboration upon repetitive typing activity

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Abstract

The objectives of this study were to quantify the electromyographic activities (EMG) of finger muscles during prolonged, low-forces, and repetitive typing with an ergonomically designed VDT workstation, as well as to analyze the occurrence and the possible mechanisms of muscular fatigue in touched typists. Thirty healthy female typists were recruited to type consecutively for 2 h. The surface EMG of extensor digitorum communis (EDC) and flexor digitorum superficialis (FDS) of both hands was recorded throughout the entire test. Electrical activity (EA) and median frequency (MDF) were calculated, and then regressed against the time courses to obtain the slopes of progress. Further analysis of the EMG parameters was done by the joint analysis of spectra and amplitudes (JASA). The results indicated that maximum voluntary electrical activation (MVE) decreased after 2-h typing, and did not recover to the initial values even after a 10-min break. Besides, there was a trend of decrement in frequency throughout the entire trail, and the MDF reduced by 25% in comparison with the initial values. With the JASA plot, 74% of the muscles manifested fatigue after 2-h typing activity. Furthermore, we observed that the EDC muscles were more susceptible to muscular fatigue than the FDS muscles. In conclusion, prolonged consecutive typing may induce muscular fatigue in the healthy typists even in an ergonomic typing environment.

Keywords: Ergonomics; Electromyogram; Dynamic contraction; Muscle fatigue; Typing

1. Introduction

Computers have extensively been used in many workplaces as well as in households. According to the Center for Office Technology, about 15 million computers were in use in the US in 1987 [12]. The number inflated to 175 million in 2001, and probably increase to 251 million by 2007 [11]. Some reports indicated that data entry operators experienced more musculoskeletal discomforts than other office workers [6]. The mechanism underlying these work-related musculoskeletal disorders was controversial, but it was generally presumed to be related to the overuse of the muscles, tendons, or nerves [3]. Highly repetitive keying, awkward posture, and static loading of the arms, hands or wrists put the VDT users at an increased risk of musculoskeletal disorders [46].

In the context of ergonomics and work physiology, muscle fatigue is defined as any exercise-induced reduction in the maximal capacity to generate force or power [49]. One straight way to determine muscle fatigue was to measure the mechanical performance capacity of muscles by repeated execution of maximum voluntary contraction (MVC) in separate occasions during the work. Such a procedure is, however, not always feasible in real work situations, since the measurements usually interrupt the work flow. Meanwhile, force produced by involving muscles may not be easy to assess exactly. Consequently, electromyogram

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(EMG), recording the patterns of muscle action potentials, was developed and used as one of the tools to reveal muscle fatigue in ergonomics [33].

The conventional parameters obtained by the EMG included electromyographic activity (EA), root mean square (RMS), median frequency (MDF), and mean power frequency (MPF). Decrease in MDF and/or MPF has been demonstrated in the quadriceps during isokinetic knee extensions [22], the gastrocnemius during isokinetic plantar flexions [21], some leg muscles during uphill running [1], the shoulder muscles during repetitive arm works [49], and in the biceps brachii during repeated elbow flexion–extension movements [9,37]. On the other hand, the EMG amplitude has been observed to increase during repetitive, dynamic submaximal efforts [21,31,36], and decrease during maximal efforts [21,31]. Luttmann proposed a new joint analysis of spectra and amplitude (JASA) method to assess fatigue of muscular activity [35,36]. The JASA method simultaneously considers the changes in the EMG amplitude and spectrum throughout the task. Therefore, the main advantage of JASA method is that the subjects do not have to interrupt the task intermittently to perform isometric contractions, such as the MVC test [27].

Although many researchers have quantified muscle fatigue with EMG recorded during dynamic contractions, little was done about continuous typing. Lundervold was one of the pioneers to investigate muscular activities through EMG during typewriting [34]. He recorded increasing muscular activities not only in the shoulder and upper arm muscles, but also in the forearm muscles. Some studies have examined the effects of typing on finger flexors and extensors by EMG. But most of these studies included only a few subjects, and the typing was of short duration [4,18,44]. Some authors used EMG as a tool to evaluate the posture resulting from space constraints of the VDT workstations or to find out the appropriate typing force on keyboard to reduce the physical loading during typing [4,18,20,38,44]. However, few academic researches were done to analyze muscular fatigue of prolonged typing activities by continuous EMG recording.

Therefore, the objectives of this study were to quantify the muscle activities during consecutive typing with well controlled VDT workstation, and to apply the JASA method to evaluate the occurrence and the possible mechanisms of muscular fatigue during typing.

2. Materials and methods

2.1. Subjects

Thirty healthy females, with a mean age of 23.0 (±2.3) years, were recruited from Bulletin Board System (BBS). All the subjects used 10-digit touch method to type and their average typing speed and accuracy, determined by the five-time typing tests were 51.6 words per minute (WPM) and 87.1%, respectively. No subject had a history of upper extremity pain lasting more than one day in the past one year, and was examined by a certified physicist to ensure no pain, tenderness, weakness, or others symptoms/signs of musculoskeletal disorders of upper extremities prior to the tests. All of them signed an informed consent after a full explanation about the study procedures.

2.2. Workstation

In the laboratory, a compartment simulating the workstation that typists used in daily working was built, according to published ergonomics guidelines [2] and related literatures [23,38]. All subjects were asked to adjust the height of the seat cushion, the height of the armrest, and the backrest inclination based on personal preference, and the researchers checked and made sure their postural angles while typing were within the range listed in Table 1. The half-split keyboard with a fixed slant opening angle of 30° and a built-in forearm–wrist support, which slopes downward from inside to outside range and extends approximately to 14 cm from the home row to the edge, was selected for use in this study. Four 5-min typing tests were performed before the start of this experiment to ensure that their typing speed and accuracy qualified for in the present study. They were also allowed for 1-min break between every two consecutive typing tests.

2.3. EMG data acquisition and analysis system

Disposable surface electrodes (Al/AgCl) with 10 mm diameter were used in this study. The electromyographic signals were recorded through the bipolar arrangement with an inter-distance of 26 mm. Surface electrodes were placed on the skin of both forearms to record the muscle activities of the underlying finger flexors (flexor digitorum superficialis (FDS)) and extensors (extensor digitorum communis (EDC)), and paralleled the direction of muscle fibers. The reference electrode was attached on the subject's lateral mal-

Table 1
Requirements of postural angles during typing experiment (modified from Ref. [23])

Postural elements	Degree (°)
Trunk inclination	90–95
Shoulder flexion	100–115
Shoulder abduction	0–20
Elbow flexion	85–100
Ulnar abduction	0–3
Wrist extension	0–5

leolus of right ankle. The placement was chosen based on the published guidelines [13,42], and was calibrated using manual resistive techniques for testing isolated motions and observing the display of the EMG signal from all monitoring muscles. The final positions of electrodes over the extensor side were located at the muscle belly, about one-third from head of ulna to the olecranon. The electrodes of the flexor side were placed at approximately 5 cm away from the bicep tendon at the elbows. In order to reduce the noise disturbances of cable motion artifact, a preamplifier with high input impedance (100 MΩ) and 350 gain was mounted behind every electrode.

The electrodes were wired to the MP100 system (BIOPAC Systems Inc.). The input impedance and common mode rejection ratio (CMRR) of the MP100 system were 1 MΩ and 90 dB, respectively. After converted from analog-to-digital (A/D), the raw EMG data at a sampling rate of 1024 Hz for every channel were fed into a specific analysis system programmed with LabView 6.0 software (National Instruments Inc.) for further analysis. The analysis system used Baratta's method to eliminate the interference of ambient electromagnetic fields [5], and was equipped with a band-pass filter in the range of 10–500 Hz. EA was derived from the raw EMG data by full-wave rectification and continuous average. The time constant was set as 400 ms according to the recommendation by Farina and Merletti [17]. In order to reduce variations and condense the enormous data, the system averaged those EA values for every 10-s epoch and normalized by the maximum voluntary electrical activation (MVE). Thereby, the mean EA was plotted against time, and then analyzed by the linear regression method. Meanwhile, we calculated power spectra density (PSD) from every 1024 samples (1-s period) by means of fast Fourier transformation. Similarly, all spectra within 10-s epoch were averaged and the mean MDF was calculated. The time course of MDF was plotted with time as the horizontal coordinate and frequency as the longitudinal coordinate.

2.4. Procedures

At first, the subjects were instructed to perform MVC test three times in sitting position [40]. They were asked to place the forearm on the desk in full pronation and parallel to the floor. The wrist was kept straight to the forearm throughout the MVC tests. A 5-kg resistance was applied at the middle phalanges of digits, and the subjects were instructed to extend their fingers to the maximum for 6 s. Verbal motivations and visual feedbacks from the oscilloscope of the data acquisition system were used to encourage their maximal efforts. Between every two MVC tests, the subjects had 5-min restitution to avoid the influence of muscle fatigue. The highest EMG value across the three tests was denoted as MVE for the finger extensors. The MVE for the finger flexors was obtained by the same protocol, but with finger flexion at the supination position.

The subjects were then requested to type for a 2-h period without pause longer than 3 s. Once the entire 2-h typing work was done, one MVC test for both finger extensors and flexors was immediately conducted again, followed by another two MVC tests with a 5-min interval between every two consecutive tests.

2.5. Joint analysis of spectra and amplitudes

The EMG data were expressed as a pair of parameters representing the slopes of the EA and MDF regressions, respectively. In the JASA plot, the change in EA over time (EA slope) is plotted in the abscissa, and the change in MDF over time (MDF slope) is shown in the ordinate. As a result, both characteristics of the EMG, i.e. EA and MDF, could be jointly considered. The results of JASA plots were classified into the following four categories:

(1) Increase in both EA and MDF over the EMG recording period, indicating an increase in muscle force (upper-right quadrant in the JASA plot).
(2) Increase in the EA along with decrease in the MDF, indicating muscle fatigue (lower-right quadrant).
(3) Decrease in the EA and increase in the MDF, indicating the adaptation of the involved muscles (upper-left quadrant).
(4) Decrease in the EA accompanied by a decrease in the MDF, indicating the decline in force produced by muscle (lower-left quadrant).

3. Results

3.1. EMG measurement during maximal voluntary contraction

Results of the EMG amplitude for the four monitored muscles during the MVC tests conducted before and after typing are presented in Fig. 1. There were significant differences in the EMG before and after the typing tests for all studied muscles ($p < 0.05$, paired Student's *t*-test). However, there was no statistical difference in EA values across those three MVC tests conducted during the recovery time (i.e. immediately, 5 and 10 min post-typing). Persistent low EA values were observed throughout the 10-min recovery time.

3.2. Time-dependent changes in the EMG

The examples of four typical patterns of EA and MDF slopes changing with time for individual muscle throughout the 2-h typing are shown in Fig. 2. Each

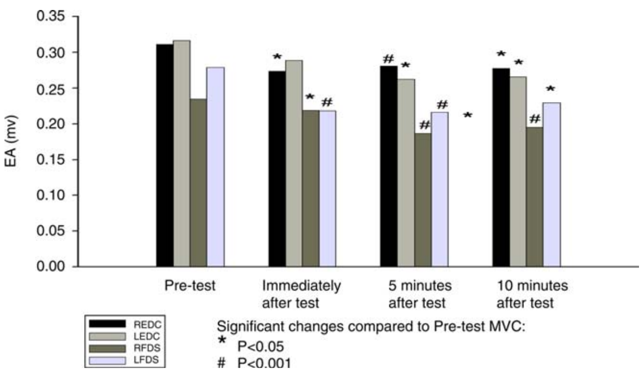

Fig. 1. Electrical activity (EA) of myoelectrical signals for the right and left forearm muscles during the MVC at various test stages ($N = 30$). REDC: right extensor digitorum communis; RFDS: right flexor digitorum superficialis; LEDC: left extensor digitorum communis; LFDS: left flexor digitorum superficialis.

point of the EA plot stood for the mean EA in a 10-s epoch and was normalized to MVE in percentage. Similarly, each point of the MDF plot represented the average MDF for every 10-s epoch. In Fig. 2, the adaptation, increase, decrease and fatigue quadrants demonstrated the positive (upward) or negative (downward) slopes in EA and MDF, and the slopes of the regression line were significantly different from zero ($p < 0.0001$). The mean slopes of EA and MDF during the time course of typing test for all subjects are summarized in Table 2. Negative regression slopes, denoting the progressive decrement in the EA or the MDF, were observed in all the studied muscles except the slope of the EA for the right flexor digitorum superficialis (RFDS). However, high variation (i.e. standard deviation) among subjects was also observed.

3.3. JASA plots

Table 3 summarizes all the 120 dots presented by the JASA method. According to the definition of the JASA plot, 74% of the 120 (EA, MDF) dots have manifested muscle fatigue or force decrease after the 2-h typing test. The other 26% were classified onto the adaptation and force increase quadrants (Table 3). The slopes of EA and MDF regression lines for all 30 study subjects are also presented by the JASA plot in Figs. 3–6. The JASA plot for right extensor digitorum communis (REDC) (Fig. 3) shows that 77% of the dots (EA, MDF) fell onto the quadrants representing fatigue and force decrease, with only few dots onto the adaptation quadrant. A similar phenomenon was found in the JASA plot for left extensor digitorum communis (LEDC) (Fig. 4). The majority of those dots fell onto the fatigue and force decrease quadrants, with only few dots belonging to the adaptation quadrant. In the JASA plots, the flexor muscles of both right and left forearms were more scattered when compared to the extensor muscles. Moreover, it was also observed that there were one dot for RFDS and three dots for left flexor digitorum superficialis (LFDS) being categorized into the force increase quadrant (Figs. 5 and 6).

4. Discussion

4.1. Assessment of muscular fatigue by conventional methods

In ergonomics, one of the conventional ways to assess muscular fatigue is the MVC test, which measures the muscular force-generation capacity through the MVE values before and after series of muscular contractions. Hägg et al. [27] proposed that if the time lag between the task work and the contraction test was brought to a minimum (2–3 s), the EMG traces would be representative of the physiological status of the muscle during work just before the interruption. From our study, significant differences in EA values between the pre- and post-MVC tests are seen (Fig. 1), and is similar to the findings of Komi [30] and Gerdle et al. [21].

Besides, the results also implied that all four muscles manifested long duration fatigue since the MVE values obtained at the recovery times were not significantly recovered in the post-test 10-min recovery time (Fig. 1). Long duration fatigue has also been called low-frequency fatigue, and the phenomenon was attributed to excitation–contraction coupling impairment [16]. There is an abundance of literatures indicating significant low-frequency fatigue on human muscles [16,47,48]. It is conceivable that the long-term typing activity might result in impairment of neuromuscular efficiency and reduction of twitch tension for the EDC and FDS muscles. Our results also demonstrated 74% of the studied muscles had a negative trend for the MDF during the 2-h typing test (Table 3). A significant decrease (25%) in the MDF with such low-intensity dynamic contractions (approximately 5–10% MVC) during the 2-h typing activity fulfilled the criteria of a decrease in MDF over 8% as being reliably identified as localized muscular fatigue [41]. The relationship between EMG amplitude and muscular fatigue, however, is more obscure than that between EMG frequency and muscular fatigue [33]. Some researchers even observed increased amplitude during dynamic fatiguing contractions [24,39]. The disconcordant phenomenon of EA among various muscles also occurred in our study (Table 2). Moreover, because of their poor correlation with torque and high variations between subjects, some researchers also disputed on the adequacy of using EMG amplitude in muscular fatigue [22]. Hence, we suggested that the MDF should be a more reliable and appropriate parameter than EA while analyzing mus-

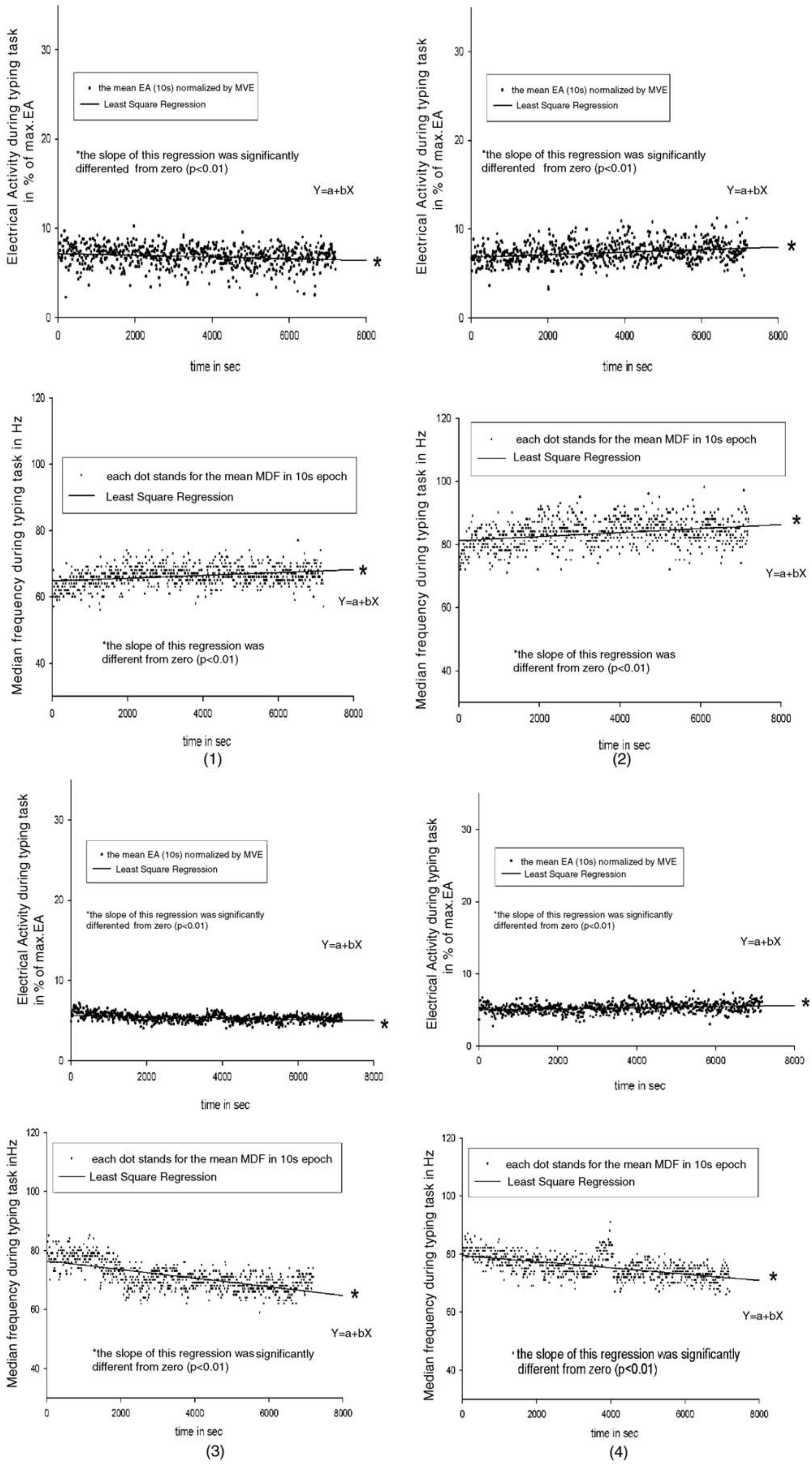

Fig. 2. Examples of EA and MDF in time series for four respective quadrants of JASA. (1) Adaptation quadrant (LEDC of subject 5), (2) increase quadrant (LFDC of subject 1), (3) decrease quadrant (REDC of subject 4), (4) fatigue quadrant (REDC of subject 14).

Table 2
Mean slope of EMG parameters for 2 h time course at different recording sites ($N = 30$)

Studied muscles	Mean slope of EMG measurements	
	EA, $\times 10^{-5}$ % MVE/s	MDF, $\times 10^{-3}$ Hz/s
REDC	−0.8 (±21.2)	−5.9 (±14.6)
LEDC	−4.0 (±12.2)	−3.5 (±13.4)
RFDS	0.7 (±32.2)	−4.9 (±34.3)
LFDS	−1.4 (±30.0)	−14.8 (±37.1)

EA: electrical activity; MDF: median frequency; REDC: right extensor digitorum communis; RFDS: right flexor digitorum superficialis; LEDC: left extensor digitorum communis; LFDS: left flexor digitorum superficialis.

cular fatigue in such a prolonged and low-force dynamic contraction.

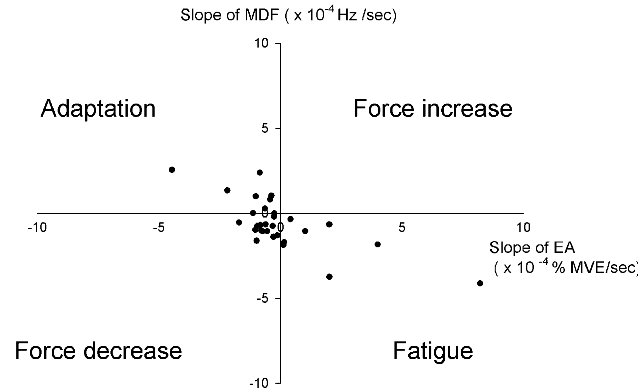

Fig. 3. JASA plot for REDC ($N = 30$).

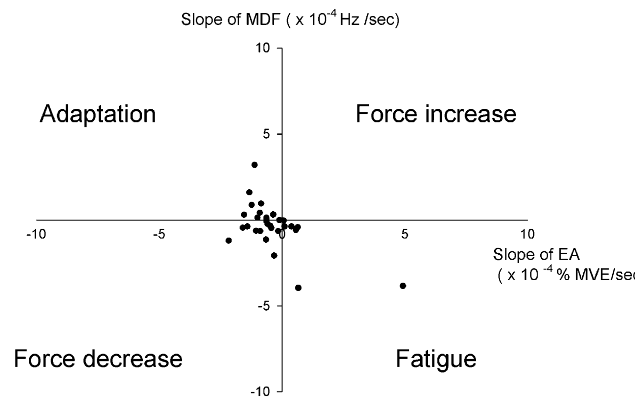

Fig. 4. JASA plot for LEDC ($N = 30$).

4.2. Assessment of muscular fatigue by JASA method

Joint analysis of EMG spectrum and amplitude (JASA) allowed us to consider the changes in amplitudes and spectrum simultaneously [26,35,36]. The prototype of the JASA method has been experimentally proven to delineate the relationship between EMG amplitude and spectrum, i.e. on the one hand, between EA and MDF, and on the other hand, between force and fatigue [35]. However, due to the complexity of the physiological processes, it is very difficult to elaborate on those variations and to further define different quadrants based on its underlying physiological mechanisms. According to natural characteristics of typing activities, we suggested defining the upper-left quadrant of JASA plot as "adaptation" rather than "recovery".

In general, the recruitment order of motor units (MUs) follows "size principle", and the recruitment occurs in sequence from low threshold (type-I MUs) to high threshold (type-II MUs) [28]. Additionally, the recruitment and derecruitment thresholds of MUs were found to be lower in movement with higher velocity [10]. Therefore, during the 2-h typing activities, we believed that the type-I MUs were recruited first and, after continuous discharging, the phenomenon of MU rotation occurred. In this moment, type-II MUs began to participate in contractions, and meanwhile, some type-I MUs recruited at the onset of contractions would withdraw and become inactive. Fast muscle fibers innervated by type-II MUs have a greater maximal rate of depolarization and repolarization than slow fibers, and therefore produce an action potential that has a shorter duration [45]. Short duration action potentials, i.e. higher conduction velocity (CV), con-

Table 3
Summary of (EA, MDF) distribution in the four quadrants of JASA plot for all studied muscles ($n = 120$)

Quadrant in JASA plot	Slope of EMG measurements		Studied muscles				
	EA	MDF	REDC	LEDC	RFDS	LFDS	Total
Force increase	+	+	0	0	1	3	31 (26%)
Adaptation	−	+	7	8	6	6	
Fatigue	+	−	8	7	20	11	89 (74%)
Force decrease	−	−	15	15	3	10	
Total			30	30	30	30	120

EA: electrical activity; MDF: median frequency; REDC: right extensor digitorum communis; RFDS: right flexor digitorum superficialis; LEDC: left extensor digitorum communis; LFDS: left flexor digitorum superficialis; +: slope increase; −: slope decrease.

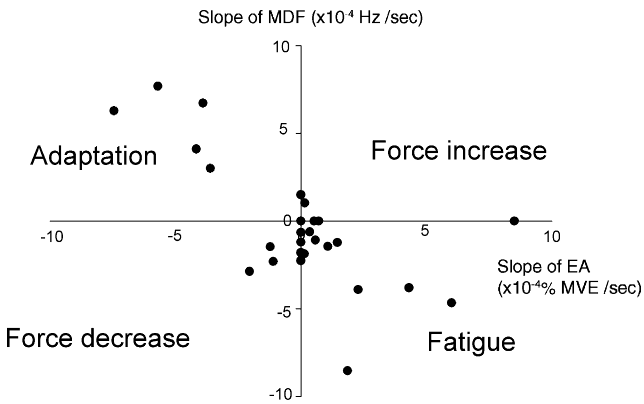

Fig. 5. JASA plot for RFDS ($N = 30$).

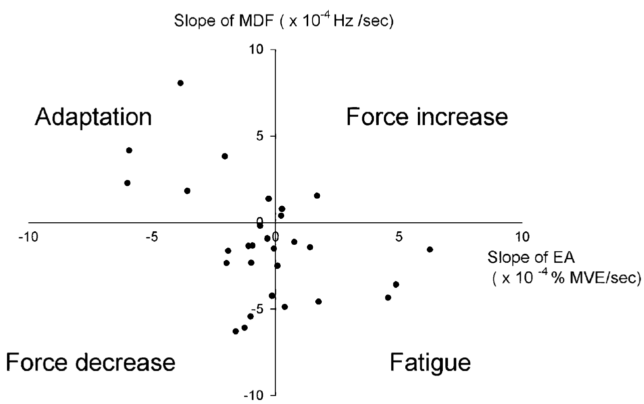

Fig. 6. JASA plot for LFDS ($N = 30$).

tribute high-frequency components to the EMG spectrum that result in a greater value in the MDF. Besides varying the number of MUs recruited, muscle force can also be modulated by rate-coding. The works of De Luca and Erim [14,15] proposed that there is a negative correlation between the recruitment threshold and the firing rate of MUs. This implied that MUs with high recruitment thresholds, such as type-II MUs, have low mean firing rate. Thereupon, the lower amplitude of myoelectrical signals might be recorded from electrodes and result in lower EA values compared to the initial stage of typing activities. After combining the observations of the increasing MDF and the decreasing EA, we propose that those muscles belonging to the upper-left quadrant of the JASA plot are in the adaptation situation.

As the muscular contractions have to sustain in long-term activities, withdrawals of type-II MUs are inevitable at this stage. Type-I MUs will take the responsibility for successive contractions and back-substitutions of some inactive type-I MUs will occasionally occur. Another mechanism, namely synchronization, would act in this stage [7,32]. Especially when only few MUs involved at low contraction level, the influence of synchronization on EMG registrations tends to be more dominant. Hägg [25] and Krogh-Lund and Jorgensen [32] have shown an additional increase in the power spectrum at 20–40 Hz while fatigue occurred, and caused increasing spectrum components in the low-frequency range. Such a situation could be used to explain why some muscles in our study have demonstrated a positive slope for EA values and a negative slope for MDF values, and then have been categorized into the "fatigue" quadrant of the JASA method.

4.3. Different patterns between extensor and flexor muscles

Theoretically, the finger flexors are the primary muscles to press down the keyboard keys while typing, whereas the extensor muscles work as the postural and antagonist muscles to bring fingers to the opposite direction against gravity. However, many studies have shown that the activities of the wrist extensor muscles during computer work are relatively high and constant [8,20,29]. In the present study, the same phenomenon could also be revealed by the JASA plots. When compared with only 13 (22%) dots of flexor muscles that fell on the decrease quadrant, 30 (50%) dots of extensor muscles fell on the decrease quadrant. It implied that extensor muscles did suffer more physical loading in the long-term typing activity, which might result from sustained lifting posture of the wrists and fingers. Moreover, the JASA plots manifested that those dots of flexor muscles dispersed more widely than those of extensor muscles Figs. 3–6. In other words, the work loading of flexor muscles of study subjects fluctuated during the typing tests, which might be attributed to variable typing force exerted by the flexor muscle. By contrast, extensor muscles, which sustained continuous exertion throughout the typing test, were mildly influenced by typing behaviors.

5. Conclusions

1. It is still possible to observe muscular fatigue by the decrement of the MDF during long-term dynamic contractions, even though the contraction force level is lower than 10% MVC.
2. In the present study, muscular fatigue occurred to 80% of the recorded EDC and FDS muscles after 2-h continuous typing activities.
3. Through the JASA method, researchers could gain insight in to the muscular fatigue condition as well as the possible underlying mechanisms.
4. During sustained typing, the EDC muscles have to maintain the finger posture against gravity throughout the work. Therefore, finger extensors are more likely to fatigue than flexors.

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