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Methodology Report

Assessing the Therapeutic Effect of 630 nm Light-Emitting Diodes Irradiation on the Recovery of Exercise-Induced Hand Muscle Fatigue with Surface Electromyogram

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This paper aims to investigate the effect of light emitting diode therapy (LEDT) on exercise-induced hand muscle fatigue by measuring the surface electromyography (sEMG) of flexor digitorum superficialis. Ten healthy volunteers were randomly placed in the equal sized LEDT group and control group. All subjects performed a sustained fatiguing isometric contraction with the combination of four fingertips except thumb at 30% of maximal voluntary contraction (MVC) until exhaustion. The active LEDT or an identical passive rest therapy was then applied to flexor digitorum superficialis. Each subject was required to perform a re-fatigue task immediately after therapy which was the same as the pre-fatigue task. Average rectified value (ARV) and fractal dimension (FD) of sEMG were calculated. ARV and FD were significantly different between active LEDT and passive rest groups at 20%–50%, 70%–80%, and 100% of normalized contraction time ($P < 0.05$). Compared to passive rest, active LEDT induced significantly smaller increase in ARV values and decrease in FD values, which shows that LEDT is effective on the recovery of muscle fatigue. Our preliminary results also suggest that ARV and FD are potential replacements of biochemical markers to assess the effects of LEDT on muscle fatigue.

1. Introduction

Muscular fatigue is manifested by a decline in the force-generating capacity during maximal contraction [1] or the incapacity to maintain required or expected muscle force for a period of time [2]. This phenomenon is dependent on the type and intensity of exercise, muscle group involved, duration of the activity, and type and size of muscle fibers [3], which means that fatigue development is a complex and multifaceted process involving physiological, biomechanical and psychological elements [2]. Although the mechanisms of fatigue development, prevention and recovery are not fully understood up to now, fatigue recovery is of great interest to the researchers due to its great significance in rehabilitation medicine, ergonomics and sports science.

In the last decades, a large amount of physical or chemical approaches have been attempted. The positive therapeutic effects of cryotherapy [4, 5], neuromuscular electrical stimulation [6], and antioxidant supplementation [7] were testified for muscle fatigue recovery. Recently, phototherapy or optical irradiation with specific wavelength range was proposed for fatigue development and recovery of skeletal muscle [8–10]. Studies on animal and human revealed that the low level laser therapy (LLLT) significantly promotes the muscle fatigue development and recovery by reducing postexercise blood lactate, decreasing the activity of creatine kinase (CK) and C-reactive protein (CRP), and improving muscle performance [8, 11–14]. Further experiments indicated that the phototherapeutic effects of LLLT were associated with depressing of oxidative stress [15] and reactive oxygen species production [16], improvement of

mitochondrial function [17, 18] and ATP synthesis [19], and enhancement of microcirculation [20]. As an alternative light source, high-power light-emitting diodes (LEDs) exhibited similar phototherapeutic effects, and the decreased muscle fatigue was observed through phototherapy with light-emitting diodes therapy (LEDT) [9, 10, 21, 22]. However, the mechanism for phototherapy in human muscle fatigue recovery is far from clear.

Muscle fatigue is a progressive course of decreasing muscle activity accompanied by physical and chemical change in muscles. Knowledge of these dynamic changes is helpful to evaluate the effects of phototherapy and make better treatment plan. Although the physiochemical changes in CK activity and CRP levels are commonly used as indirect indicators for the estimation of muscle fatigue [10, 23], it is not suitable for continuously monitoring the physiological state of muscle during muscle contraction. Surface electromyography (sEMG) is a widely used electrophysiological technique for muscle activity detection and has been used to characterize the myoelectric properties of muscle fatigue in onset time of mechanical fatigue [24, 25] as well as the neuromuscular properties of muscle fatigue [26]. The average rectified value (ARV) and fractal dimension (FD) of sEMG were successfully used to evaluate the status of muscle fatigue by measuring firing rate of motor unit and its recruitment pattern [2, 27, 28]. The present study is to investigate the effect of phototherapy on hand muscle fatigue recovery by comparing the ARV and FD values of the LEDT and control groups.

2. Materials and Methods

2.1. Subjects. Ten healthy right-handed university students (five males and five females) volunteered to participate in the experiment. The participants' inclusion criteria were (i) healthy with no history of myopathology and neuropathology and (ii) free of intense exercise in 24 hours before the experiment. Experiments were conducted after receiving approval from the local ethics committee. Each participant was given an oral and written summary of the experimental protocol and the purpose of the study and then was required to sign a consent form prior to the experiment.

2.2. Experimental Procedure. Each subject was seated upright in a comfortable chair with his/her hip and knee joint flexed at 90° and their right forearm resting on a supporting armrest. The elbow was positioned in palm downward with the elbow in approximately 120° flexion. The forearm and wrist were stabilized to the armrest with nylon tapes. The subject was asked to produce a force with the combination of four fingers (IMRL, I = index, M = middle, R = ring, and L = little). The exerted forces of individual fingers were recorded by four load cells (linear operation range 0–196 N, JLBS, JinNuo Inc., China), respectively.

The experimental protocol consisted of the following phases.

Phase 1 (Maximal Voluntary Contraction (MVC) of IMRL). MVC was taken as the maximum of three isometric contractions of the right forearm flexors with IMRL. Each contraction lasted 5 seconds with 2-minute recovery period between two successive contractions. Verbal encouragement was provided during MVCs to obtain maximal effort. A 5-minute rest was taken after the maximal contractions.

Phase 2 (Prefatigue). Immediately after Phase 1, the subject was instructed to perform a sustained fatiguing isometric contraction at 30% MVC of IMRL until exhaustion, which was defined as the point at which the force decreased by 5% of the target force for more than 2 seconds [29].

Phase 3 (Therapy). Participants were randomly divided into two equal sized groups, that is, active LEDT group (four males and one female) and passive rest therapy group (one male and four females). The fatigued forearm hand muscle received an active LEDT through photon therapy equipment with a multidiode cluster probe (Carnation66, Shenzhen Lifotronic Tech. Inc., Shenzhen, China) or a passive rest therapy. The therapy started immediately after Phase 2 and ended 120 seconds before Phase 4.

The subject's forearm was positioned in neutral rotation during the therapy. For LEDT, the center of the light spot was located at approximately 50% of landmark line from the medial epicondyle to the styloid process of the ulna, which was the center belly of flexor digitorum superficialis. The subject's forearm maintained the rest state without moving during the therapy.

Irradiation with LEDT (100 LEDs with wavelength 630 nm, spot size 2.5 cm^2, power density 0.048 W/cm^2, and energy density 57.6 J/cm^2) was performed in non-contact mode with the probe held stationary at a vertical distance of 60 mm between light source and skin surface. The total time of therapy was 20 minutes. Opaque goggles were used for all participants during the therapy to protect their eyes from the treatment and assure the blindness of the study.

Phase 4 (Refatigue). Each subject was required to perform the same fatigue task again as that did in Phase 2.

The actual force of IMRL (30% MVC) was recorded by a 12-bit data acquisition card (USB-6008, National Instruments, USA) in Phases 1, 2, and 4. The actual force and the target force were shown on an LCD screen for real-time visual feedback to the subject in Phases 2 and 4. Surface EMG signals were recorded from the right flexor digitorum superficialis during Phases 1, 2, and 4. The skin was prepared by abrading and cleaning the recording area with alcohol. sEMG signals were detected by two disposable ECG electrodes (Shanghai LITU Medical Appliances Co., model LT-601, China) with 20 mm interelectrode distance. The electrodes were centered around the 50% point on the line joining the medial epicondyle to the styloid process of the ulna [29]. A groud electrode was attached on the dorsal surface of the wrist. All force signals and sEMG signals were recorded simultaneously by the multichannel physiological recorder apparatus (RM6280, Chengdu Instrumentation Inc.) at a rate of 2000 samples per second. The force and sEMG signals were band-pass filtered within the frequency ranges of 0–30 Hz and 8–500 Hz, respectively. The quality

of the sEMG signal was visually checked before actual recording.

2.3. Data Analysis. Data analysis was performed off line using MATLAB 7.8 (The MathWorks Inc., Natick, USA). Bipolar signals were band-pass filtered using a seven-order elliptic filter (10 Hz–500 Hz). Bipolar sEMG signals of flexor digitorum superficialis during fatigue were divided into several 10 s segments. For each 10 s segment, a 2048-point sEMG epoch was equally divided into four subepochs to estimate ARV and FD. The ARV and FD values obtained from the 4 subepochs were averaged to get the overall estimations of ARV and FD for each 10 s segment.

The ARV of sEMG signal in the time domain is defined as

$$\mathrm{ARV} = \frac{1}{N}\sum_{i=1}^{N}|x_i|, \quad (1)$$

where x_i is the ith sample of the signal and N is the number of the samples in the epoch.

The FD value of a one-dimensional physiological signal is calculated as the change in length of recursively defined self-similar curves with the measurement scale. The length of curve used in computation was the same as described in the study of Arjunan and Kumar [30]. By plotting the logarithm of the average length of curve versus the logarithm of the time interval, the FD is obtained as the slope of the fitted linear line.

The ARV values were normalized by values obtained at 100% MVC contraction because the absolute level of each parameter differed among the subjects. Because the task time was not the same for each subject, we normalized the contraction time by setting the task time as 100%. The task time of each subject was divided into 10 equal segments. The variables were obtained at every 10% time. If there was no measurement value at the resampled point, an interpolated value was calculated from the nearest sampled values. The ARV and FD values were averaged for all the subjects in the same group.

2.4. Statistical Analysis. Statistical analysis was performed with SPSS 13.0 in our study. Normality of the distributions of ARV and FD values was checked with the Kolmogorov-Smirnov test prior to statistical testing, and the results were positive. The t-test was employed to test if there was a significant difference between the two experimental groups for ARV and FD of prefatigue task at the end of the fatiguing contraction (i.e., 100% of contraction time). The difference between two types of therapies during refatigue task was also assessed by the t-test at each time instant. Changes in ARV and FD over the normalized contraction time were assessed by linear regression analysis. Results were reported as mean and standard deviation (SD) in the text and standard error (SE) in the figures. The level of statistical significance was set at 0.05.

Table 1: Results of linear regression analysis for refatigue task.

sEMG parameter	Group	Slope	P value
ARV	LEDT	0.136	<0.001
	Control	0.227	0.001
FD	LEDT	−0.015	0.085
	Control	−0.04	0.002

3. Results

The average age of participants was 23.7 years (SD ± 1.19). Their average weight and height were 55.6 kg (SD ± 9.38) and 165.5 cm (SD ± 6.70), respectively. For the LEDT group, the average lengths of the prefatigue and refatigue tasks were 815.4 s (SD ± 595.3) and 311.4 s (SD ± 109.5), respectively, and the average lengths of the prefatigue and refatigue tasks for passive rest therapy group were 1000.0 s (SD ± 254.7) and 602.8 s (SD ± 195.8), respectively.

Examples of the sEMG signals recorded from the right flexor digitorum superficialis and the forces generated during the experiment from the two treatment groups are presented in Figure 1. Figures 2 and 3 plot the changes of mean normalized ARV and mean FD along the normalized contraction time, respectively. From Figures 2(a) and 2(c), it can be observed that there are no statistical differences for ARV between the LEDT and control groups at the 100% of the normalized contraction time during prefatigue task ($P > 0.05$). The same observation can be obtained from Figures 3(a) and 3(c) for FD.

The results of linear regression analysis for the refatigue task are summarized in Table 1. The mean ARV value of the two groups increases over contraction time after both therapies as shown in Table 1. Comparing Figure 2(b) with Figure 2(d), the mean ARV values of the LEDT group are significantly smaller than those of the passive rest therapy group. The statistically significant difference between the mean ARV values of the two groups can be found at 10%–50%, 70%–80%, and 100% of the normalized contraction time ($P < 0.05$).

From Figure 3(d), it can be easily observed that the mean FD value decreases over the normalized contraction time for passive rest group, which is confirmed by Table 1 ($P < 0.05$). For active LEDT group, the mean FD value has a trend of decreasing (Figure 3(b)) but not statistically significant ($P = 0.085$ as shown in Table 1). The statistically significant difference between the mean FD values of the two groups can be found at 0% and 20%–100% of the normalized contraction time ($P < 0.05$).

4. Discussion

Unlike biochemical indicators commonly used in previous studies, we attempt to use electrophysiological indicators for assessing the therapeutic effect of LEDT on the recovery of muscle fatigue. The aim of the present study is to verify the effect of LEDT by using two parameters extracted from sEMG: ARV and FD. There was no significant difference between the two groups for both sEMG variables during

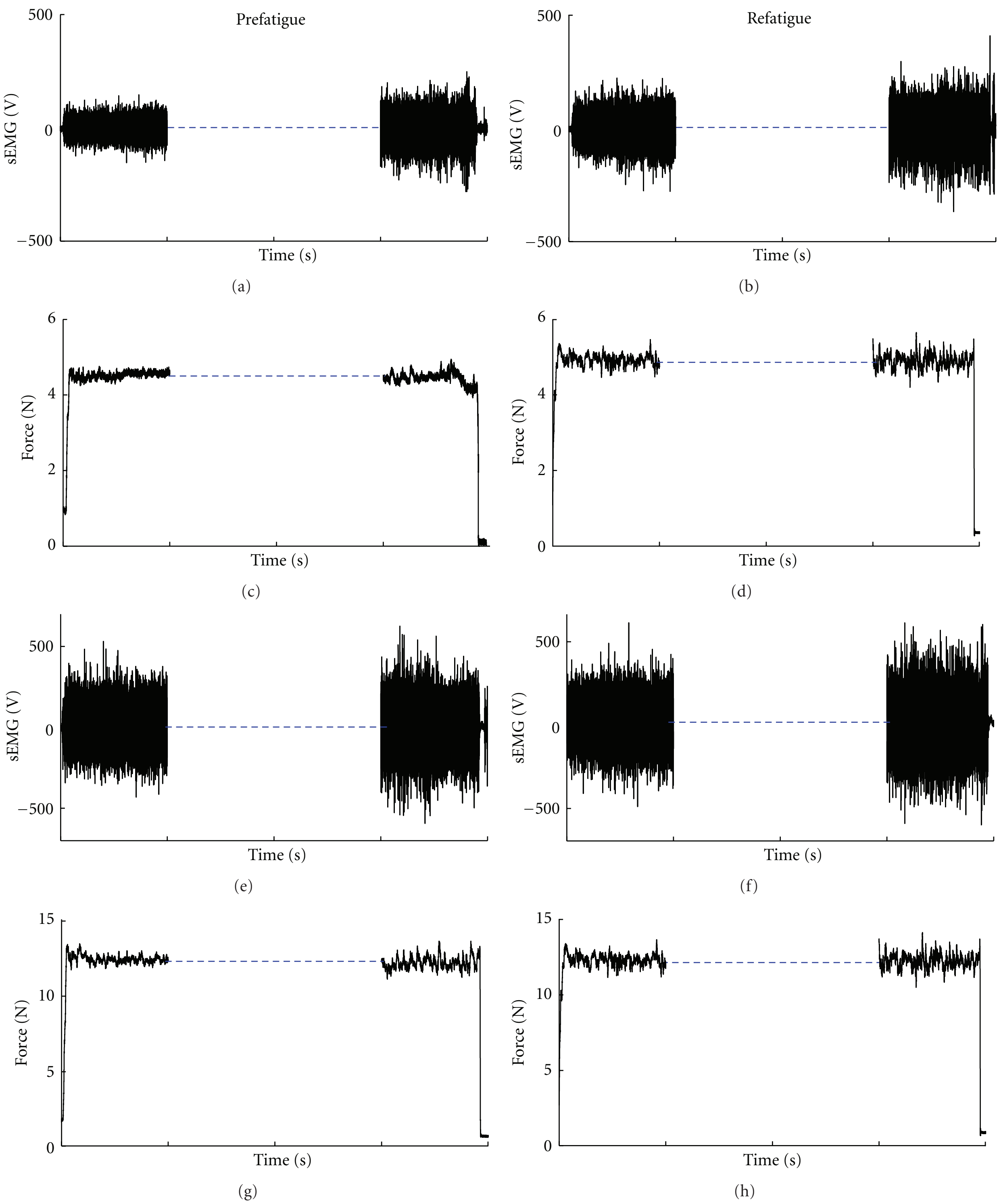

Figure 1: Examples of sEMG signals and the forces recorded during the prefatigue and refatigue tasks until exhaustion for the two types of treatments. (a)–(d) Passive rest therapy, (e)–(h) Active LEDT.

prefatigue task. Therefore, any difference found in ARV and FD between the two groups during the refatigue task cannot be attributed to possible pre-existing uncontrolled differences. Compared with passive rest, irradiation of the flexor digitorum superficialis with active LEDT after muscle fatigue resulted in significantly smaller changes of ARV and FD values along the contraction time, which demonstrates that LEDT is effective at accelerating fatigue recovery.

Compared with passive rest group, smaller increase of the sEMG ARV value along the contraction time was observed

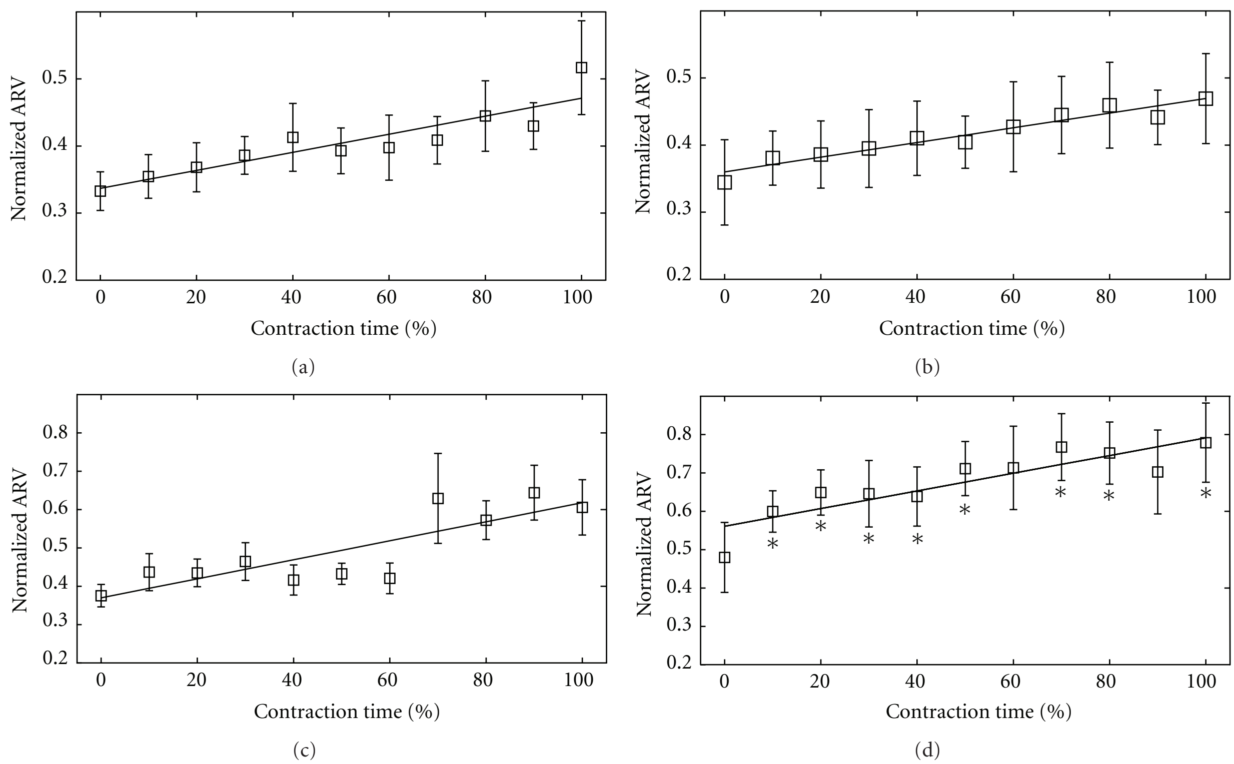

Figure 2: The changes of the mean normalized ARV (±SE) over the normalized contraction time during the prefatigue (a) and refatigue (b) tasks of the LEDT group and the prefatigue (c) and refatigue (d) tasks of the passive rest group. The symbol "*" indicates that the difference between the mean normalized ARV values of the two groups in the corresponding normalized contraction time is statistically significant.

in LEDT group, indicating that prefatigued muscle tends to return to its initial unfatigue state faster after LEDT. The sEMG ARV reflects the total potential of activating motor units during muscle contraction. Thus, increased ARV value under sustained contraction is mainly a consequence of the recruitment of additional motor units and the decrease of conduction velocity [31]. Hence, if muscle function did not recover completely from prefatigue status, it might need to recruit more new motor units to maintain the desired force, which results in larger and faster increase of sEMG ARV. Previous studies have reported that sEMG amplitude can return to their initial status from fatigue status after appropriate rest [32, 33]. However, 20 min recovery is not enough to enable the flexor digitorum superficialis to fully recover after long fatiguing contraction at low force level [34]. Therefore, the difference of the ARV values between the two groups in our study suggests that LEDT certainly has effect on fatigue recovery and refatigue development.

It can also be observed that although the ARV value increases along the contraction time, it never exceeds 40%–60% of the maximal level for the active LEDT group and 70%–90% of the maximal level for the passive rest group (Figure 2). Moreover, the ARV value at 100% of contraction time is group dependent ($P < 0.05$). Previous studies found that the central fatigue occurred inevitably at lower contraction intensities when muscle fatigue was induced by means of sustained, submaximal isometric contractions of limb and hand muscles [35]. Recent studies also found deficit in average EMG in hand and limb muscles of subjects performing submaximal contractions, which was inversely related to contraction intensity, with much larger deficits in the low-intensity task [36]. In our study, we observed that the LEDT group has smaller sEMG deficits than the control group, suggesting the inhibiting effect of LEDT on driving motor neurons.

Next, significant decrease of FD value over contraction time was observed in the passive rest group in our study. The FD of sEMG signal can be used to quantify the complexity of motor unit recruitment patterns [25, 27]. The decrease in discharge rate of motor unit as well as the increase in duration of motor unit action potentials [37] and the level of synchronism of motor units [38] would account for the decrease of FD during the refatigue task as an adaptation to muscle fatigue. When the task muscle without recovering completely from fatigue status was required to work again, the larger changes of the three aforementioned factors would lead to distinct reduction of FD over contraction time. Many studies reported that the power spectrum of sEMG showed an increased median frequency during recovery [39], which is the opposite process with the development of muscle fatigue. This means that the change of FD for the LEDT group should be smaller than that of the passive rest group, which is in accordance with our results. Moreover, the differences between the two treatment groups occur at all instants except for 10% contraction time, which is another indication of the LEDT effect on skeletal muscle fatigue recovery.

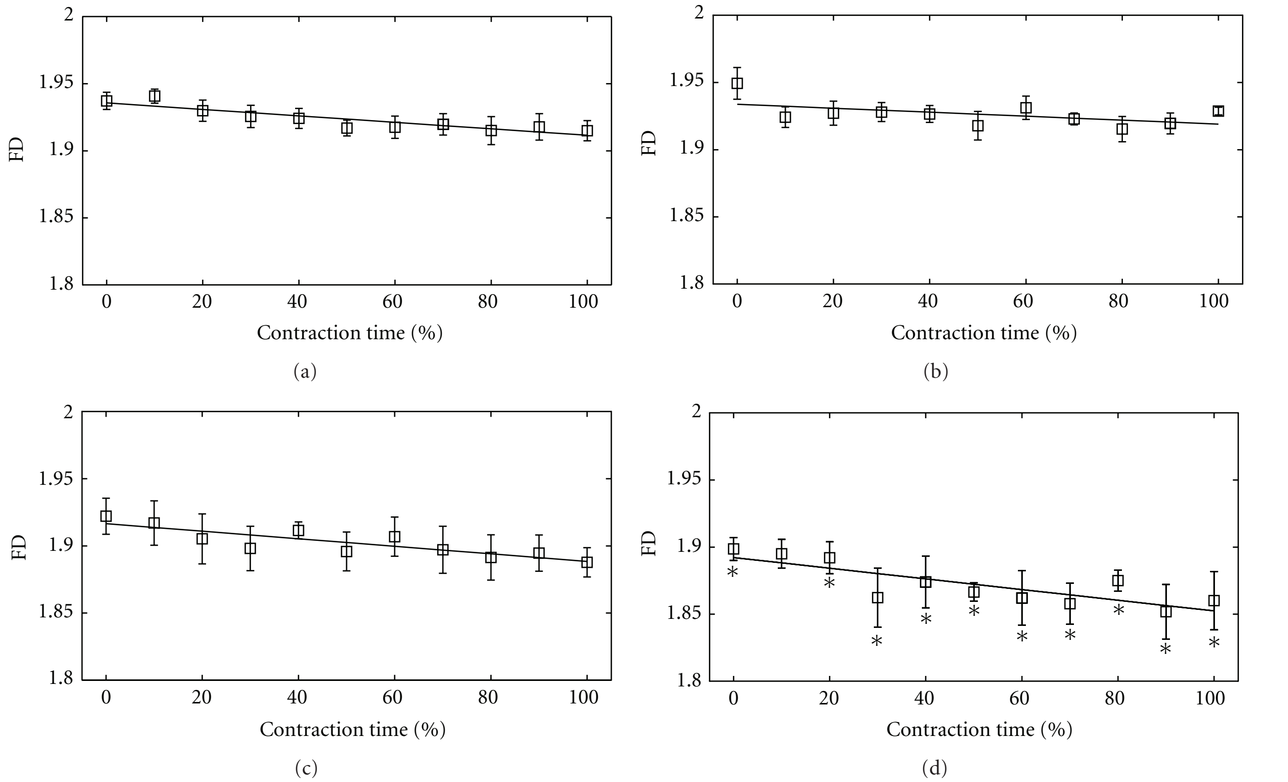

Figure 3: The changes of mean FD (±SE) over the normalized contraction time during the prefatigue (a) and refatigue (b) tasks of the LEDT group and the prefatigue (c) and refatigue (d) tasks of the passive rest group. The symbol "∗" indicates that the difference between the mean FD values of the two groups in the corresponding normalized contraction time is statistically significant.

In addition, it can be observed that the two sEMG parameters show difference in the time instances to be statistically significant different between the two groups. One possible explanation is that the two parameters characterize muscle fatigue from a couple of different perspectives. Compared with FD, ARV is an indicator of sEMG amplitude in the time domain, which is more sensitive to peripheral fatigue [28]. FD is the most promising index of central fatigue and mainly affected by the level of motor unit synchronization and weakly affected by either conduction velocity or fat layer thickness [25, 28]. However, the lack of consistency of EMG amplitude is a common problem to many electromyographic studies. Therefore, it was suggested that myoelectric manifestations of fatigue could be better described by two parameters sensitive to central and peripheral fatigue, respectively [28].

A recent study found that LEDT administrated before exercise could cause a slight delay in the development of skeletal muscle fatigue, decrease blood lactate levels, and inhibit the release of CK and CRP [9]. An other study has also found that LEDT has potential to improve short-term postexercise recovery by inhibiting postexercise increase in blood lactate level and CK activity [10]. Although the exact working mechanism of LEDT remains unknown, some thought that this positive effect might be due to the improved peripheral microcirculation [20], increment in mitochondrial capacity [17, 18], reduced oxidative stress [15], and decreased reactive oxygen species [16] after laser treatment. These changes could improve the muscle fatigue recovery at cellular level [34] and thus affect the physiologic properties of fatigued muscles. If complete blood perfusion is allowed, the metabolic products occurred during muscle fatigue are rapidly washed out so that the muscle fiber membrane function [40] and sEMG spectral content [41] almost completely recover after 5 min rest. Thus, these positive results of LEDT or LLLT indirectly support our findings, suggesting that ARV and FD can be served as valid parameters to investigate the changes of muscle function induced by LLLT or LEDT.

There are several limitations in our study. We investigated the effects of a commercially available LEDT device with red wavelength on muscle fatigue recovery by means of noninvasive sEMG analysis and the preliminary results were encouraging. However, the exact mechanism of how LEDT promotes short-term fatigue recovery cannot be revealed in our study. We also observed that the trend of ARV and FD for one subject was opposite to others, which might be due to the architectural and functional complexity of flexor digitorum superficialis [42] and spatial-dependence center strategy to cope with fatigue [43]. Due to the small sample size, the preliminary results obtained in our study need to be examined with a large-scale study by using both biochemical marks and sEMG parameters.

5. Conclusion

The aim of this study is to use the electrophysiological parameters extracted from sEMG signals instead of biochemical indicators for assessing the effect of light therapies on muscle fatigue recovery. Two electrophysiological parameters used in our experiments, ARV and FD, are sensitive to peripheral and central fatigue, respectively. Our experimental results showed that active LEDT induced smaller increasing rate of ARV and decreasing rate of FD than passive rest over sustained contraction time during the refatigue task, which suggests that active LEDT recovers the muscle fatigue faster than passive rest. In the future, we will conduct a larger-scale study involving more subjects and search for other useful electrophysiological parameters.

Acknowledgments

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References

[1] E. Verburg, H. M. S. Thorud, M. Eriksen, N. K. Vøllestad, and O. M. Sejersted, "Muscle contractile properties during intermittent nontetanic stimulation in rat skeletal muscle," *American Journal of Physiology-Regulatory Integrative and Comparative Physiology*, vol. 281, no. 6, pp. R1952–R1965, 2001.

[2] M. Cifrek, V. Medved, S. Tonković, and S. Ostojić, "Surface EMG based muscle fatigue evaluation in biomechanics," *Clinical Biomechanics*, vol. 24, no. 4, pp. 327–340, 2009.

[3] F. Billaut, F. A. Basset, M. Giacomoni, F. Lemaître, V. Tricot, and G. Falgairette, "Effect of high-intensity intermittent cycling sprints on neuromuscular activity," *International Journal of Sports Medicine*, vol. 27, no. 1, pp. 25–30, 2006.

[4] M. Utsunomiya, K. Nitta, H. Sawagichi et al., "Changes in blood flow, temperature and muscle endurance in association with Cryotherapy," *Journal of Physical Therapy Science*, vol. 22, no. 1, pp. 43–49, 2010.

[5] V. Perciavalle, M. Coco, and L. Gurrisi, "Alternating hot and cold water immersion accelerates blood lactate decrease after maximal anaerobic exercise," *Acta Medica Mediterranea*, vol. 24, no. 1, pp. 19–21, 2008.

[6] N. Babault, C. Cometti, and N. A. Maffiuletti, "Does electrical stimulation enhance post-exercise performance recovery?" *European Journal of Applied Physiology*, vol. 111, no. 1, pp. 2501–2507, 2011.

[7] A. Dutta, K. Ray, V. K. Singh, P. Vats, S. N. Singh, and S. B. Singh, "L-carnitine supplementation attenuates intermittent hypoxia-induced oxidative stress and delays muscle fatigue in rats," *Experimental Physiology*, vol. 93, no. 10, pp. 1139–1146, 2008.

[8] E. C. Pinto Leal Jr., R. A. Brandao Lopes-Martins, L. Frigo et al., "Effects of low-level laser therapy (LLLT) in the development of exercise-induced skeletal muscle fatigue and changes in biochemical markers related to postexercise recovery," *Journal of Orthopaedic & Sports Physical Therapy*, vol. 40, no. 8, pp. 524–532, 2010.

[9] E. C. P. Leal Junior, A. B. Lopes-Martins, B. M. Baroni et al., "Comparison between single-diode low-level laser therapy (LLLT) and LED multi-diode (cluster) therapy (LEDT) applications before high-intensity exercise," *Photomedicine and Laser Surgery*, vol. 27, no. 4, pp. 617–623, 2009.

[10] E. C. Leal Junior, V. de Godoi, J. L. Mancalossi et al., "Comparison between cold water immersion therapy (CWIT) and light emitting diode therapy (LEDT) in short-term skeletal muscle recovery after high-intensity exercise in athletes-preliminary results," *Lasers in Medical Science*, vol. 26, no. 4, pp. 493–501, 2011.

[11] R. Á. B. Lopes-Martins, R. L. Marcos, P. S. Leonardo et al., "Effect of low-level laser (Ga-Al-As 655 nm) on skeletal muscle fatigue induced by electrical stimulation in rats," *Journal of Applied Physiology*, vol. 101, no. 1, pp. 283–288, 2006.

[12] B. M. Baroni, E. C. P. Leal Junior, T. De Marchi, A. L. Lopes, M. Salvador, and M. A. Vaz, "Low level laser therapy before eccentric exercise reduces muscle damage markers in humans," *European Journal of Applied Physiology*, vol. 110, no. 4, pp. 789–796, 2010.

[13] E. C. P. Leal Junior, R. Á. B. Lopes-Martins, B. M. Baroni et al., "Effect of 830 nm low-level laser therapy applied before high-intensity exercises on skeletal muscle recovery in athletes," *Lasers in Medical Science*, vol. 24, no. 6, pp. 857–863, 2009.

[14] E. C. P. Leal Junior, R. Á. B. Lopes-Martins, P. De Almeida, L. Ramos, V. V. Iversen, and J. M. Bjordal, "Effect of low-level laser therapy (GaAs 904 nm) in skeletal muscle fatigue and biochemical markers of muscle damage in rats," *European Journal of Applied Physiology*, vol. 108, no. 6, pp. 1083–1088, 2010.

[15] L. I. Fillipin, J. L. Mauriz, K. Vedovelli et al., "Low-level laser therapy (LLLT) prevents oxidative stress and reduces fibrosis in rat traumatized Achilles tendon," *Lasers in Surgery and Medicine*, vol. 37, no. 4, pp. 293–300, 2005.

[16] Y. Fujimaki, T. Shimoyama, Q. Liu, T. Umeda, S. Nakaji, and K. Sugawara, "Low-level laser irradiation attenuates production of reactive oxygen species by human neutrophils," *Journal of Clinical Laser Medicine and Surgery*, vol. 21, no. 3, pp. 165–170, 2003.

[17] T. Karu, "Mitochondrial mechanisms of photobiomodulation in context of new data about multiple roles of ATP," *Photomedicine and Laser Surgery*, vol. 28, no. 2, pp. 159–160, 2010.

[18] P. C. L. Silveira, E. L. Streck, and R. A. Pinho, "Evaluation of mitochondrial respiratory chain activity in wound healing by low-level laser therapy," *Journal of Photochemistry and Photobiology B*, vol. 86, no. 3, pp. 279–282, 2007.

[19] P. C. L. Silveira, L. A. D. Silva, D. B. Fraga, T. P. Freitas, E. L. Streck, and R. Pinho, "Evaluation of mitochondrial respiratory chain activity in muscle healing by low-level laser therapy," *Journal of Photochemistry and Photobiology B*, vol. 95, no. 2, pp. 89–92, 2009.

[20] F. R. M. Ihsan, "Low-level laser therapy accelerates collateral circulation and enhances microcirculation," *Photomedicine and Laser Surgery*, vol. 23, no. 3, pp. 289–294, 2005.

[21] E. C. P. Leal, R. Á. B. Lopes-Martins, R. P. Rossi et al., "Effect of cluster multi-diode Light Emitting Diode Therapy (LEDT) on exercise-induced skeletal muscle fatigue and skeletal muscle recovery in humans," *Lasers in Surgery and Medicine*, vol. 41, no. 8, pp. 572–577, 2009.

[22] B. M. Baroni, E. C. P. Leal, J. M. Geremia, F. Diefenthaeler, and M. A. Vaz, "Effect of light-emitting diodes therapy (LEDT) on knee extensor muscle fatigue," *Photomedicine and Laser Surgery*, vol. 28, no. 5, pp. 653–658, 2010.

[23] Y. Zhou, Y. Li, and R. Wang, "Evaluation of exercise-induced muscle damage by surface electromyography," *Journal of Electromyography and Kinesiology*, vol. 21, no. 2, pp. 356–362, 2011.

[24] S. Kumar and Y. Narayan, "Spectral parameters of trunk muscles during fatiguing isometric axial rotation in neutral posture," *Journal of Electromyography and Kinesiology*, vol. 8, no. 4, pp. 257–267, 1998.

[25] A. Troiano, F. Naddeo, E. Sosso, G. Camarota, R. Merletti, and L. Mesin, "Assessment of force and fatigue in isometric contractions of the upper trapezius muscle by surface EMG signal and perceived exertion scale," *Gait and Posture*, vol. 28, no. 2, pp. 179–186, 2008.

[26] L. A. C. Kallenberg and H. J. Hermens, "Behaviour of a surface EMG based measure for motor control: motor unit action potential rate in relation to force and muscle fatigue," *Journal of Electromyography and Kinesiology*, vol. 18, no. 5, pp. 780–788, 2008.

[27] Z. Xu and S. Xiao, "Fractal dimension of surface EMG and its determinants," in *Proceedings of the 1997 19th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, pp. 1570–1573, November 1997.

[28] L. Mesin, C. Cescon, M. Gazzoni, R. Merletti, and A. Rainoldi, "A bi-dimensional index for the selective assessment of myoelectric manifestations of peripheral and central muscle fatigue," *Journal of Electromyography and Kinesiology*, vol. 19, no. 5, pp. 851–863, 2009.

[29] S. Kattla and M. M. Lowery, "Fatigue related changes in electromyographic coherence between synergistic hand muscles," *Experimental Brain Research*, vol. 202, no. 1, pp. 89–99, 2010.

[30] S. P. Arjunan and D. K. Kumar, "Decoding subtle forearm flexions using fractal features of surface electromyogram from single and multiple sensors," *Journal of NeuroEngineering and Rehabilitation*, vol. 7, no. 1, article no. 53, 2010.

[31] D. Farina, F. Leclerc, L. Arendt-Nielsen, O. Buttelli, and P. Madeleine, "The change in spatial distribution of upper trapezius muscle activity is correlated to contraction duration," *Journal of Electromyography and Kinesiology*, vol. 18, no. 1, pp. 16–25, 2008.

[32] F. Danion, S. Li, V. M. Zatsiorsky, and M. L. Latash, "Relations between surface EMG of extrinsic flexors and individual finger forces support the notion of muscle compartments," *European Journal of Applied Physiology*, vol. 88, no. 1-2, pp. 185–188, 2002.

[33] C. Larivière, D. Gravel, A. B. Arsenault, D. Gagnon, and P. Loisel, "Muscle recovery from a short fatigue test and consequence on the reliability of EMG indices of fatigue," *European Journal of Applied Physiology*, vol. 89, no. 2, pp. 171–176, 2003.

[34] D. G. Allen, G. D. Lamb, and H. Westerblad, "Skeletal muscle fatigue: cellular mechanisms," *Physiological Reviews*, vol. 88, no. 1, pp. 287–332, 2008.

[35] T. D. Eichelberger and M. Bilodeau, "Central fatigue of the first dorsal interosseous muscle during low-force and high-force sustained submaximal contractions," *Clinical Physiology and Functional Imaging*, vol. 27, no. 5, pp. 298–304, 2007.

[36] K. Schmitt, C. DelloRusso, and R. F. Fregosi, "Force-EMG changes during sustained contractions of a human upper airway muscle," *Journal of Neurophysiology*, vol. 101, no. 2, pp. 558–568, 2009.

[37] J. W. Chung, C. Kim, and W. D. McCall, "Effect of sustained contraction on motor unit action potentials and EMG power spectrum of human masticatory muscles," *Journal of Dental Research*, vol. 81, no. 9, pp. 646–649, 2002.

[38] R. Merletti and S. Roy, "Myoelectric and mechanical manifestations of muscle fatigue in voluntary contractions," *Journal of Orthopaedic and Sports Physical Therapy*, vol. 24, no. 6, pp. 342–353, 1996.

[39] K. S. Sunnerhagen, U. Carlsson, A. Sandberg, E. Stålberg, M. Hedberg, and G. Grimby, "Electrophysiologic evaluation of muscle fatigue development and recovery in late polio," *Archives of Physical Medicine and Rehabilitation*, vol. 81, no. 6, pp. 770–776, 2000.

[40] R. G. Miller, D. Giannini, H. S. Milner-Brown et al., "Effects of fatiguing exercise on high-energy phosphates, force, and EMG: evidence for three phases of recovery," *Muscle and Nerve*, vol. 10, no. 9, pp. 810–821, 1987.

[41] L. S. Krivickas, S. F. Nadler, M. R. Davies, G. F. Petroski, and J. H. Feinberg, "Spectral analysis during fatigue: surface and fine wire electrode comparison," *American Journal of Physical Medicine and Rehabilitation*, vol. 75, no. 1, pp. 15–20, 1996.

[42] T. L. McIsaac and A. J. Fuglevand, "Motor-unit synchrony within and across compartments of the human flexor digitorum superficialis," *Journal of Neurophysiology*, vol. 97, no. 1, pp. 550–556, 2007.

[43] D. Falla and D. Farina, "Non-uniform adaptation of motor unit discharge rates during sustained static contraction of the upper trapezius muscle," *Experimental Brain Research*, vol. 191, no. 3, pp. 363–370, 2008.

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