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Time and Frequency Analysis of Electromyography Signals for Simultaneous Evaluation of Knee Muscles in Concentric and Eccentric Strength Training in Healthy Men

Mahdi ZeighamJahani[1], PhD candidate; Ali Yaghoubi[1*], PhD; Mohamad Amin Younessi Heravi[2], PhD

[1]Department of Physical Education and Sport Sciences, Islamic Azad University, Bojnourd Branch, Bojnourd, Iran
[2]Department of Medical Physics and Radiology, School of Medicine, North Khorasan University of Medical Sciences, Bojnurd, Iran

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ABSTRACT

Background: Strength training has been a common intervention used to improve neuromuscular activity within the synergic and/or agonist-antagonist muscles. This study aimed to evaluate simultaneous electrical activity of quadriceps and hamstring muscles after strength eccentric training versus concentric training.
Methods: This experimental study has a between-group comparison design with a population of 26 males divided into two groups, namely the eccentric training group and the concentric training group. Maximal knee extension force and bipolar surface electromyography (EMG) signals from quadriceps and hamstring muscles were simultaneously recorded pre- and post-concentric and eccentric strength training. After EMG pre-processing for noise reduction, EMG signals were evaluated in two groups by time and frequency analysis. Nine EMG features (six time features and three frequency features) were analyzed in two groups pre- and post-training by statistical analysis.
Results: The results showed that the maximal voluntary isometric contraction (MIVC) of quadriceps muscles was significantly increased in both groups from pre- to post-training ($P<0.05$). Moreover, eccentric training resulted in greater increases in time features of EMG for quadriceps and hamstring muscles compared to concentric training ($P<0.05$). All frequency features showed significant changes in pre- and post-tests for the eccentric training group ($P<0.05$); however, no significant difference was observed in the frequency features in the post-test compared to the pre-test in the concentric training group ($P>0.05$).
Conclusion: Based on the current results, great changes in time and frequency features of quadriceps and hamstring EMGs were achieved using eccentric training. Thus, eccentric strength training could be more effective in triggering neuromuscular activity within the agonist and antagonist muscles simultaneously.

Introduction

A greater knee abduction-adduction moment during sport activities has been reported to be the major cause of knee injury [1]. The quadriceps and hamstring muscles have the potential to provide dynamic frontal-plane knee stability because of their abduction and/or adduction moment arms [2, 3]. Because the co-activation of quadriceps and hamstrings plays a critical role in knee injury prevention, optimizing exercise training to improve hamstring/quadriceps activation has received considerable attention from scientists and

Corresponding author:* Ali Yaghoubi, Department of Physical Education and Sport Sciences, Islamic Azad University, Bojnourd Branch, Postal code: 94176-97796, Bojnourd, Iran. **Tel: +98 9155855080
Email: yaghoubiali65@gmail.com

clinicians [4]. Although all forms of exercise may induce significant improvement in neuromuscular activity, it is not always clear which method is best for maximizing it. An imbalance in hamstring and quadriceps contraction puts pressure on the knee and can increase the risk of knee injury. Accordingly, the type of exercise performed on knee muscles can have an effect on preventing knee injury.

Of the three types of muscle contractions that can be utilized during exercise (concentric, isometric, and eccentric), eccentric exercises are those actions in which the muscle is lengthened, inducing muscle fiber damage [5, 6]. It is a given that the central nervous system employs a different neural strategy to control skeletal muscles during eccentric contractions versus isometric or concentric muscle contraction [7]. Therefore, it is expected that knee agonist and antagonist muscles will show different adaptations to eccentric exercise as compared to concentric exercise.

Surface electromyography (EMG) is the main method used to study muscle functions. The EMG signal measures electrical currents generated in a muscle during its contraction, which represents neuromuscular activities [8]. The nervous system always controls muscle activity (contraction/relaxation); thus, the EMG signal is complicated, controlled by the nervous system, and dependent upon the anatomical and physiological properties of muscles [9]. The processing of EMG signals arising from muscle activities is considered as a useful tool in clinical diagnoses, rehabilitation, and sports medicine (9). Many different methods for evaluating EMG signals in time and frequency domains have been reported [10-14].

Most previous studies have focused on muscle activity analysis in the time domain. The results of muscle signal processing have shown that this process to be very important in the frequency as well as the time domain, because most of the information that is not easily observed in the time domain can be detected in the frequency domain. The current study aimed to evaluate the electrical activity of quadriceps and hamstring muscles after resistance eccentric training versus concentric training by EMG analysis of knee agonist–antagonist muscles in time and frequency domains.

Methods

Subjects

This experimental study with a between-group comparison design was performed in the sports science laboratory of Bojnourd University. Considering the effect sizes in previous studies [6, 15], a confidence interval of 95%, and a test power of 80%, the sample size was determined to be 13 for each group. All subjects were right leg dominant and had not been involved in regular exercise of their knee extensor muscles for at least one year before the experiment. None of the participants had central or peripheral neurological or orthopedic diseases. Subjects who took medication affecting their muscle activity were excluded from the study. If autonomic neuropathy symptoms emerged during exercise, the participant was excluded. Participants who were unwilling to continue the exercise or failed to complete the training program were also excluded. All participants signed an informed consent form before entering the study. Subjects were randomly divided into two groups, namely the eccentric training group (No.=13) and the concentric training group (No.=13). The study was conducted in accordance with the Declaration of Helsinki and approved by the Local Ethics Committee (18248524-990024). Written informed consent was obtained from all subjects prior to inclusion.

Data Collection in Concentric and Eccentric Strength Training

Subjects performed eccentric exercise of their quadriceps using a weight-training machine (Universal Gym, USA) in a supine position. The subject lowered the load in an eccentric mode from the starting position (180º knee extension) to the end position (90º knee flexion) in a controlled maneuver. Two assistants helped the subject bring the leg to the starting position, allowing the subject to perform multiple repetitions using eccentric contraction against relatively high loads and to delay the onset of fatigue by eliminating the concentric contraction. The concentric group also performed concentric exercises from the starting position (90º knee flexion) to the finish position (180º knee extension) on a weight-training machine (Universal Gym, USA) in the same position as the eccentric training group. A one-repetition maximum (1-RM) was determined for each subject using concentric contraction. Subjects in the two training groups performed 3 sets of 12 repetitions with 80% of the 1-RM and three minutes of rest between sets. Subjects performed these training exercises 3 days per week for 12 weeks; every week, 1-RM was evaluated for each subject, and the weights were adjusted accordingly. Each subject sat comfortably on a chair fixed with a belt at the hip and with the right knee in 90º of flexion. Maximal isometric voluntary contraction (MIVC) of muscle was measured using a load cell (SIWAREX R, 500 kg, Siemens, Germany). A strap, connected by a chain to a load cell, was attached to the ankle to measure knee extension isometric force. Force was provided to the subject as visual feedback on an oscilloscope. The subject performed a total of three 5-second MIVCs of knee extension, each separated by a 2-min rest. During each MIVC, subjects were verbally encouraged to exceed the previous force level. The highest MIVC value was considered as the reference value [6]. Surface EMG signals were simultaneously recorded from the quadriceps and hamstring muscles of the right leg during MIVC of the quadriceps muscle. Four pairs of electrodes (circular Ag–AgCl surface electrodes: Ambu Neuroline, conductive area 28 mm^2) were carefully placed in the bipolar configuration (Figure 1). Before electrode placement, the skin was shaved and lightly abraded in the selected locations. Surface EMG signals were amplified (EMG amplifier, EMG-16, LISiN-OT Bioelettronica, Torino, Italy, bandwidth 10–500 Hz), sampled at 2048 Hz, and stored after 12-bit A/D conversion. A ground electrode was placed around the right ankle.

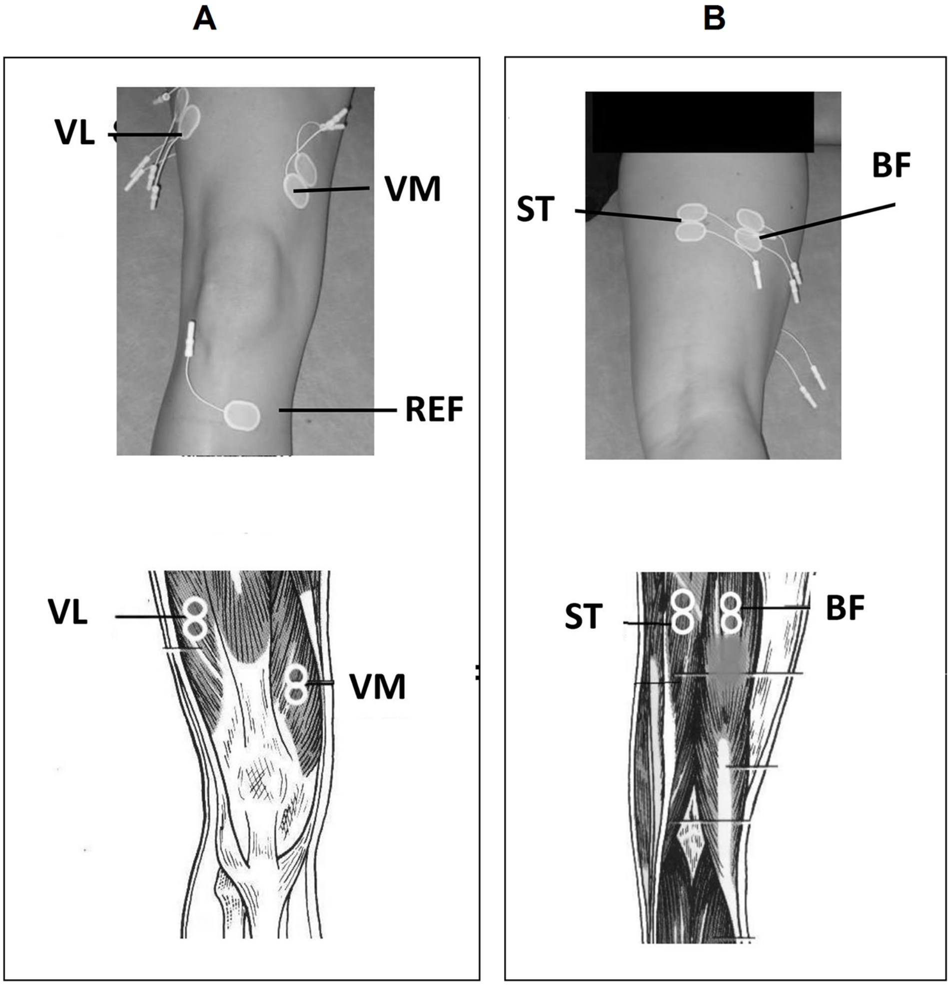

Figure 1: Electromyography electrode placements and schematic electrode position. (A) shows the vastus lateralis (VL) and vastus medialis (VM) of the quadriceps muscle in anterior right. (B) shows the semitendinosus (ST) and biceps femoris (BF) of the hamstring muscle in posterior right. REF represents reference electrode position.

Data Analysis

To cover the EMG signal frequency range, a 500-Hz cut-off low-pass filter and a 10-Hz cut-off high-pass filter were applied. A notch filter with a cut-off frequency of 50 Hz was also used to eliminate power line interference. After EMG pre-processing for noise reduction, all EMG features were estimated for epochs of 250 ms. The values obtained from 250 ms were averaged within the 5-second MIVCs. The 6 time features and the 3 frequency features were considered for EMG processing.

To evaluate EMG signals, time features are widely applied to EMG processing. Six frequently suggested time domain features with high computational efficiency for EMG processing were assessed from specific windows of EMG signals [16]. The root-mean-square (RMS) is the most common method for detecting the amplitude of the EMG signal. Mean Absolute Values (MAV) calculates the average absolute value of a signal in a time window. Standard deviation (SD) calculates variations in a signal's amplitude relative to its mean in a time window. Zero-cross (ZC) is the number of times the signal changes from positive to negative or vice versa. The Mean of Peak Value (MPV) is obtained by calculating the maximum signal in a time window. The Integral Absolute Value (IAV) is the absolute value of the area below the signal graph in a time window. These features were extracted as six features in the time domain.

The frequency contents of the signals were observed from the power spectrum density (PSD), which is actually the amount of power per unit frequency. Based on this, the Welch algorithm and the Hamming window were used to calculate the FFT of the signals [17]. The mean frequency (MNF), medium frequency (MDF), and frequency ratio (FR) were extracted from the PSD of the signals. MNF is an average frequency value of PSD [14]. MDF is the frequency at which the EMG power spectrum is divided into two parts with equal amplitude [18]. FR provides information to differentiate between contraction and relaxation of muscle and is defined as the ratio of power spectra at low-frequency and high-frequency bands [19]. These features were extracted as three features in the frequency domain. Figure 2 shows the schematic of recording muscle performance and EMG signals pre- and post-eccentric and concentric strength training.

Statistical Analysis

The Kolmogorov-Smirnov test was used to evaluate the normality of the extracted features pre- and post-test. After EMG feature extraction, an analysis was carried out using the paired sample t-test / Wilcoxon test, which was used to determine differences. An independent sample t-test / Mann-Whitney U test was used to determine the most effective training in the extracted features. EMG signal processing was performed by the signal processing

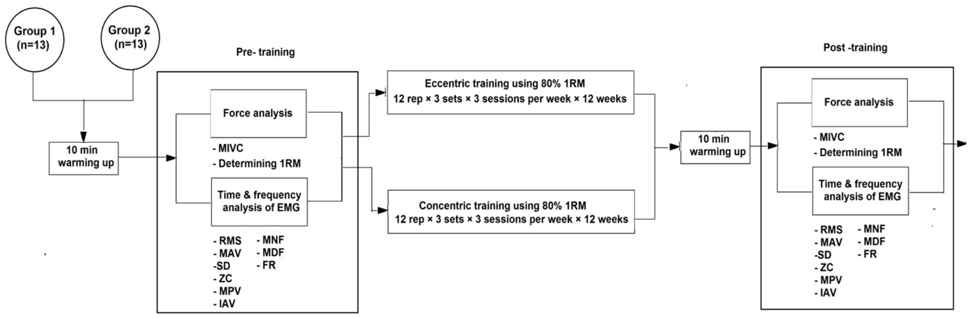

Figure 2: Schematic representation of recording muscle performance and electromyography (EMG) signals pre- and post-eccentric and -concentric strength training.

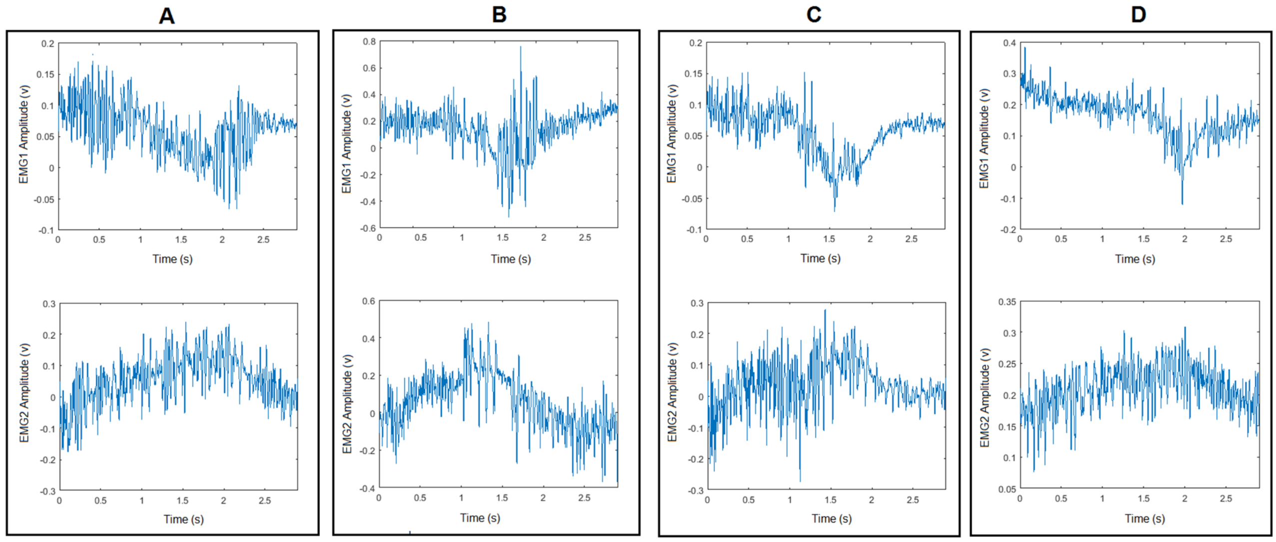

Figure 3: Shows an example of electromyography signals recorded in two channels for pre- and post-eccentric and -concentric strength training. (A) and (B) shows Subject 1 in pre- and post-concentric training, respectively. (C) and (D) shows Subject 14 for pre- and post-concentric training, respectively. The signals at the top and bottom of Figure 3 are the quadriceps EMGs and the hamstring electromyography, respectively.

Table 1: Results of time domain features

Features	Type of training	Pre	Post	P value for within the group
RMS	Eccentric	2.22±0.83	2.53±0.74	0.18†
	Concentric	2.43±0.63	5.89±0.71	0.04†*
MAV	Eccentric	0.63±0.13	0.83±0.21	0.03†*
	Concentric	0.68±0.15	0.98±0.18	0.01×*
SD	Eccentric	0.12±0.05	0.13±0.06	0.28×
	Concentric	0.08±0.02	0.11±0.01	0.02†*
ZC	Eccentric	1521.61±456.12	2682.55±361.85	<0.01†*
	Concentric	1411.22±398.25	2436.16±439.51	<0.01×*
MPV	Eccentric	0.22±0.14	0.18±0.16	0.54†
	Concentric	0.24±0.17	0.43±0.11	<0.01†*
IAV	Eccentric	12.16±5.42	11.33±3.98	0.42†
	Concentric	11.21±4.25	11.21±4.31	0.15†

Root-mean-square (RMS), mean absolute values (MAV), standard deviation (SD), zero-cross (ZC), mean of peak value (MPV), integral absolute value (IAV). Paired test †, Wilcoxon test×, P<0.05

toolbox for MATLAB software (MathWorks, Version 2018A). Statistical analysis was performed with SPSS software (Statistic Software Package: Version 20). Data was expressed as means±standard deviation (SD). A value of P<0.05 was considered statistically significant.

Results

Subjects recruited for the current study comprised 26 males (age, mean±SD, 21.6±2.1-year, body mass 73.3±6.9 kg, height 1.76±0.05 m). No significant differences were found between the groups in terms of age, body mass, or weight. MIVCs in pre- and post-training were respectively 55.63±3.64 Kg and 79.04±4.39 Kg (for the eccentric group), 34.23±2.69 Kg and 42.91±2.26 Kg (for the concentric group). MIVCs were significantly increased in both groups from pre- to post-training (P<0.05). Moreover, MIVC was significantly higher after eccentric training than after concentric training

Figure 3 shows an example of EMG signals recorded in two channels for pre- and post-different training. As can be seen in Figure 3, the amplitude of the signals was higher in post-eccentric training than in pre-training as well as with concentric training.

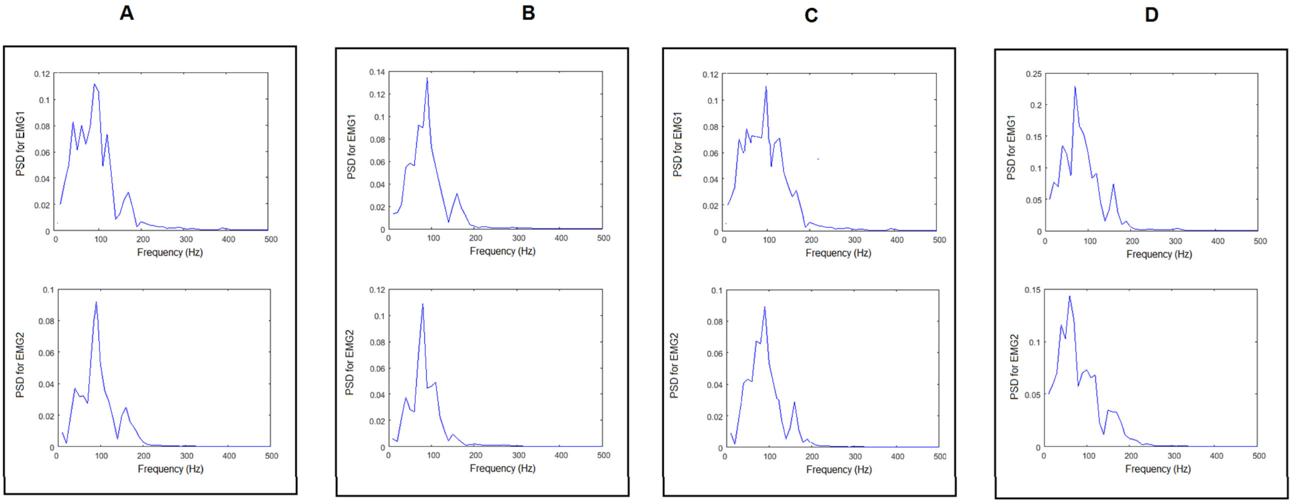

Figure 4: Shows an example of electromyography power spectral density in two channels for pre- and post-eccentric and -concentric strength training. (A) and (B) show the spectrum density of Subject 1 for pre- and post-concentric training, respectively. (C) and (D) show the spectrum density of Subject 14 for pre- and post-eccentric training, respectively. The signals at the top and bottom of Figure 4 are the quadriceps and hamstring electromyography, respectively.

Table 2: Results of frequency domain features

Features	Type of training	Pre	Post	P value for within the group
MNF	Eccentric	80.25±4.86	78.36±6.55	0.39×
	Concentric	75.11±7.31	51.44±4.89	0.01†*
MDF	Eccentric	5.46±1.31	4.73±1.44	0.26†
	Concentric	5.08±1.82	3.17±1.92	<0.01†*
FR	Eccentric	3.79±1.28	3.05±1.16	0.09†
	Concentric	3.62±1.31	2.67±1.11	0.04×*

Mean frequency (MNF), medium frequency (MDF), frequency ratio (FR). Paired test †, Wilcoxon test×, P<0.05

Table 1 shows the results of time domain features. In the time domain analysis, MAV and ZC showed significant changes in pre- and post-tests for both eccentric and concentric training. For the eccentric training group, other features including RMS, SD, and MPV of the signal showed a significant difference between pre- and post-tests. For the concentric training group, there were no significant differences from pre- to post-training in these features (RMS, SD, and MPV) (P<0.05). However, significant differences were observed between the concentric and eccentric training groups for SD and MPV (P<0.05). Significant changes in all time features except IAV indicates eccentric training induced more simultaneous activity of the leg muscles.

Figure 4 shows an example of PSD of quadriceps and hamstring EMG signals for pre- and post-different training. Based on the information in Figure 4, the nature of frequency properties and PSD amplitude were more different post-eccentric training than pre-training as well as with concentric training. Table 2 shows the result of extracted frequency domain features. Frequency features of EMG signals, including MNF, MDF, and FR, showed significant changes in pre- and post-test results for the eccentric training group; however, no significant difference was observed in the frequency features in the post-test compared to the pre-test in the concentric training group. The frequency features of EMG decreased after training, especially in the eccentric training group, because of a change in the nature of frequency features. This indicates that more movement units are involved in this type of training.

Discussion

The current study aimed to evaluate simultaneous electrical activity of the quadriceps and hamstring muscles after eccentric and concentric training. To evaluate simultaneous activity knee muscles, time and frequency analyses were performed to extract nine features of both quadriceps and hamstring EMG signals. The results of time domain analysis of EMGs showed that MAV and ZC were significantly increased pre- and post-training in both groups. MAV calculates the average absolute value of a signal in a time window. It is an easy way to detect muscle contraction levels [20]. This result showed that muscle contraction levels in both groups were significantly increased. ZC is the number of times that the amplitude value of the EMG signal crosses the zero y-axis. In the EMG feature, the threshold condition is used to avoid including background noise [9]. This result showed that both groups had the same conditions for background noise. In the eccentric training group, other features including RMS, SD, and MPV were significantly increased between pre- and post-tests. In the concentric training group, these features showed no significant differences in extracted time features from pre- to post-training. These features are related to the constant force and neuromuscular activity within the agonist and antagonist muscles. A higher difference in these features of EMG after eccentric training may be explained by neural mechanisms underlying eccentric contractions to control skeletal muscles.

The results of frequency domain analyses of EMGs showed that all frequency features in the eccentric group were significantly decreased from pre- to post-training. These features are related to the preferential recruitment of fast twitch motor units [18]. The decrease in EMG features is most likely due to unique neural strategies to control synergic muscle during eccentric training.

It should be noted that the present work was conducted in continuation of the authors' previous work [7], in which a time feature (RMS) of the quadriceps and hamstrings muscles was used for knee muscle analyses in eccentric and concentric training. The main findings of the previous study showed that strength training using eccentric action resulted in greater improvement in quadriceps strength as compared to concentric exercise. Moreover, the EMG RMS of the quadriceps (VM and VL) and hamstring (ST and BF) muscles measured after eccentric strength training was significantly larger than those observed after concentric strength training. Nevertheless, in the present work, we used nine features and analyzed the EMGs of knee muscles simultaneously. This resulted in the better processing of EMG signals and enhanced results of knee electrical activity as compared to our previous work [7]. As a limitation of the present work, it should be emphasized that the present findings are translatable to healthy non-athletic men; future studies are needed for different people.

Previous studies have reported the effects of resistance training on neuromuscular adaptation of the quadriceps muscle (15). Their results showed higher increases in muscle force output and EMG activity after eccentric resistance training. The current results are in good agreement with the aforementioned reports, while the present study used strength training and evaluated EMG signals in the quadriceps and hamstring muscles simultaneously.

Conclusion

Based on the current results, changes in the EMG features of time and frequency domains after eccentric training can be attributed to the increased neural signals to muscle fibers, which in turn result in greater motor unit recruitment and muscle tension. This may indicate that strength training using eccentric contraction can more effectively trigger neuromuscular activity within the agonist and antagonist muscle simultaneously. This could be mean improving the simultaneous activity of the quadriceps and hamstrings in this type of training.

Conflicts of Interest: None declared.

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