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Original Research

Comparison of the EMG Frequency Spectrum of Lower Limb Muscles during Weight Training with Traditional and Novel Equipment

AmirAli Jafarnezhadgero[*1], Amirhosein Sadri[1], Mohammad Mahdi Bahrami Sharif[1], Milad Alipour Sarinasirloo[1]

**1. Department of Physical Education and Sport Sciences, Faculty of Educational Sciences and Psychology, University of Mohaghegh Ardabili, Ardabil, Iran.*

ABSTRACT

Many practitioners and trainers advise designing and executing resistance training programs that include free weights and machines for strength training. The aim of the present study was to compare the frequency spectrum of lower limb muscles during weight training with traditional and novel equipment. Fourteen healthy power lifters (age: 26±7 years) were participated in this study. A portable EMG system with six pairs of bipolar surface electrodes was used to record the electrical activity of the selected lower limb muscles at a sampling frequency of 1200 Hz. Participants had enough experience to perform Free Weights Squat, Smith Machine Squat, Smith Machine Squat with one leg and the Dead lift movements. Participants carried out each movement, 5 times at an intensity equal to 50% of one-repetition-maximum level. The results showed higher median frequency of the vastus lateralis muscle during free weight single-leg squat than those that in the free weight squat (p=0.001) and dead lift (p=0.000) movements in lifting phase. Also, the median frequency of vastus lateralis muscle in single-limb squat with smith machine was significantly higher than that in the dead lift movement (p=0.021). The median frequency spectrum of the gastrocnemius muscle in the free weight squat movement showed a significant increase during the downward phase relative to the free weight single-leg squat movement (p=0.039). In order to strengthen vastus lateralis muscle in athletes or individuals with weak vastus lateralis muscle, free weight single-leg squat movement is more effective than those that in the other movements.

Keywords: Frequency spectrum, Lower limb, Squat, Smith machine, Dead lift.

Introduction

At least one set of strengthening exercises twice a week is recommended for athletes by the American College of Exercise Medicine [1]. Many practitioners and trainers advise designing and executing resistance training programs that include free weights and machines for strength training. Squat movement is an integral part of strengthening programs for many sports, such as football, handball, and bodybuilding, which require high quadriceps muscular strength. Squat primarily strengthens the muscles of the hip and knee, as well as the bone structure of these areas that play a major role during recreational activities such as running [1]. Strengthening exercises with free weights or machines can improve neuromuscular function in individuals, which can increase the physiological cross-sectional area, increase level muscle capillary, and improve coordination in the motor unit's recruitment [2]. Of the common movements in the bodybuilding are the free weights squat, squat with a smith machine, single-leg free squat with and without the smith machine and a dead lift. These movements reinforce the muscles of the lower limbs and are similar to many sports exercises, such as running and jumping in terms of neuromuscular and biomechanical [3]. Because closed-kinetic-chain exercises are more similar to people daily activities, rehabilitation clinics use these types of exercises more often than open-kinetic-chain exercises [4-6].

The movements used in this study are considered as part of the closed-kinetic-chain exercises, which are often considered in clinical settings such as knee rehabilitation after anterior cruciate ligament surgery [7, 8], knee osteoarthritis [9], and patellofemoral pain syndrome [10]. There are several studies on the extent of electromyography activity of the muscles during squat movements [5, 11-14]. Various studies have compared the level of muscle activity during the execution of the squat with the smith machine and with free weights [15-17]. According to different methodologies of these studies, different results have been reported regarding the amount of activity in the lower limb muscles [15-17]. Athletes use free weights more as tools for improving muscular strength and power. However, most beginners use these tools for their relative safety and ease of use of resistance training machines [18]. Resistance training machines offer fixed or variable resistance [19]. One of the scientific methods for assessment of the rate of involvement of each muscle during various strengthening exercises is recording of the electromyography activity of the muscles during these activities.

Electromyography is a method for measuring the electrical activity produced by skeletal muscle that results in contraction [20]. Recently, there have been many applications for electromyography in the sports, medicine and engineering [21, 22].

Usually, the analysis of electromyographic signals can be investigated in two ways based on the time domain and frequency domain characteristics [23]. In the frequency domain, several variables are considered as the main characteristics of electromyographic power spectrum. The two characteristics of the frequency spectrum, which are commonly and frequently studied, include the mean and median frequencies [24]. The relationship between different types of motor units and characteristics of the frequency spectrum of surface electromyography signals during an isometric contraction was reported in a previous study [25]. The researchers showed that the techniques used to process electromyographic signals during isometric movements could also be used for dynamic movements [24]. Typically, the study of the power frequency parameters of surface electromyography signals is used to evaluate changes in response to fatigue [26, 27]. During isometric tasks, the increase in the frequency domain is accompanied by a linear increase in muscular force, while in dynamic contractions, it is not the case [28, 29]. Despite the importance of frequency domain analysis of the muscles in dynamic activities such as free weight squat, squat with a smith machine, single-leg squat with and without the smith machine and dead lift. The researcher could not find any study that looked at this subject. The aim of the present study was to compare the frequency contents of the muscles (vastus medialis, rectus femoris, vastus lateralis, biceps femoris, semimembranosus, gastrocnemius and erector spinae) The aim of the present study was to compare the frequency spectrum of lower limb muscles during weight training with traditional and novel equipments.

Materials and Methods

The statistical sample of this study was 14 healthy powerlifter men, with mean age of 26 ± 7 years, height of 177 ± 5 cm, and weight of 81± 15 kg. The participants had at least 3 years of experience in squat with and without smith machine, single leg squat with and without smith machine, and the dead lift. Participants regularly used these exercises in their training program. All participants completed and signed the written consent letter and medical-sports information questionnaire before the test. The inclusion criteria were no history of knee injuries, lower limb surgery and fractures, and postural abnormalities. Before the test, the procedure for completing the movements was fully described for the participants and the one repetition maximum for each person was measured as a valid method [12] in each movement.

In the movements of the squat and the lift, the distance of the legs was equal to 108% of the shoulder width (Fig. 1). The starting and ending points included 90-degree flexion and complete knee extension. The metronome was used to control the speed of the movements. Rising phase was considered to be one second. Four Vicon cameras and 16 Retro reflective markers were used to detect the knee joint angle (Fig. 1). The placement of markers was on the right and left lower limbs according to the Plugin-gait marker set.

The standard Olympic barbell bar with a weight of 20.5 kg, a special weight for the Barbell, smith machine (made in Iran, Mobarez company; with a length of 120cm, a width of 220 cm and a height of 230 cm) were used in this study. Participants warmed up using stretching and other movements for 10 minutes [2]. To prevent injury, an experienced trainer accompanied the subjects to properly control the movements. Surface EMG signals were collected using a 16-channels wireless electromyography system (BTS FREE EMG 300, Italy) with a sampling frequency of 1200 Hz and a signal-to-noise ratio of over 100 dB. Ag-AgCl disposable adhesive electrodes were used in this study. Initially, the hair of the lower limb was completely cut and the skin was cleansed and then, cotton and medical alcohol were used to reduce the electrical resistance of the skin. Afterwards, the electrodes were installed on the muscles of the right liimb (vastus medialis, rectus femoris, vastus lateralis, biceps femoris, semimembranosus, gastrocnemius and erector spinae (third lumbar vertebra)) according to the SENIAM European protocol [30]. The distance from the center to the center of the electrodes was 2 centimeters.

Figure 1. Position of electrodes and markers from two different views

The subjects performed each of the movements, namely free weight squat, squat with the smith machine, single leg squat with and without smith machine, and a dead lift with 5 repetitions and 50% 1-repetition maximum intensity.

About 5 minutes of rest were considered between each movement. The order of the movements was selected randomly. In the present study, the effect of fatigue was minimized by selecting the working load below the maximum value, low number of repetitions, high level of subjects' readiness and considering sufficient rest between the movements. The sampling rate was equal to1200 Hz in the present study. Gain value and CMRR were equal to 1000 and 100,000:1, respectively. The signal-to-noise ratio was also 110 dB. For analyzing raw data (Fig. 2), the EMG analyzer software with the band-pass filter of 10 to 500 Hz were used. A 60 Hz Notch filter was also used to remove noise from urban power.

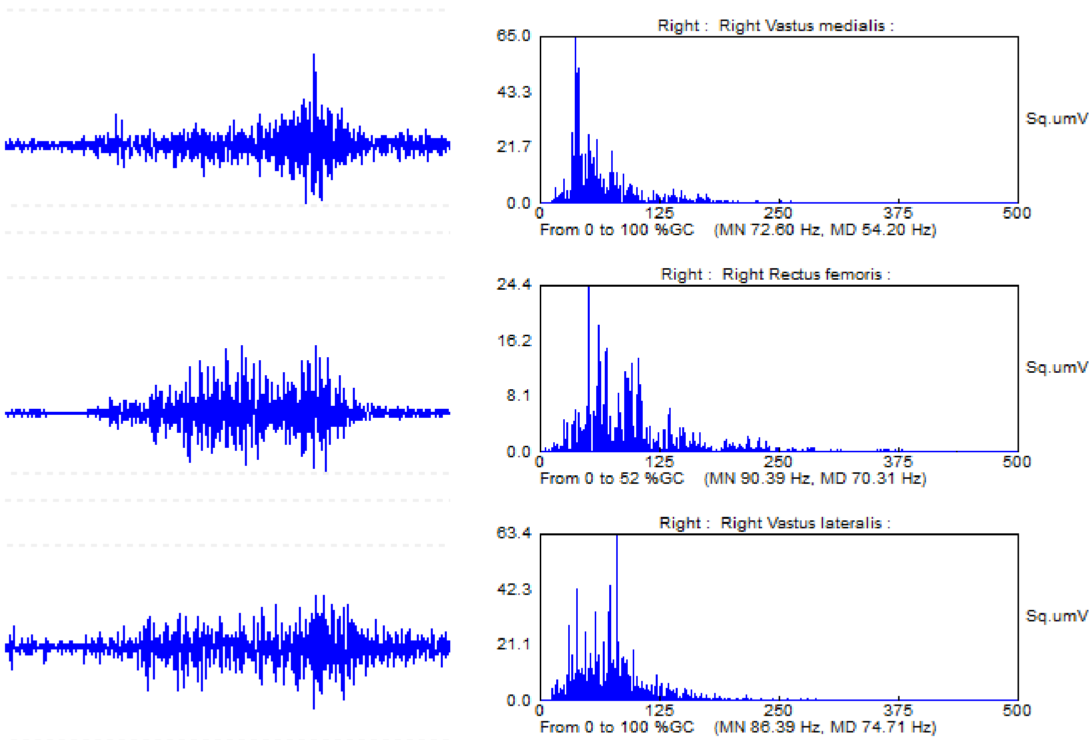

Figure 2. Raw EMG data (left) and their frequency content (right)

Statistical analysis

Shapiro-Wilk test confirmed the normal distribution of data. Also, for statistical analyzing, the ANOVA repeated measure test was used. In this study, the significance level was considered $p<0.05$. SPSS software (version 18) was used to analyze the data.

Results

The median frequency of vastus medialis, rectus femoris muscle, semimembranosus, gastrocnemius and erector spinae did not show any significant differences between the five different movements during the rising phase (p<0.05) (Table 1). During the rising phase, the median frequency of vastus lateralis muscle in single leg squat without smith machine was significantly higher than those that in the free weight squat (p=0.001) and dead lift movements (p=0.000) (Table 1). Also, the median frequency of the vastus lateralis in the single leg squat with smith machine was significantly higher than that in the dead lift (p=0.021) (Table 1). The median frequency of biceps femoris muscle in squat movement with smith machine was significantly higher than those that in the other movements (p<0.05) (Table 1).

Table 1. Comparing the muscular frequency contents in five different movements during rising phase.

Muscle	Single leg squat without smith machine	Dead lift	Single leg squat with smith machine	Squat with smith machine	Free weight squat

Vastus medialis	62.7±8.3	61.4±11.1	64.2±9.1	62.9±10.6	64.7±10.4
Rectus femoris	82.5±8.7	75.6±8.8	79.1±16.9	79.3±12.12	81.2±10.9
Vastus lateralis	§*65.5±2.1	§¥58.9±2.7	¥65.7±5.6	60.3±7.3	*60.7±4.0
Biceps femoris	$53.1±4.7	¥57.67±19.1	$¥#†79.14±16.9	#49.1±8.6	†52.8±11.9
Semimembranosus	58.2±5.1	48.8±12.8	59.4±8.4	54.0±12.2	50.9±18.8
Gastrocnemius	87.0±6.1	90.7±13.9	96.8±18.2	89.7±15.9	87.1±8.9
Erector spinae	59.1±7.8	56.5±8.5	59.1±15.7	68.9±25.0	61.7±16.0

* Significant difference between free weight squat and single leg squat without smith machine
¥ Significant difference between single leg squat with smith machine and dead lift
§ Significant difference between single leg squat without smith machine and dead lift
† Significant difference between free weight squat and single leg squat with smith machine
# Significant difference between squat with smith machine and single leg squat with smith machine
$ Significant difference between single leg squat with and without smith machine

During the falling phase, the findings showed no statistically significant difference in the median frequency of vastus medialis during five different movements ($p<0.05$). Nevertheless, the median frequency of the rectus femoris showed the highest value in the squat movement with the smith machine, and the dead lift movement showed the lowest value during the falling phase. The findings of this study on the mean frequency of vastus lateralis muscle during lifting were significantly lower than those that in the free weight squat ($p=0.042$) and single leg squat with the smith machine ($p=0.060$) (Table 2). The median frequency of the gastrocnemius showed a significant increase in the free weight squat during the falling phase compared to the single leg squat ($p=0.039$). The median frequency of biceps femoris, semimembranosus, and erector spinae muscles did not show any significant differences between the five movements during the falling phase ($p<0.05$) (Table 2).

Table 2. Comparing the muscle frequency spectrum in five different movements during the falling phase

Muscle	Single leg squat without smith machine	Dead lift	Single leg squat with smith machine	Squat with smith machine	Free weight squat
Vastus medialis	58.7±5.7	‡58.63±9.7	64.1±11.9	‡65.0±12.2	60.7±10.4
rectus femoris	€§$62.8±6.3	Š‡¥§ 48.6±15.4	¥67.0±15.2	Š ‡$€ 77.9±13.4	Š 69.7±12.9
Vastus lateralis	63.4±1.9	Š¥ 63.2±6.1	¥68.7±7.9	65.0±5.6	Š 67.7±5.1
Biceps femoris	61.7±3.2	60.8±11.0	62.4±7.5	62.6±12.7	58.0±8.8
Semimembranosus	72.6±7.8	59.6±17.5	67.6±17.9	75.1±21.6	66.5±20.0
Gastrocnemius	*89.0±11.5	97.9±18.3	100.4±28.6	97.2±33.4	*102.5±21.1
Erector spinae	55.6±7.1	61.5±13.8	62.4±14.8	70.8±24.4	60.5±15.2

* Significant difference between free weight squat and single leg squat without smith machine
¥ Significant difference between single leg squat with smith machine and dead lift
§ Significant difference between single leg squat without smith machine and dead lift
† Significant difference between free weight squat and single leg squat with smith machine
# Significant difference between squat with smith machine and single leg squat with smith machine
$ Significant difference between single leg squat with and without smith machine

According to the results of this study, in the free weight squat movement, the median frequency of rectus femoris muscle increased significantly during the rising phase ($p=0.008$). Also, in squat movement with the smith machine ($p=0.013$) and the free weight squat ($p=0.000$), the frequency of vastus lateralis muscle during the falling phase was higher than those that in the rising phase. Furthermore, the results of this study showed that in the single leg squat with smith machine, the median frequency of rectus femoris muscle showed a significant increase during the rising phase than that in the falling phase (p=0.005). Also, the results of this study indicated that in the dead lift movement, the median frequency of the rectus femoris in the rising phase (p=0.000) and the vastus lateralis in the falling phase (*p=0.016*) showed a significant increase. Moreover, the results of this study showed that in the single leg squat without smith machine, the median frequency of the vastus medialis, rectus femoris, vastus lateralis during the rising phase were greater than those that in the falling phase (Table 3).

Table 3. Comparison of the muscular frequency contents of the main muscles during the rising and falling phases.

Movements	Muscle	Falling phase	Rising phase	Significance level	Effect size
Free weight squat	Vastus medialis	60.7±10.4	64.7±10.5	0.244	0.38
	Rectus femoris	69.7±12.9	81.2±10.9	0.008*	0.96
	Vastus lateralis	67.6±5.1	60.7±4.0	0.000*	1.51
Squat with smith machine	Vastus medialis	65.0±12.2	62.9±10.6	0.520	0.18
	Rectus femoris	77.9±13.4	79.3±12.1	0.704	0.10
	Vastus lateralis	65.0±5.5	60.3±7.3	0.013*	0.73
Single-leg squat with smith machine	Vastus medialis	64.1±11.9	64.2±9.1	0.963	0.01
	Rectus femoris	67.0±15.2	79.1±16.9	0.005*	0.94
	Vastus lateralis	68.7±7.9	65.7±5.6	0.070	0.44
Dead lift	Vastus medialis	58.6±9.7	61.4±11.1	0.223	0.26
	Rectus femoris	48.6±15.4	75.6±8.8	0.000*	2.23
	Vastus lateralis	63.2±6.1	58.9±2.7	0.016	0.97
Single leg squat without smith machine	Vastus medialis	58.5±5.7	62.7±8.3	0.026*	0.6
	Rectus femoris	62.8±6.3	82.5±8.6	0.000*	2.64
	Vastus lateralis	63.4±1.9	65.5±2.1	0.001*	1.05

*Significant difference *p<0.05*

Discussion and Conclusion

The purpose of the present study was to compare the muscle frequency spectrum (vastus medialis, rectus femoris, vastus lateralis, biceps femoris, semimembranosus, gastrocnemius, erector spinae) in the lower limb and trunk The aim of the present study was to compare the frequency spectrum of lower limb muscles during weight training with traditional and novel equipments**.**

The findings showed that the median frequency of the biceps femoris muscle was significantly higher in squat movment with the smith machine compared to other movements. Also, the median frequency of vastus lateralis muscle in the single leg free weight squat during the rising phase was significantly higher than that of the free weight squat and dead lift movement. It has been reported that median frequency can be used as an indicator for identifying control strategies for using different muscles along different levels of force [31-35]. With regard to the higher frequency of vastus lateralis and biceps femoris during the single leg squat compared to the free weight squat and dead lift movements, it can be concluded that the single leg squat without smith machine are more suitable for the patients with osteoarthritis of medial compartment of the knee joint than the two other movements [36]. The reason for this is that, with greater involvement of the vastus lateralis and biceps femoris muscles, the knee joint directed co-contraction increases that could reduce the load on the medial knee joint compartment [36]. Because of the unstable condition, part of the muscle activity is used to stabilize the additional movements of the joints. Therefore, the activity of the agonist and antagonist muscles increase during work with free weights in comparison with the training machines [37].

The findings also showed that the median frequency of vastus lateralis in the single leg squat movement with the smith machine was significantly higher than that of the dead lift. In general, using frequency domain analysis, we can obtain more accurate information on the degree of participation of the specific frequencies of the surface electromyography signal [32].

The median frequency of the rectus femoris in the squat with smith machine was the highest during the falling phase and lowest in the dead lift during the falling phase. In many skeletal muscles, the increase in the conduction velocity or the median frequency of electromyography is associated with an increase in the output force, which is higher by the use of higher and faster motor units [38-40]. Athletes use strengthening exercises to improve performance and reduce injuries. According to the findings of the present study, during the falling phase, the squat with smith machine has a higher involvement of motor units and firing rate in the rectus femoris muscle than the other movements. The findings of this study showed lower levels in the median frequency of vastus lateralis muscle during dead lift movement in the falling phase compared to the free squats and single leg squat with smith macine. The median frequency of the gastrocnemius in the free squat movement during the falling phase showed a significant increase compared to the single leg squat movement without smith machine. A number of studies have shown that changes in muscle frequency are influenced by two factors: fatigue [41, 42] and type of muscle fiber [43, 44]. On the other hand, some sources [29] have argued that the increase in frequency does not necessarily indicate the activity of most of the fast twitch units, but may be the result of a high amount of firing in slow twitch units, reduced coordination of motor units or other probabilities. It has been reported that different dynamic conditions produce different levels of joint power, while unstable conditions are associated with lower power efficiency [45]. The motor strategy during exercise under unstable conditions may not be effective as part of the muscular activity is used to stabilize undesirable movements [46]. One study showed that the leg muscles (especially the vastus medialis and biceps femoris) had more electromyographic activity during free weight squat compared with squat with the smith machine. In the stabilizing muscles of the leg, higher electromyographic activity was reported during free weight squat compared to squat the smith machine [47]. Extensors of the knee (vastus lateralis) and erector spinae showed a greater amplitude than electromyographic activity, while abdominal, biceps femoris, and planterflexors stabilizers showed a relatively lower electromyographic activity [47]. Schwanbeck et al. showed that the activity of biceps femoris during free weight squat movement could increase the role of knee flexors in fixing and supporting ankle, knee and hip joints in a destabilized environment. Antagonistic muscle activity increases to increase the stability and stiffness of the joints [47]. Unlike the results of Schwanbeck et al. [15], Anderson and Behm [16], showed no significant difference in the biceps femoris muscle activity between the squat with free weights and smith machine. These results are likely due to differences in their methodology compared to the current study.

The findings of this study showed that the frequency of the quadriceps muscle group in general (5 cases) had a higher frequency during raising phase (concentric contraction) compared to the falling phase (eccentric contraction). When the muscle performs an eccentric action, the muscle length increases. Therefore, the elastic properties of muscle, tendons and supportive ligaments contribute to the production of eccentric muscle power [48]. But, in concentric contractions, there is no participation in this category and the length of the muscle is shortened. For this reason, it can be concluded that eccentric movement, in order to produce the same level of force, require less muscular activity than concentric contractions and their electromyographic activity is less [49]. The results of this study confirmed these cases in relation to the frequency spectrum.

The present study has some limatations that include the absence of female gender in the sample and the lack of registration of knee joint kinetics in order to accurately measure the amount of forces and loads on the knee joint.

In conclusion, In order to improve the engagement of vastus lateralis muscle in athletes, single leg free squat movement is better than other movements. Generally, the frequency of the main agonist muscles during the raising phase was higher than the frequency of these muscles during the falling phase.

Conflicts of interest: None.

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Corresponding Author: Dr. AmirAli Jafarnezhadgero, Department of Physical Education and Sport Sciences, Faculty of Educational Science and Psychology, University of Mohaghegh Ardabili, Ardabil, Iran. Email: Amiralijafarnezhad@gmail.com, Tel: +98 9105146214

چکیده فارسی

مقایسه طیف فرکانس الکترومایوگرافی عضلات اندام تحتانی طی تمرینات با وزنه با ابزار سنتی و جدید

امیرعلی جعفرنژادگرو[1*]، امیرحسین صدری[1]، محمد مهدی بهرامی شریف[1]، میلاد علیپورساری نصیرلو[1]

1- گروه تربیت بدنی و علوم ورزشی، دانشکده علوم تربیتی و روانشناسی، دانشگاه محقق اردبیلی، اردبیل، ایران.

چکیده فارسی

هدف پژوهش حاضر مقایسه طیف فرکانس عضلات اندام تحتانی طی طی تمرینات با وزنه با ابزار سنتی و جدید بود. چهارده پاورلیفتر مرد سالم (سن: ۷±۲۶ سال) در این پژوهش شرکت نمودند. از دستگاه الکترومایوگرافی با شش جفت الکترود سطحی جهت ثبت سیگنال‌های الکترومایوگرافی منتخبی از عضلات اندام تحتانی با فرکانس نمونه‌برداری ۱۲۰۰ هرتز استفاده شد. شرکت‌کننده‌ها تجربه کافی در اجرای حرکت اسکات با و بدون دستگاه اسمیت، اسکات تک پا با و بدون دستگاه اسمیت، و حرکت لیفت مرده را داشتند. شرکت‌کننده‌ها هر حرکت را ۵ بار با شدتی برابر ۵۰ درصد یک تکرار بیشینه اجرا نمودند. نتایج نشان می‌دهد که میانه فرکانس عضله پهن خارجی در حرکت اسکوات آزاد تک پا طی فاز بالا آمدن نسبت به حرکت اسکوات آزاد (P=۰/۰۰۱) و حرکت لیفت (P=۰/۰۰۰) به طور معناداری بالاتر بود. همچنین، میانه فرکانس پهن خارجی درحرکت اسکوات تک پا با دستگاه اسمیت به طور معناداری از حرکت لیفت بالاتر بود (P=۰/۰۲۱). میانه طیف فرکانس عضله دوقلو در حرکت اسکوات آزاد طی فاز پایین آمدن نسبت به حرکت اسکوات آزاد تک پا افزایش معناداری را نشان داد (P=۰/۰۳۹). جهت تقویت بهتر عضله پهن خارجی در ورزشکاران و یا افراد دارای ضعف عضله‌ی پهن خارجی، حرکت اسکات آزاد تک پا نسبت به سایر حرکت بهتر می‌باشد.

واژه‌های کلیدی: طیف فرکانس، اندام تحتانی، اسکوات، دستگاه اسمیت، لیفت مرده