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Features of EEG and EMG Signals Before and After Different Forms of Isokinetic Contraction of the Upper Limb Muscle of Male Basketball Players

This study explores the differences between peripheral fatigue and central fatigue after eccentric and concentric contraction fatigue. Eight male basketball student-athletes were selected as study subjects, with an age of 20.0±1.2 years, height 190.3±7.6 cm and weight 90.1±5.8 kg. Each subject was required to perform 10 sets of 10 eccentric and concentric contraction fatigue tests at equal speeds. During equal-speed training, EMG signals of the biceps and triceps were recorded simultaneously. Centrifugal contraction was performed one week after centriolar contraction. The EMG signal and EEG signal were processed and analyzed using the MR3 EMG signal analysis software and MATLAB. Paired sample t-test was conducted for peak torque before and after isokinetic contraction, EMG, MF, MPF of EMG signal and power spectrum ratio of EEG signal in each frequency band. One-way ANOVA was conducted for each index after centripetal contraction and eccentric contraction. The inflection point of the peak moment of isokinetic muscle force is basically the same as that of the electromyographic signal. The fatigue time of centripetal contractile muscles is earlier than that of centrifugal contractile muscles, and the degree of peripheral fatigue after centripetal contractile muscles is obviously higher than that of centrifugal contractile muscles. The degree of central fatigue after centrifugal motion is greater than that after centripetal contraction.

Keywords: exercise-induced muscle fatigue, concentric contractions, eccentric contractions, EMG, EEG.

Introduction

Exercise-induced muscle fatigue results from a transient decrease in the maximal voluntary contraction capacity (MVC) of the muscles engaged in exercise due to excessive exertion [1, 2]. It is a prominent research topic in exercise training and physiology [3]. According to the different physiological parts of fatigue, it can be classified as central fatigue and peripheral fatigue [4]. Central fatigue can be attributed to the degree of active activation of nerves and a reduction in the ability of nerve impulses to generate fatigue signals, which in turn create a psychological resistance response. Peripheral fatigue, in contrast, is the decline in musculoskeletal motor function caused by excessive exercise [5]. Both types of physiological fatigue directly affect athletes' balance ability, muscle control ability, movement accuracy and so on, thereby significantly impacting sports performance. The effective regulation of athletes' neuromuscular systems has become the way for athletes to choose their own training methods [6]. Currently, EEG and EMG can be used to evaluate human exercise fatigue [7]. It has been shown that there is a large change in the threshold in the EMG signal after exercise fatigue in humans [8], and the EEG signal changes accordingly with body fatigue [9]. The synchronous coordination of EEG, EMG and sports can provide a better theoretical basis for athletes' training.

At present, some scholars [10–12] have combined isokinetic training instruments with surface electromyography technology to study the functional characteristics of muscles, such as the changes in muscle peak torque and EMG time domain indexes (iEMG, RMS, etc.) and frequency domain indexes (MF, MPF, etc.) during isokinetic training. However, few scholars combine isokinetic training systems with EMG and EEG testing systems to observe the physiological changes in athletes after exercise fatigue. Therefore, muscle fatigue is induced by different forms of isokinetic training with centrifuge and centrifuge; the changes in EMG and EEG signals on the surface of the lower limbs before and after muscle fatigue are detected. The two signals are analyzed synchronously with the isokinetic testing system, and the difference in fatigue mechanism between centrifugal and centrifugal isokinetic contraction is discussed, which provides a reference for scientific training of upper limb muscle strength of athletes.

Materials and methods

1 Research subjects

Eight male basketball student-athletes, aged 20.0 ±1.2 years, height 190.3 ±7.6 cm and weight 90.1 ±5.8 kg, were recruited as subjects. All subjects had healthy upper limb joints, no history of brain injury, regular routine of work and rest for nearly three months, and no strenuous exercise within 72 hours before the experiment. All subjects signed informed consent forms before the experiment.

2 Experimental instruments

The PHYSIOMED CON-TREX MJ Multi-Joint Isokinetic Training System (Germany) was used to induce upper limb muscle fatigue in the subjects. The occurrence time of muscle fatigue was determined by measuring the peak torque.

EMG signal of subjects during isokinetic contraction was measured by a Noraxon surface EMG tester (USA), which included a wireless data receiving box, surface electromyogram acquisition module, electrode piece and data line, and the sampling frequency was 1000 Hz. The surface electromyographic signals of the biceps brachii and triceps brachii were measured and recorded during centripetal and centrifugal isokinetic flexion and extension of the elbow joint.

EEG signals of subjects before and after fatigue during isokinetic centrifugal and centrifugal exercise were recorded using the BP-32 electroencephalogram signal acquisition system produced by Brain Products, Germany. The hardware includes 32 conductive caps, amplifiers, external power supplies and computers, and the software includes BP Recorder 2.0 signal acquisition software and EEGLAB signal processing analysis software (Figure 1).

Figure 1. Display diagram of experimental equipment and test site example

2.1 Experimental procedure

2.2 Isokinetic muscle strength training and testing

The elbow joint of the subject was fixed according to the operation manual of the Con-Trex MJ isokinetic training system, and the subject was required to complete each flexion and extension with maximum strength. The test mode was “elbow flexion and extension isokinetic — normal”, the movement mode was

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“centripetal — centripetal”, the test speed was 60 °/s, 10 groups ×10 times, rest between groups for 1 min, and the movement range was 60 °. At an interval of one week, the same test method was used to induce muscle fatigue training in the “centrifugal — centrifugal” exercise mode, and the surface EMG signals were recorded at the same time. After 1 min of rest after exercise, EEG signals were collected immediately.

2.3 Collection and Processing of EEG Signals

EEG signals before exercise and EEG signals after 10 groups × 10 isokinetic centripetal and centrifugal movements were collected from each subject 3 times. The preparation was completed before the experiment in strict accordance with the requirements. The impedance of each channel is less than 10 KΩ, and the sampling frequency is 1000 Hz.

2.4 EMG signal acquisition and processing

Acquisition: The subjects of this experiment were collected twice with an interval of one week, which were 10 groups ×10 isokinetic centripetal and isokinetic centrifugal motions. The dominant side of the upper limb of the subjects was the right side, so the right biceps brachii and triceps brachii were selected for testing. After 75 % medical alcohol disinfects the tested part, the electrode piece is stuck along the muscle fiber. The center distance between the two electrodes was approximately 2 cm. Connect the electrode and the amplifier with wires. Checking the signal, the subjects carry out the active muscle force and collect the surface EMG signal.

Processing: full wave rectification, smoothing, filtering and “normalization” of EMG signals by the ratio of EMG amplitude to maximum peak torque are performed on the collected EMG signals.

2.5 Statistical analysis

Statistical statistics were performed using SPSS 20.0. Data are reported as the mean ± standard deviation (SD). Images were processed by use of Graphpad Prism 5 (GraphPad Software, La Jolla, CA, United States) and Adobe Photoshop (Adobe, San Jose, CA, United States). Student’s t-test was used for analysis between two groups with only one factor involved. A one-way ANOVA was used for analysis when more than two treatments were compared. Significant differences were established at $p < 0.05$.

Results

3 Changes in force parameters during isokinetic contractions of different forms

Processing for averaging the calculation of the peak moment of isometric contraction movement for the subject 10 times/group yielded the peak moment average/group. Trends in peak moment changes during isometric contraction of the subject’s biceps brachii with triceps, as shown in Figure 2A, elbow flexors and extensors both showed a tendency to peak moment drops during centripetal versus eccentric contractions with significant inflection points. Contrasting the centripetal versus the peak moment change during eccentric contraction for biceps and triceps reveals that the time to peak moment change during eccentric contraction lags behind that during centripetal contraction (Figure 2).

Contrasting the peak moment values before and after the peak moment drop inflection points during isometric contraction of biceps and triceps (Table 1), there was a significant difference in peak moment values before and after the peak moment drop inflection points between elbow flexors and extensors when they performed centripetal and centrifugal contractions ($P < 0.05$). Therefore, it was judged that the muscle might have developed fatigue after the peak moment showed an obvious descending inflection point.

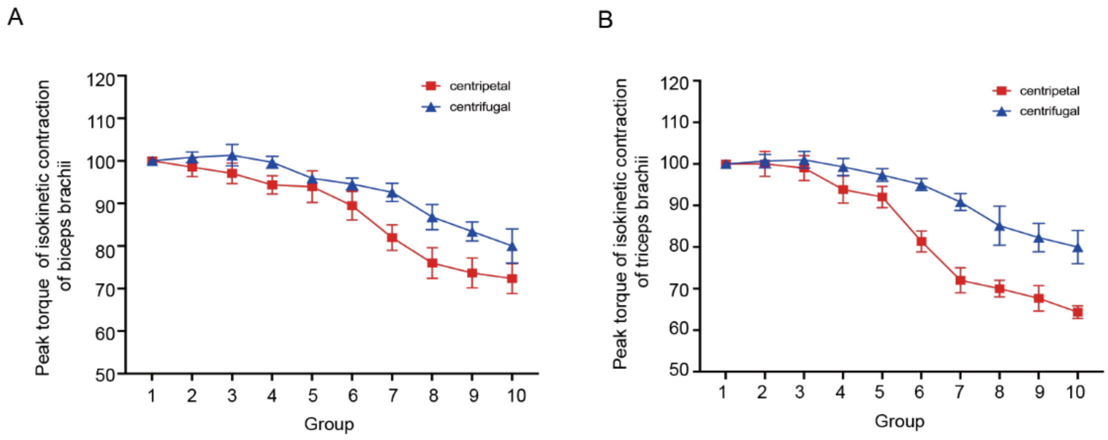

Figure 2. Variation in the peak torque of isokinetic contractions of the biceps and triceps brachii

Table 1

Comparison of the isokinetic peak contraction moment of the biceps and triceps brachii before and after inflection point (Nm)

		Before inflection point	After inflection point	t	P
biceps	centripetal	44.1±6.2	35.8±5.3	2.878	0.012
	centrifugal	42.5±5.2	36.8±4.2	2.413	0.03
triceps	centripetal	34.5±5.2	27.6±4.5	2.832	0.013
	centrifugal	39.8±4.2	34.6±4.9	2.279	0.039

3.1 Changes in sEMG parameters during different forms of isokinetic contraction

3.1.1 iEMG changes during isokinetic contraction

Based on the data of integrated EMG values after normalization to the brachial biceps, it was found that the inflection point of the change in integrated EMG values of the biceps in centripetal contraction appeared significantly earlier than that of the inflection point in eccentric contraction (Figure 3A). Based on the changes in integrated EMG values after normalization to the triceps, it was concluded that the inflection point of the rise of integrated EMG values during centripetal contraction was earlier than that during eccentric contraction (Figure 3B).

When the biceps brachii were subjected to centripetal and eccentric contraction, respectively (Table 2), the iEMG after the emergence of the inflection point was all significantly higher than that before the inflection point ($P < 0.05$); When the triceps brachii underwent centripetal contraction (Table 2), the iEMG after the inflection point was significantly higher ($P < 0.01$) than that before the inflection point, and the iEMG after the inflection point increased ($P < 0.05$) during isometric eccentric contraction. The biceps brachii gradually developed fatigue after performing group 6 isometric centripetal contraction exercise and group 8 isometric centrifugal exercise, respectively; Triceps brachii developed muscle fatigue after group 6 isometric centrifugation exercise and group 7 isometric centrifugal exercise, respectively (Figure 3). The inflexions of the iEMG changes of the biceps and triceps centripetally were all found to occur significantly earlier than the inflexions of their respective eccentric contractions.

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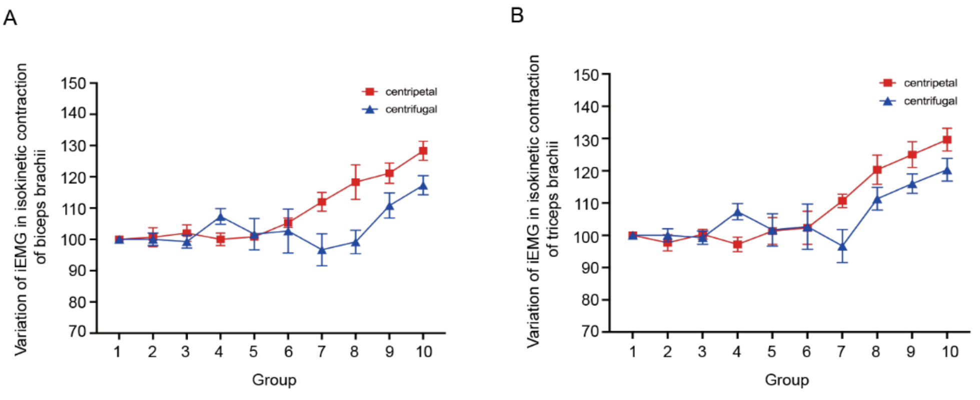

Figure 3. Variation of iEMG in isokinetic contractions of biceps and triceps brachii

Table 2

Comparison of isokinetic iEMG of biceps and triceps brachii before and after inflection point (uV*s)

		Before inflection point	After inflection point	t	P
biceps	centripetal	163.1±20.2	194.8±23.3	2.908	0.011
	centrifugal	151.5±18.3	171.8±16.2	2.349	0.034
triceps	centripetal	168.5±18.9	208.6±28.3	3.332	0.005
	centrifugal	163.8±20.3	195.8±23.9	2.886	0.012

According to the following formulas, the iEMG growth rate after different forms of isometric contraction-induced muscle fatigue was calculated, and using one-way ANOVA, we concluded that the iEMG growth of biceps and triceps after isometric centrifugation contraction-induced muscle fatigue were both significantly larger than the growth value after isometric centrifugal contraction ($P < 0.01$), so the degree of muscle fatigue was greater after isometric centrifugation contraction (Fig.4A). The time to fatigue of the muscle during isometric centripetal contraction is significantly earlier than the time to fatigue of the muscle during isometric centrifugal contraction (Figure 3). Thus, isometric centripetal contraction is more prone to peripheral muscle fatigue.

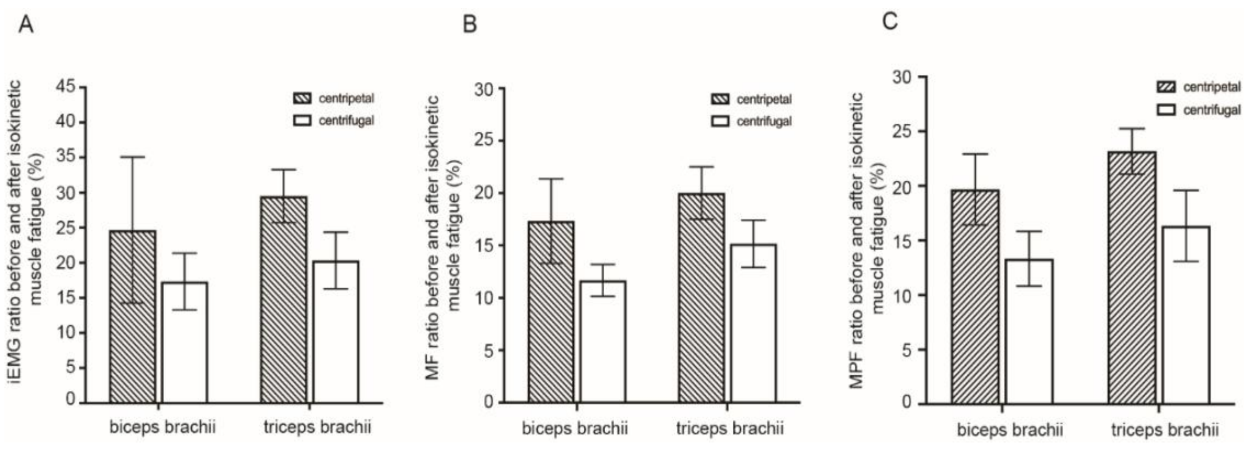

Figure 4. Rate of iEMG, MF and MPF before and after isokinetic muscle fatigue in different forms

Calculation formula: R_{iEMG} = [iEMG (10) — iEMG (1)] iEMG (1);

Note: R_{iEMG} represents the rate of integral EMG growth, iEMG (10) represents the integrated EMG of the tenth set of isokinetic movements, and iEMG (1) represents the integrated EMG of the first set of isokinetic movements.

3.1.2 MF changes during isokinetic contraction

The time inflexions of the change in the median frequency of centripetal contractions of both biceps and triceps were significantly earlier than those of eccentric contractions (Figure 5). The normalized MFS after the appearance of the inflexion point was significantly lower than that before the inflexion point ($P < 0.05$), and the tendency for the MF to decrease was largely consistent with its peak moment as well as with the inflexion point at the appearance of the iEMG (Table 3). Taken together, the decreasing trend of MF in EMG indicates fatigue phenomenon in muscle.

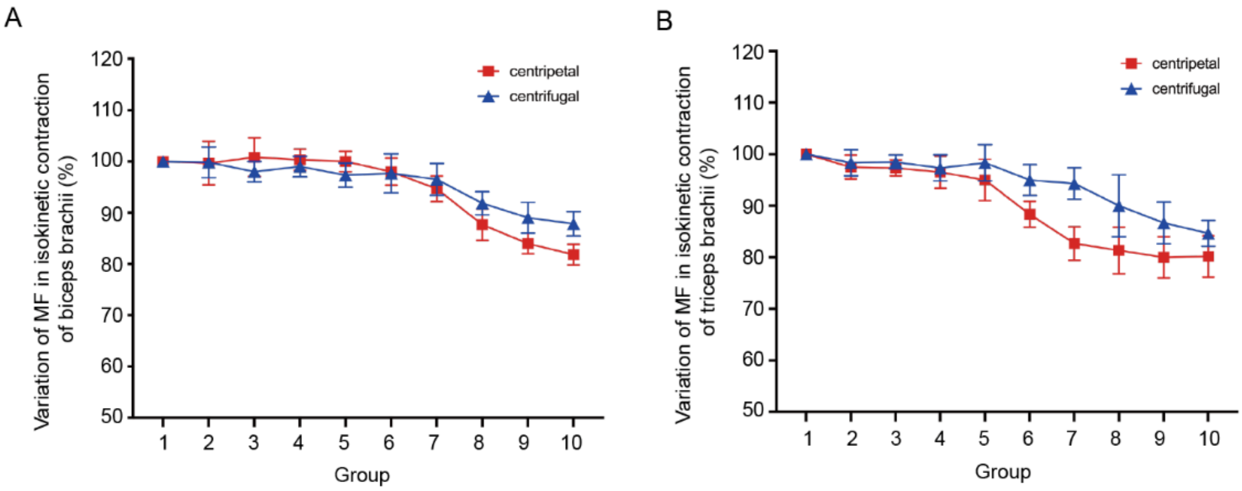

Figure 5. Variation of MF in the isokinetic contractions of biceps and triceps brachii

Table 3

Comparison of the isokinetic MF of the biceps and triceps brachii before and after the inflection point (Hz)

		Before inflection point	After inflection point	t	P
biceps	centripetal	63.2±9.6	51.3±8.2	2.665	0.018
	centrifugal	64.1±8.3	55.4±7.8	2.16	0.048
triceps	centripetal	65.4±10.2	52.3±7.1	2.981	0.009
	centrifugal	64.5±9.8	54.3±7.8	2.303	0.037

According to the following formula, the decline rate of the median frequency of the EMG signal after different forms of isokinetic contraction induced muscle fatigue was calculated (Figure 4), and one-way ANOVA was performed to conclude that the decline of the median frequency of biceps and triceps after isokinetic contraction induced muscle fatigue were both larger than that after isokinetic centrifugal contraction ($P < 0.01$), so the degree of muscle fatigue was greater after isokinetic centrifugation contraction. The fatigue time that the muscles appeared during isometric centripetal contraction was significantly earlier than that during isometric centrifugal contraction (Figure 5), and this result was basically consistent with the iEMG results of the elbow flexor and extensor muscle groups. Therefore, isometric centripetal contraction is more likely to produce peripheral muscle fatigue than isokinetic centrifugal contraction.

Calculation formula: : $R_{MF}=[MF(1)-MF(10)]/MF(1)$

Note. RMF represents the median frequency rate of decline, MF (10) represents the median frequency of the tenth set of isokinetic movements, and MF (1) represents the median frequency of the first set of isokinetic movements.

3.2.3 MPF changes during isokinetic contraction

During progressive centripetal and eccentric contractions, the normalized mean power frequency (MPF) of the biceps and triceps showed an overall gradual decline with significant inflection points. The MPF values after the appearance of the inflexion point were significantly lower than those before the inflexion point ($P < 0.05$), largely consistent with their inflexions in iEMG and MF values (Table 4), and the change in MPF

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during centripetal contraction occurred significantly earlier than the inflexion point during eccentric contraction (Figure 6), a result that was identical to the change in MF after fatigue during isometric contraction.

Table 4

Comparison of the isokinetic MF of biceps and the triceps brachii before and after the inflection point (Hz)

		Before inflection point	After inflection point	t	P
biceps	centripetal	94.1±17.5	77.3±13.2	2.168	0.048
	centrifugal	104.1±15.6	88.4±12.7	2.207	0.045
triceps	centripetal	96.5±16.2	75.3±10.5	3.106	0.008
	centrifugal	105.5±17.1	85.3±11.2	2.795	0.014

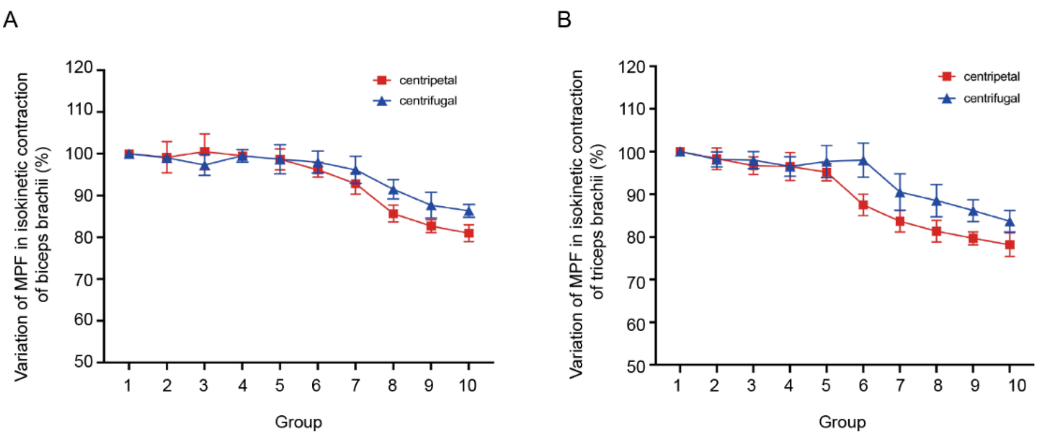

Figure 6. Variation of MPF in isokinetic contractions of biceps and triceps brachii

According to the following formula, to calculate the decline rate of the MPF value of the electromyographic signal (Figure 4C), The decrease in the average power frequency of the biceps and triceps after muscle fatigue caused by isometric cardiac contraction was significantly greater than that caused by isometric cardiac contraction ($P < 0.01$). In other words, muscle fatigue was greater after isometric centrifugation contraction. The time that the muscle developed fatigue during isometric centripetal contraction was significantly earlier than that during isometric centrifugal contraction (Figure 6); this result was consistent with the muscle contraction EMG signal iEMG and MF results. Thus, isometric centripetal contraction is more prone to fatigue in peripheral muscles than isokinetic eccentric contraction.

Calculation formula: : R_{MPF}=[MPF(1)-MPF(10)]/MPF(1) ;

Note. R_{MPF} represents the average rate of power frequency decline, MPF (10) represents the average power frequency of the tenth set of isokinetic movements, and MPF (1) represents the average power frequency of the first set of isokinetic movements.

3.3 Changes in EEG parameters before and after different forms of isokinetic contraction

3.3.1 EEG power spectral changes before and after isokinetic contraction

The subjects underwent EEG signal acquisition and processing in triplicate before, after centripetal, and after eccentric exercise, to derive the ratio of energy at different frequency bands in each lead. The power of the prefrontal and parietal leads was studied when the change in EEG power values was greater after exercise fatigue.

By comparing the percentage of wave power values obtained before and after isometric centripetal movement, the wave power values obtained for the leads of the FP1, F3, F4, FC1, FC2, C3 and C4 channels all improved after isometric centripetal movement (P < 0.05), indicating that waves in the frontal and parietal lobes following isometric centripetal movement power increased (Tab. 5). The power ratio of EEG signal waves increased significantly (P < 0.01) in the FP1, FP2, F3, FC1, FC2, C3, C4 and CP1 channels after isometric centrifugal exercise compared to that before exercise. There was a significant increase in the power of the prefrontal and parietal EEG signal waves after the subject performed an isokinetic centrifugal contraction exercise (Figure 7).

Table 5

Ratio of δ power before and after exercise (%)

Lead	Before exercise	After centripetal movement	After eccentric exercise
Fp1	16.4±2.5	20.3±3.8*	23.2±4.1**
Fp2	16.6±3.1	19.8±3.6	22.2±4.2**
F3	17.8±3.5	21.9±4.0*	24.3±4.5**
F4	16.7±3.2	20.6±3.4*	21.8±4.6*
Fc1	16.4±3.2	20.8±3.6*	23.2±4.1**
Fc2	16.6±3.3	21.3±4.1*	22.8±4.5**
C3	17.0±3.8	22.3±4.3*	24.8±3.9**
C4	17.1±4.1	22.8±4.2*	25.2±4.8**
CP1	17.0±4.2	21.3±4.1	23.8±4.6**
CP2	16.6±3.5	19.5±4.0	21.8±4.3*

*Notes**. Indicates significant difference before and after fatigue ($P < 0.05$).
*Notes***. Indicates a highly significant difference before and after fatigue ($P < 0.01$).

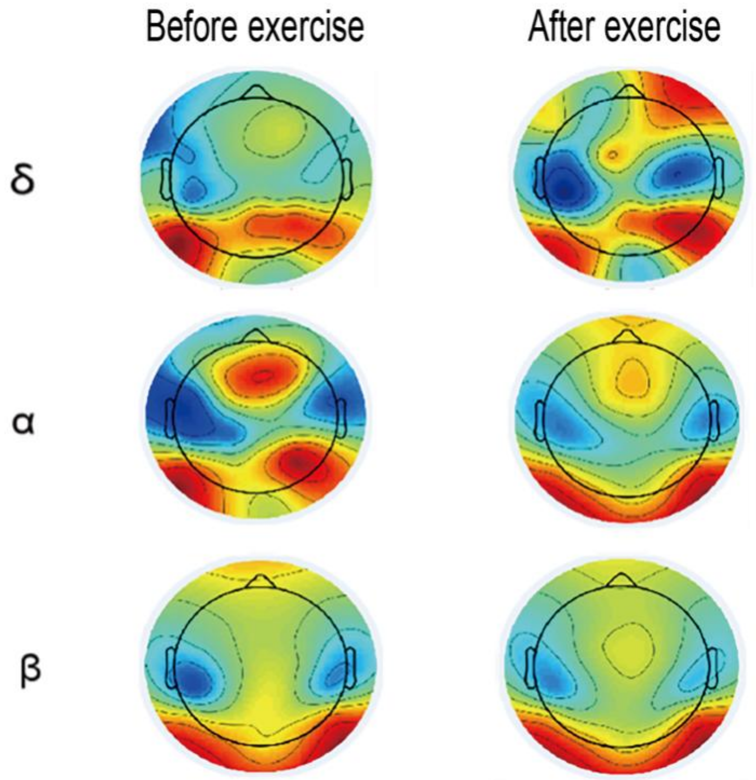

Figure 7. Changes in brain topography before and after isokinetic exercise

The percentage change in the wave power value of brain waves after isometric centripetal movement compared with that before movement was not statistically significant for all channels ($P > 0.05$, Table 6). The decrease in the ratio of the power value of the EEG signal wave of the four channels F4, C3, C4 and CP1 after isometric centrifugal exercise was statistically significant ($P < 0.05$). Therefore, part of the EEG signal wave power in the parietal lobe decreased when the subject performed isokinetic centrifugal contraction exercise.

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Table 6

Ratio of θ power before and after exercise (%)

Lead	Before exercise	After centripetal movement	After eccentric exercise
Fp1	18.5±3.4	19.8±3.5	17.9±3.8
Fp2	18.7±3.6	19.2±4.1	18.5±3.1
F3	20.3±4.3	19.3±4.0	17.6±3.4
F4	20.4±3.8	21.8±3.6	16.4±3.5*
Fc1	20.2±3.2	20.8±3.9	19.2±3.6
Fc2	20.6±3.3	21.5±3.6	18.6±3.2
C3	21.0±3.8	20.3±3.5	16.5±3.5*
C4	21.5±4.1	20.8±4.3	17.5±3.1*
CP1	21.0±3.9	19.5±4.1	17.2±3.2*
CP2	20.6±3.5	19.8±3.9	18.9±3.4

*Notes**. Indicates a significant difference before and after fatigue ($P < 0.05$).

After isometric centripetal movement, all channels α None of the changes in the ratio of wave power values (Table 7) were statistically significant ($P > 0.05$). When the subject performed isokinetic eccentric contraction exercise, the C3 and C4 channel EEG signal α wave power decreased somewhat ($P < 0.05$), consistent with the trend of changes in brain topography (Figure 7).

Table 7

Ratio of α power before and after exercise (%)

Lead	Before exercise	After centripetal movement	After eccentric exercise
Fp1	46.5±8.4	43.6±7.4	41.8±6.9
Fp2	45.7±7.6	43.9±7.1	41.6±7.2
F3	42.0±8.3	39.7±6.3	39.5±6.6
F4	42.8±7.8	40.8±6.5	39.1±6.1
Fc1	43.3±7.2	41.6±6.2	40.7±5.8
Fc2	42.7±8.3	39.3±7.4	38.3±6.5
C3	42.5±8.8	38.8±6.5	35.9±6.3*
C4	41.3±9.1	38.3±7.2	35.2±6.2*
CP1	42.3±7.9	39.6±6.8	38.5±7.3
CP2	42.7±8.5	40.9±8.4	38.8±6.4

*Notes**. Indicates significant difference before and after fatigue ($P < 0.05$).

After isometric centripetal movement, there was no change in channels β Wave power. When subjects performed isokinetic eccentric systolic exercise postexercise (Table 8), EEG signals were obtained from FC2, C3, and C4 channels β Wave power decreased compared with that before exercise ($P < 0.05$), and this result was in the same trend as that of brain topography (Figure 7).

Table 8

Ratio of β power before and after exercise (%)

Lead	Before exercise	After centripetal movement	After eccentric exercise
Fp1	18.5±3.4	17.3±4.1	16.6±3.1
Fp2	18.7±3.6	17.8±3.9	16.5±3.7
F3	20.3±4.3	19.3±4.1	17.3±3.2
F4	20.4±3.8	21.1±4.8	19.2±3.8
Fc1	20.2±3.2	20.9±3.7	17.9±3.5
Fc2	20.6±3.3	19.3±3.8	16.3±3.2*
C3	21.0±3.8	17.2±4.1	16.2±3.1*
C4	21.5±4.1	18.5±3.7	16.5±3.5*
CP1	21.0±3.9	20.5±4.1	19.5±3.9
CP2	20.6±3.5	19.6±3.9	18.6±4.1

Notes.* Indicates a significant difference before and after fatigue ($P < 0.05$).

3.3.2 Comparison of EEG power spectral changes before and after centrifugation contraction

When human exercise produces central fatigue, there is a left shift in the EEG signal energy spectrum, that is, an increase in the power of EEG signal waves at low frequencies, whereas α Wave and β Wave such high frequency segment wave form power overall shows a decreasing trend [13–16]. The results were generally consistent with the conclusion that the wave occupancy ratio was higher after centrifugation and centrifugation than before exercise in some channels α Wave and β the bozantic ratio appears reduced.

Table 9

The change value in δ power after different forms of isokinetic fatigue (%)

Lead	Centripetal contraction	Eccentric contraction	P
Fp1	3.9±1.1	6.8±1.8	0.002
Fp2	3.2±1.3	5.6±1.2	0.002
F3	4.1±1.4	6.5±1.7	0.008
F4	3.9±1.1	5.1±1.3	0.066
Fc1	4.4±1.2	6.8±1.7	0.006
Fc2	4.7±1.4	6.3±1.4	0.038
C3	5.3±1.3	7.8±2.3	0.018
C4	5.7±1.2	8.1±1.8	0.007
CP1	4.3±1.5	6.8±1.7	0.008
CP2	3.3±1.1	5.2±1.8	0.023

When isokinetic centrifugal contraction exercise fatigue was followed, the specific growth rate of brain wave power accounted for by all channels in the prefrontal and parietal lobes was higher than the isokinetic centrifugal contraction fatigue growth rate (Table 9), indicating that isokinetic centrifugal contraction exercise generated a greater degree of central fatigue.

Discussion

4.1 Relationship between sEMG and peripheral fatigue during different forms of isokinetic exercise

When muscle appears fatigued, it shows a tendency of increasing time domain indexes and decreasing frequency domain indexes. During the experiment, the time-domain index iEMG gradually increased, while the frequency-domain indexes MF and MPF both showed a gradual decreasing trend. When each cycle of isometric movement reached a certain amount, significant inflexions occurred in the broken line plots between iEMG, MF, and MPF and the number of movements, and the data before and after the inflexions were all significantly different. The appearance times of iEMG, MF, and MPF inflexions during isometric centrifugation contraction were all earlier than those during isometric centrifugation contraction. In addition, the isometric centripetal contraction iEMG growth rate was significantly higher than the isometric centrifugal contraction growth rate. Similarly, centripetal contraction had a higher rate of MF and MPF decline after fatigue than did centrifugal contraction. Thus, centripetal contractions are more likely to produce muscle fatigue than eccentric contractions.

IEMG indicates the sum of myofiber discharge involved in muscle contraction in unit time, and an enlarged iEMG indicates an increased number of myofibers involved in movement or discharge from each muscle fiber. Edwards et al. (1956) noted an increase in time and exercise intensity with a consequent increase in the slope of the iEMG curve and as the slope increased the point at which the muscle began experiencing fatigue. The experimental results were consistent with the findings of Edwards et al. When the exercise load increases, the fast twitch fibers involved in locomotion gradually increase, the slow twitch fibers decline in number, and the fast twitch fibers have higher amplitudes than the slow twitch fibers, thus producing an elevation of the integrated electromyographic value. In addition, the number of myofibers mobilized by the muscle increases to satisfy the contractile activity of the muscle, so the overall discharge of the muscle increases, manifested as an increased integrated myoelectric value.

When a muscle experiences fatigue, there is an overall upward trend in iEMG, possibly because the fatiguing muscle needs to recruit more muscle fibers to participate in exercise (Figure 2B). The muscle fatigability of the upper limb muscles when performing centripetal contraction was significantly higher than that during eccentric contraction, and the change time was also earlier than that during eccentric contraction. This may be because contraction is met by fewer myofibers recruited when the muscle is undergoing initiation of centripetal contraction, fatigue occurs when the muscle is subjected to increased exercise time, and centrifugal contraction is met by more myofibers recruited to the movement, as well as more fast myofibers recruited to the contraction. Therefore, the integral EMG value increased less after fatigue in eccentric contraction muscles than in centripetal contraction, and the recruitment of new myofibers to exercise by centripetal contraction also occurred earlier than in eccentric contraction.

The spectrum and power spectrum obtained from the fast Fourier transform (FFT) of the surface EMG, MF and MPF, can respond to the change in the EMG signal between different frequencies. The EMG power spectrum is essentially a reflection of the relationship between EMG energy and frequency. Therefore, some scholars have proposed [18] analysis of the frequency-domain index of the EMG signal, which can reflect the number of different types of muscle fibers involved in exercise during muscle contraction and the discharge amount of muscle in different frequency bands. In turn, the EMG frequency-domain analysis is used as an analysis method for judging muscle fatigue. When the muscle produces fatigue, the spectrum of the muscle EMG signal shifts to the left, so that the median frequency and mean power frequency of the muscle EMG show decreased numerical MF and MPF values [19–21]. When the degree of muscle fatigue deepens, the amplitude of the left shift of the frequency-domain index of EMG signal increases, which manifests as the decrease amplitude of MF and MPF of the frequency-domain index of EMG signal increases [22]. The main reason why the frequency-domain index of EMG appears to decrease when muscle appears fatigued at present is the following points: some scholars believe [23] that muscle appears fatigued when it produces accumulation of acidic metabolites such as lactate, leading to the decrease of action potential conduction velocity of muscle fiber; Another scholars believe [24] that the proportion of type II muscle fibers involved in exercise increases when the muscle fatigues, resulting in the decrease of frequency-domain indexes; It has also been argued that muscle fibers involved in exercise when fatigue occurs produce fatigue, and muscle recruits more slow muscle fibers to participate in exercise, thus leading to a decrease in frequency-domain metrics [25]. Taken together, the mechanistic level of the generation of EMG changes after fatigue awaits further study by scholars.

4.2 Relationship between EEG power spectra and central fatigue during different forms of isokinetic exercise

When muscles fatigued with isometric centripetal movement, the ratio of power values of EEG signal waves in leads of FP1, F3, F4, FC1, FC2, C3 and C4 channels significantly improved ($P < 0.05$). The power values of channel EEG signals in the frontal and parietal lobes of FP1, FP2, F3, F4, FC1, FC2, C3, C4, CP1, CP2 all had significantly higher values after isometric centrifugal exercise muscle fatigue compared to before exercise ($P < 0.05$, Table 5). When fatigue is induced by exercise, the EEG signal wave energy of the prefrontal and parietal lobes of the brain will increase, indicating that the brain center also produces fatigue. The central nervous system prevents excessive fatigue in the brain. The inhibitory signal of the cerebral cortex is constantly increasing, the excitation signal is gradually decreasing. Therefore, the phenomenon of the left shift of the EEG signal energy spectrum and the proportion of slow wave energy in the main wave will increase. However, when the exercise muscle fatigued by centrifugal contraction, the proportion of power value of EEG signal wave of F4, C3, C4 and CP1 four channels decreased significantly ($P < 0.05$, Table 6), because the wave was the same slow wave as the wave, but the wave was 4-7 Hz waveform, while the wave was 1-3 Hz waveform, so the reason for the wave decline might be that during the 10 group isometric centrifugal exercise, the center developed fatigue before the end of the exercise, fatigue and continued to perform isometric centrifugal exercise after fatigue, leading to the deepening of fatigue, This causes a continuing left shift of the EEG signal energy spectrum, producing a rise and fall of waves after isometric centrifugal exercise fatigue.

Contractile movements of skeletal muscle are innervated by brain centers, and brain EEG signals control muscle fiber gains and losses during muscle contraction via motor nerves, which in turn control the contractile effects of peripheral skeletal muscle while, when stimulated peripherally, feedback to the central nerves in the form of electrical signals [26]. Changes in EEG signals are a protective behavior during central motor fatigue [27]. When the brain receives fatigue signals from peripheral feedback, the center will produce inhibitory transmitters, at the same time excitatory transmitters gradually decrease, in turn leading to the cerebral cortex less excitability in the frequency of neural excitation, and the phenomenon of producing an EEG signal energy spectrum shift to low frequency.

When the growth rate of the power occupied ratio of brain waves in most channels of the prefrontal and parietal lobes was higher than that of the fatigue of isokinetic centrifugation contraction after isokinetic centrifugal motion (Table 9), that is, the degree of central fatigue generated by isokinetic centrifugal contraction exercise was greater, and this result agreed well with the results of previous scholars' research. There are studies that induced fatigue in knee extensors by isometric muscle strength trainers and extracted central activation level VA for analysis after fatigue of centripetal and centrifugal contraction, the central fatigue after isometric centrifugal exercise is greater than that of centripetal exercise [28–30]. However, there are mixed accounts of the mechanisms leading to central fatigue after isometric centrifugal contraction exercise. Michaut et al. (2002) considered that isokinetic centrifugal contraction when exercise, muscle fiber over contraction caused muscle pain and weakness sensation, the motor nerve transmitted the signal to the central nerve in the form of negative feedback, the brain to avoid producing excessive fatigue, the cerebral cortex of reduced excitability, higher inhibition, produces the phenomenon of central fatigue, and then leads to the decrease of the brain's ability to innervate muscle contraction. Martin et al. (2005) suggested that the mechanism of central fatigue after isokinetic eccentric exercise may be due to muscle class III and IV afferent fibers being affected by accumulated metabolic substances.

Conclusion

In the process of muscle fatigue induced by isokinetic training, the extrinsic performance of muscle and the change in electrical signal have mutual reference value, and the index of isokinetic muscle force and the index of electromyographic signal can be combined as an evaluation index of muscle fatigue. Elbow flexors and extensors developed significant muscle fatigue after performing 100 cycles of maximal isometric centrifugation and isometric eccentric exercise, and the rate of change of iEMG, MF, and MPF of EMG signal after isometric centrifugation fatigue was higher, and the inflection point of change was earlier than that of centrifugal contraction, indicating that centrifugal contraction was more fatigue resistant and the degree of peripheral fatigue after centrifugation contraction was higher than that of centrifugal contraction. There was a clear increase in the wave to duty ratio of the brain's prefrontal and parietal EEG signals, indicating that centripetal and centrifugal isokinetic movements produced significant central fatigue. The magnitude of the increase in the wave duty ratio was greater after isometric centrifugal exercise, and the degree of central fatigue was stronger after isometric centrifugal exercise than after isometric centripetal exercise.

Ethical statements

The study was approved by the Biomedical Research Ethics Committee (No. 5/2018) and was conducted in accordance with the Declaration of Helsinki. The study was approved by the Bioethics Committee of Research of the School of Kinesiology and Health Promotion of Dalian University of Technology. All participants gave written informed consent to participate in the study and publish the obtained results including registered images. Personal data and the images of patients were collected and processed in a database that complies with the personal data protection regulations. The equipment used in the tests did not pose any threat that could in any way affect the safety of the human body.

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References

1 Lievens, E., Klass, M., Bex, T., et al. (2020). Muscle fiber typology substantially influences time to recover from high-intensity exercise. *Journal of Applied Physiology, 128*(3), 648–659. DOI: 10.1152/japplphysiol.00636.2019.

2 Andersen, B., Westlund, B., & Krarup, C. (2003). Failure of activation of spinal motoneurones after muscle fatigue in healthy subjects studied by transcranial magnetic stimulation. *The Journal of Physiology, 551*(1), 345–356. DOI: 10.1113/jphysiol.2003.043562.

3 Kenney, W., Wilmore, J., & Costill, D. (2021). *Physiology of sport and exercise* (7th ed.). Human Kinetics.

4 Skurvydas, A., Kazlauskaite, D., Zlibinaite, L., et al. (2021). Effects of two nights of sleep deprivation on executive function and central and peripheral fatigue during maximal voluntary contraction lasting 60 s. *Physiology & Behavior, 229,* 113226. DOI: 10.1016/j.physbeh.2020.113226.

5 Silva-Cavalcante, M. ., Couto, P.G., Azevedo, R.A., et al. (2019). Stretch–shortening cycle exercise produces acute and prolonged impairments on endurance performance: Is the peripheral fatigue a single answer? *European Journal of Applied Physiology, 119*(7), 1479–1489. DOI: 10.1007/s00421-019-04135-4.

6 Naderifar, H., Minoonejad, H., Barati, A.H., et al. (2018). Effect of a neck proprioceptive neuromuscular facilitation training program on body postural stability in elite female basketball players. *Journal of Rehabilitation Sciences & Research, 5*(2), 41–45.

7 Brambilla, C., Pirovano, I., Mira, R.M., et al. (2021). Combined use of EMG and EEG techniques for neuromotor assessment in rehabilitative applications: A systematic review. *Sensors, 21*(21), 7014. DOI: 10.3390/s21217014.

8 Enoka, R.M. (2019). Physiological validation of the decomposition of surface EMG signals. *Journal of Electromyography and Kinesiology, 46,* 70–83. DOI: 10.1016/j.jelekin.2019.03.010.

9 Yang, Z., & Ren, H. (2019). Feature extraction and simulation of EEG signals during exercise-induced fatigue. *IEEE Access, 7,* 46389–46398. DOI: 10.1109/ACCESS.2019.2909035.

10 Portela, M.A., Sánchez-Romero, J.I., Pérez, V.Z., et al. (2020). Torque estimation based on surface electromyography: Potential tool for knee rehabilitation. *Revista de la Facultad de Medicina, 68*(3), 438–445. DOI: 10.1016/j.jneumeth.2020.108998.

11 Sheng, Y., Liu, J., Zhou, Z., et al. (2021). Musculoskeletal joint angle estimation based on isokinetic motor coordination. IEEE Transactions on Medical Robotics and Bionics, 3(4), 1011–1019. DOI: 10.1109/TMRB.2021.3122931.

12 Weavil, J.C., Sidhu, S.K., Mangum, T.S., et al. (2015). Intensity-dependent alterations in the excitability of cortical and spinal projections to the knee extensors during isometric and locomotor exercise. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology, 308(12),* R998–R1007. DOI: 10.1152/ajpregu.00021.2015.

13 Ghorbani, M., & Clark, C.C.T. (2021). Brain function during central fatigue induced by intermittent high-intensity cycling. *Neurological Sciences, 42(9),* 3655–3661. DOI: 10.1007/s10072-020-04965-7.

14 Engchuan, P., Wongsuphasawat, K., & Sittiprapaporn, P. (2019). Brain electrical activity during bench press weight training exercise. *Asian Journal of Medical Sciences, 10(5),* 80–85. DOI: 10.3126/ajms.v10i5.21034.

15 Liu, J., Sheng, Y., Zeng, J., et al. (2019). Corticomuscular coherence for upper arm flexor and extensor muscles during isometric exercise and cyclically isokinetic movement. *Frontiers in Neuroscience, 13,* 522. DOI: 10.3389/fnins.2019.00522.

16 Li, D., & Chen, C. (2022). Research on exercise fatigue estimation method of Pilates rehabilitation based on ECG and sEMG feature fusion. *BMC Medical Informatics and Decision Making, 22(1),* 1–11. DOI: 10.1186/s12911-022-01808-7.

17 Edwards, R.G., & Lippold, O.C.J. (1956). The relation between force and integrated electrical activity in fatigued muscle. *The Journal of Physiology, 132(3),* 677–681. DOI: 10.1113/jphysiol.1956.sp005558.

18 Turgunov, A., Zohirov, K., Rustamov, S., et al. (2020). Using different features of signal in EMG signal classification. *In 2020 International Conference on Information Science and Communications Technologies (ICISCT)* (pp. 1–5). IEEE. DOI: 10.1109/ICISCT50599.2020.9351392.

19 Cadore, E.L., González-Izal, M., Grazioli, R., et al. (2019). Effects of concentric and eccentric strength training on fatigue induced by concentric and eccentric exercises. *International Journal of Sports Physiology and Performance, 14(1),* 91–98. DOI: 10.1123/ijspp.2018-0254.

20 Rampichini, S., Vieira, T.M., Castiglioni, P., et al. (2020). Complexity analysis of surface electromyography for assessing the myoelectric manifestation of muscle fatigue: A review. *Entropy, 22(5),* 529. DOI: 10.3390/e22050529.

21 Jung, C.Y., Park, J.S., Lim, Y., et al. (2018). Estimating fatigue level of femoral and gastrocnemius muscles based on surface electromyography in time and frequency domain. *Journal of Mechanics in Medicine and Biology, 18(05),* 1850042. DOI: 10.1142/S0219519418500422.

22 Liu, X., & Li, Z. (2021). Influence mechanism of running sportswear fatigue based on BP neural network. *EURASIP Journal on Advances in Signal Processing, 2021(1),* 1–15. DOI: 10.1186/s13634-021-00778-8.

23 Farina, D., Fosci, M., & Merletti, R. (2002). Motor unit recruitment strategies investigated by surface EMG variables. *Journal of Applied Physiology, 92(1),* 235–247. DOI: 10.1152/jappl.2002.92.1.235.

24 Solomonow, M., Baten, C., Smit, J.O.S., et al. (1990). Electromyogram power spectra frequencies associated with motor unit recruitment strategies. *Journal of Applied Physiology, 68(3),* 1177–1185. DOI: 10.1152/jappl.1990.68.3.1177.

25 Klaver-Krol, E.G., Hermens, H.J., Vermeulen, R.C., et al. (2021). Chronic fatigue syndrome: Abnormally fast muscle fiber conduction in the membranes of motor units at low static force load. *Clinical Neurophysiology, 132(4),* 967–974. DOI: 10.1016/j.clinph.2020.11.043.

26 McArdle, W.D., Katch, F.I., & Katch, V.L. (2006). Essentials of exercise physiology (3rd ed.). *Lippincott Williams & Wilkins.*

27 Markus, I., Constantini, K., Hoffman, J.R., et al. (2021). Exercise-induced muscle damage: Mechanism, assessment and nutritional factors to accelerate recovery. *European Journal of Applied Physiology, 121(4),* 969–992. DOI: 10.1007/s00421-020-04566-4.

28 Souron, R., Nosaka, K., & Jubeau, M. (2018). Changes in central and peripheral neuromuscular fatigue indices after concentric versus eccentric contractions of the knee extensors. *European Journal of Applied Physiology, 118(4),* 805–816. DOI: 10.1007/s00421-018-3816-0.

29 Michaut, A., Pousson, M., Babault, N., et al. (2002). Is eccentric exercise-induced torque decrease contraction type dependent? *Medicine and Science in Sports and Exercise, 34(6),* 1003–1008. DOI: 10.1097/00005768-200206000-00016.

30 Martin, V., Millet, G.Y., Lattier, G., et al. (2005). Why does knee extensor muscles torque decrease after eccentric-type exercise? *Journal of Sports Medicine and Physical Fitness, 45(2),* 143–151.

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