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MYOELECTRICAL MANIFESTATIONS OF QUADRICEPS FATIGUE DURING DYNAMIC EXERCISE DIFFER IN MONO- AND BI-ARTICULAR MUSCLES

M. Hu[1, 5], T. Finni[3], M. Alén[2], J. Wang[4], L. Zou[1], W. Zhou[5], S. Cheng[2]
[1]Dept. of Sports and Health, Guangzhou Institute of Physical Education, Guangzhou, China; Depts. of [2]Health Science, [3]Biology of Physical Activity, University of Jyväskylä, Finland; [4]School of Education, Zhejiang University, China; [5]School of Life Science, Sun Yat-sen University, Guangzhou, China

Abstract. Objectives: The purpose of this study was to investigate different myoelectrical manifestations of neuromuscular fatigue among individual quadriceps muscle during high-load dynamic knee extension exercise (KEE). Methods: Seventy-four untrained males (aged 20-45) performed bilateral KEE consisting of five sets of ten repetitions at maximum load (2-min rest between sets). Surface electromyogram (SEMG) of vastus laterals (VL), vastus medialis (VM) and rectus femoris (RF) of right leg and torque were recorded continuously during KEE. Pre- and immediately post-KEE, maximal voluntary contraction (MVC) and corresponding EMG were measured. Results: MVC decreased 17±15% ($p<0.001$) after KEE. During KEE, significant decrease of torque occurred since set 4. In each set, average EMG (aEMG) had a trend to increase whilst mean power frequency (MPF) tend to decrease in quadriceps with increasing repetitions. Interestingly, myoelectrical manifestations of fatigue in RF were different from that in two vastii. Significant aEMG reduction in RF was observed not only in between-set comparison but also in pre-post comparison during MVC, but no changes were found for VL and VM. Similarly, in contrast with VL and VM, more pronounced decrease of MPF occurred in RF in between-set comparison and in pre-post comparison during MVC. Conclusions: The results suggest that RF is more susceptible to fatigue than two vastii when making dynamic KEE against heavy load, and corresponding divergence of neuronal coding mechanisms might exist in the central nervous system.

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Key words: Knee extension exercise - Neuromuscular fatigue - Electromyography - Mono-articular muscle - Bi-articular muscle

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Reprint request to: Sulin Cheng, Ph.D, Professor, Dept. of Health Sciences, University of Jyväskylä, PO Box 35, FIN-40014 Jyväskylä, Finland
Tel:+358 14 2602091, Fax:+358 14 2602011, E-mail:cheng@sport.jyu.fi

Introduction

Muscle fatigue could be defined as a failure to maintain an expected force level, whose causes can be central or peripheral in origin [3,4]. It may arise not only because of changes in the contractile processes of the muscle, but also because the recruitment of the new motor units and/or the firing frequency of the active units are reduced. This is accompanied by multiple events occurring at central and peripheral sites. Surface electromyography (SEMG) is one of non-invasive methods which have been widely used to investigate mechanisms of neuromuscular fatigue during voluntary contractions.

Knee extension exercise (KEE) is a popular model to investigate quadriceps fatigue. At the knee joint, the functional group responsible for knee extensor torque production is the quadriceps femoris (QF), which consists of the bi-articular rectus femoris (RF) and mono-articular vasti, such as vastus laterals (VL) and vastus medialis (VM). Among previous studies which investigated causes of QF fatigue, VL and/or VM had been frequently examined in both dynamic and isometric exercise. Nevertheless, some researchers [1,2,11,12,19] found that EMG fatigue patterns accompanying isometric fatiguing knee-extensions were different in mono- and bi-articular muscles, and observed that there was lack of evidence of fatigue in VL and VM in contrast with RF. However, data on EMG activities among individual QF during dynamic KEE is lacking.

The aim of this experiment was to investigate the myoelectrical activities among individual QF during acute neuromuscular fatigue induced by high-load intermittent KEE in 20-45 years old untrained men. We hypothesize that in the course of fatigue induced by dynamic KEE against heavy load, RF would also be more susceptible to fatigue than the two vastii.

Materials and Methods

Subjects: The subjects were recruited through advertisements in the University campus area and in the local newspaper grade in the city of Jyväskylä. Eighty-five men met the screening criteria (no diseases or medication that affect muscle activity and the cardiovascular system, and having performed regular exercise no more than once a week during the past 3 years). After the pretest, finally, 74 healthy men aged 20-45 years participated in this study. The mean age of the subjects was 31.7 years (SD 7.3). The mean body height was 179.7 cm (SD 5.4), weight 80.7 kg (SD 10.1), and body fat 19.0% (SD 4.8).

Written informed consent was obtained from the subjects prior to the measurements, and the study was conducted according to the Declaration of Helsinki. Approval for the project was obtained before its initiation from the Ethics Committee of the Central Hospital of Central Finland.

Protocol and experimental procedures: The subjects were familiarized with the measurement apparatus in the week preceding the experiment. Before the test, the subjects carried out a 10-min warm-up on a electrically-braked bicycle ergometer (Monark 839E, Sweden) at a self-selected power output. The maximal voluntary contraction (MVC) and SEMG activities of the right QF were measured before and after the fatigue-inducing KEE. Throughout the KEE, the torque, the knee joint angle and EMG activity of the QF were recorded continuously.

Fatigue-inducing KEE: Fatigue was induced through bilateral KEE. During the exercise the subjects sat in a knee extension ergometer which used the pneumatic resistance principle (Ab Hur Oy, Kokkola, Finland). First the subjects performed a few warm-up contractions with light loads. Then the resistance of each individual was set according to their performance in the familiarization session. Extraneous movement of the upper body was limited by two belts across the chest and abdomen respectively, with hip joint fixed about 110°. The subjects were required to perform concentric KEE from a 90° starting position to full extension (=180°) and thereafter lower the load back to the starting position. Each subject performed 5 sets of 10 repetitions each with two minutes between sets. Verbal encouragement was given, and it was ensured that with every repetition a minimum target angular position of 170° was reached. If the load could not be lifted voluntarily up to the target angle the subject was assisted slightly during the last 1-3 repetitions of the set while he maintained his maximum performance. If necessary, the loads were adjusted during the resting periods so that 5 sets could be completed.

Strength measurement: Peak torque of MVC during isometric knee extensions was measured bilaterally using the same ergometer as for the KEE. The results reported here are from right leg where SEMG was recorded. For isometric performances the lever arm of the device was secured at the knee angle of 120°. Extraneous movement of the upper body was limited as mentioned above. The axis of the dynamometer was aligned with the knee flexion-extension axis, and the lever arm was attached to the right shank by using a strap. Torque during maximal voluntary contractions was recorded before and immediately after the KEE. The subjects were asked to exert maximum force as rapidly as possible and to maintain that force for 3-s.

SEMG recordings: SEMG activities of the RF, VL and VM of right thigh were obtained using self-adhesive pairs of disposable Ag/AgCl surface electrodes (Blue Sensor M-00-S, Ambu, Denmark). Low impedance at the skin-electrode interface was obtained (Z<10 KΩ) by skin preparation procedure of shaving, light abrasion and cleaning. An interelectrode distance of 20 mm was used. The recording electrodes were fixed lengthwise over the muscle belly according to recommendations by SENIAM [6]. Specifically, pairs of electrodes were located on VL on the 2/3 of the line from anterior spina iliaca to the lateral side of patella, on RF, half way between the anterior spina iliaca and superior part of patella and on VM, on the 4/5 of the line from anterior spina iliaca to the joint space in front of anterior border of medial ligament. Furthermore, the electrode placement was confirmed by palpations of muscle bulk during brief maximal isometric contraction. The electrode placement, for minimizing crosstalk, was validated by the method of Winter *et al.* [22].

The raw SEMG signal was recorded at the sampling rate of 1000Hz, amplified (differential amplifier, common mode rejection ratio, 110dB; preamplifier gain, 305) with a bandwidth from 8 to 500Hz, analog-to-digital converted (14-bit) using a device (ME6000, Mega Electronics, Finland), and stored in a personal computer. The average EMG (aEMG) and mean power frequency (MPF) for the three muscles (VL, VM and RF) were calculated and used for further analyses. The EMG signal analyzed during the KEE was taken in each repetition between knee angles of 170° and 100° for each muscle. aEMG was calculated using the rectified signal with a 512 ms window. MPF was defined as the weighted mean value of the data forming the single spectrum and processed by Fast Fourier Transform algorithms where a 512 data point window was used to calculate the single spectrum. During the MVC, aEMG and MPF was calculated using a 1024 ms window.

Blood samples: Blood samples for the determination of blood lactate were taken from the antecubital vein of the right arm pre- and immediately post the KEE. Blood lactate concentrations were analyzed enzymatically (Boehringer Mannheim, Germany).

Statistical analysis: All data were checked for normality using the Shapiro-Wilk test in SPSS 12.0 for Windows. Descriptive statistics were used to present the anthropometric data as mean ±SD. For each study variable comparisons were made with a Paired-Sample T-Test between the non-fatigued and the fatigued state. The differences between 5 sets and 10 repetitions of measurements from the KEE were analyzed using ANOVA with repeated measures and followed by Bonferroni adjustment for multiple comparisons. Correlation coefficients were calculated to determine the relationships between selected parameters.

Results

Torque during fatigue: (Fig. 1). There was a trend for torque to decrease with repetitions within each set. However, significant differences between the sets were observed. Compared to the set 1, mean value of the torque in the set 2 increased from 96±19 Nm to 98±20 Nm, but then decreased significantly in set 4 and 5 ($p<0.001$) after the adjustment in the 10 RM load.

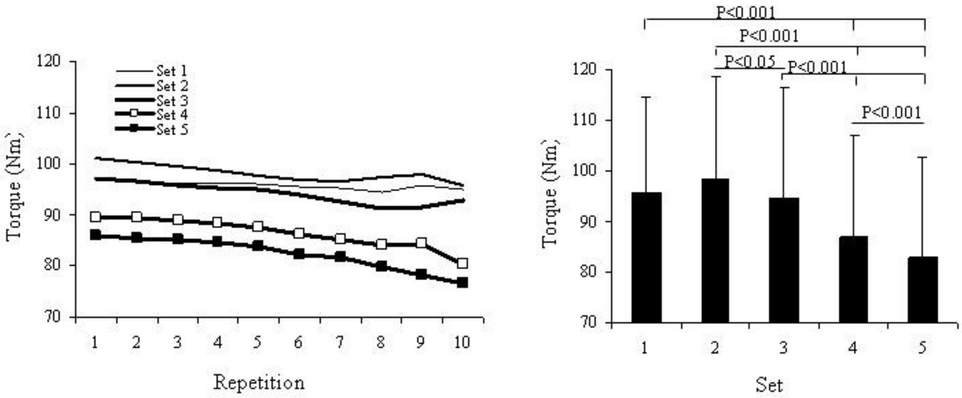

Fig. 1 [A1]
Torque profile during the KEE in healthy males. The torque progressively decreased within each set (left panel). The mean torque was greatest in the set 2 and thereafter decreased significantly in set 4 and 5 ($p<0.001$) compared to the 1st set (data in right panel are expressed by mean ±SD)

aEMG and MPF of QF muscles during fatigue: (Fig. 2 and 3, respectively). When the individual QF were examined, there were differences between bi-articular RF and mono-articular VL and VM muscles. Within each set (compared with each 1st repetition), the significant aEMG increment were observed in RF after the 6th repetition within set 1 and 10th repetition in set 2, and in VL after the 7th repetition within the set 1, but no significant changes were found in VM. These data implied that in the first two sets, aEMG in RF had a relatively greater increment than in VL and VM. But, when comparing aEMG between sets, no significant changes occurred in VL and VM, while aEMG in RF decreased significantly.

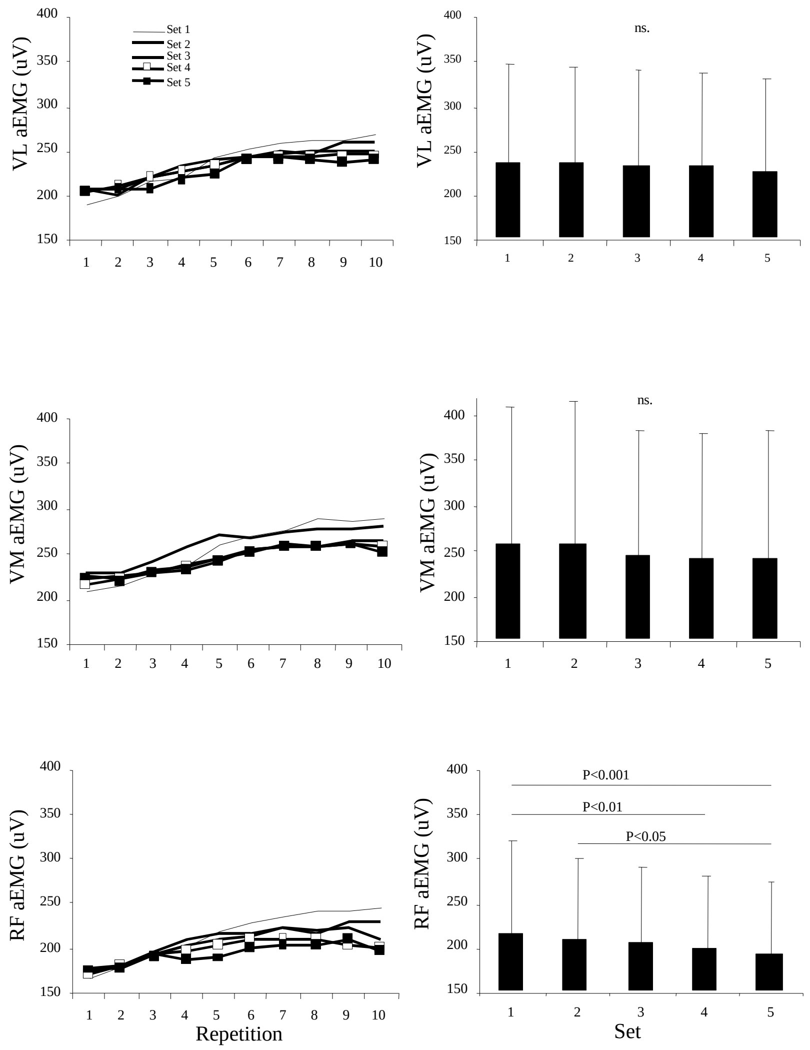

Fig. 2
aEMG of VL (top), VM (mid) and RF (bottom) during the KEE in healthy males. Left panel: aEMG had a trend of progressive increment within each set and showed significant increases in the 7th, 8th, 9th ($p<0.05$, respectively) and 10th ($p<0.01$) repetition in set 1 in VL; in the 7th ($p<0.05$), 8th, 9th and 10th ($p<0.01$, respectively) repetition in set 1, and 10th ($p<0.05$) repetition in set 2 in RF. Right panel: aEMG comparison between sets (data are expressed by mean ±SD)

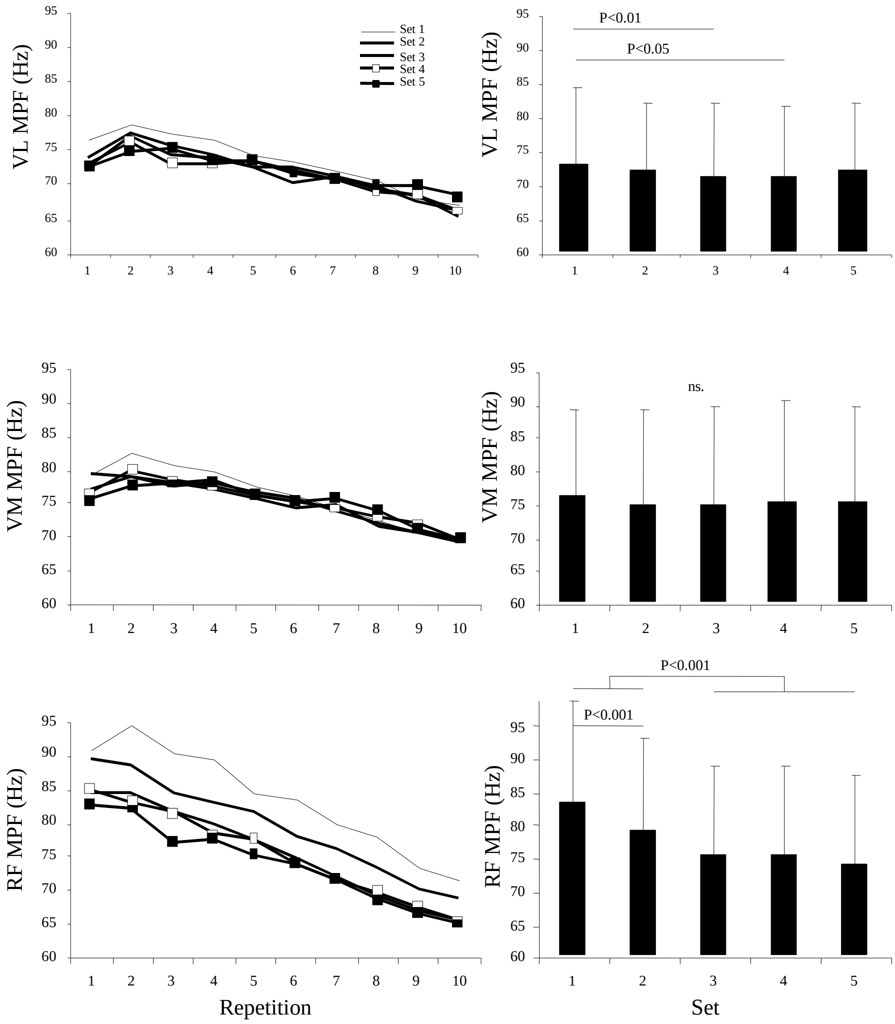

Fig. 3
MPF of VL (top), VM (mid) and RF (bottom) during the KEE in healthy males. Left panel: MPF in RF decreased significantly after 5-6[th] repetitions within each set ($p<0.05-<0.001$), whilst significant decreases in MPF of VL and VM were only found after 7-8[th] repetition within set 1 and 2 ($p<0.05-0.001$). Right panel: MPF comparison between sets (data are expressed by mean ±SD)

Compared to the 1st repetition in each set, significant reductions in MPF occurred earlier and more pronouncedly in RF compared to VL and VM. Comparing MPF between sets, significant decrease of MPF was observed for RF ($p<0.001$), but no significant reduction was observed for VM. As for VL, though it decreased in set 2-4, MPF in set 5 returned to the same level as set 1.

MVC and corresponding EMG: (Table 1). Peak MVC torque decreased significantly ($p<0.001$) and was 17±15% smaller when compared to pre-fatigue value. Nonetheless, 10% of the subjects actually increased their MVC torque after the fatigue test (mean 8.3±7%), while the remaining 90% of the subjects decreased it. MPF decreased significantly in the pre-post comparison ($p<0.001$). Among the QF, the most pronounced relative change occurred in RF, which decreased 16.4±8.4% in MPF and 12.6±33.6% in aEMG during MVC. aEMG in VL and VM did not change.

Table 1
Torque and SEMG activities during MVC pre- and post KEE in healthy males

	Pre	Post	Paired t-test P-value
MVC torque (Nm)	216±49	178±46	0.000
aEMG during MVC (μV)			
VL	186±76	184±79	0.667
RF	147±54	134±58	0.005
VM	159±54	164±63	0.222
MPF during MVC (Hz)			
VL	75±11	69±11	0.000
RF	94±15	78±12	0.000
VM	77±15	70±15	0.000

Values are means ±SD

Blood lactate: The mean lactate concentration increased from resting 1.94±0.65 to 11.60±2.92 ($mmol \cdot L^{-1}$, $p<0.001$) when measured immediately after the KEE. The individual values of blood lactate concentration recorded after the KEE correlated significantly ($r=0.25$; $p<0.05$) with the individual decreases of MVC. In addition, there was a negative correlation between lactate concentration and MPF of different muscles ($-0.31<r<-0.45$; $p<0.01$).

Discussion

Previously, neuromuscular fatigue in the knee extensors has mainly focused on VL and/or VM. However, the main findings of the present study show that in the present conditions of dynamic fatigue-inducing KEE against heavy resistive loading, fatigue was more pronounced in RF than in the two vastii of the quadriceps muscle. Even though the mechanisms of this non-uniformity remain not very clear, the observed distinct differences could substantiate previous findings and provide new evidence for clarifying some observations in similar protocols.

Causes of fatigue: In the present study, the decline in maximum voluntary force was considered to be an important indicator of fatigue. Actually, dynamic torque of knee extension already decreased significant after only 2-3 sets of KEE. To compensate for the impaired muscle function which may be caused by metabolic changes in the knee extensors, an increased recruitment of additional motor units, and possibly synchronization of motor unit firing as well as decreased firing rate were indicated by the changes in EMG (central command) amplitude and frequency. This suggests that the subjects made an effort to execute the intended task by increasing neural drive. Even though the two-minute rest between sets was associated with restoration of the amplitude and frequency of the EMG signal to some extent, the between-set reduction of force production and the corresponding aEMGs reflected an inadequate ability to counteract fatigue, as we can find that that the MPF and aEMG decreased from set 2 and set 4 onwards in RF muscle respectively.

Apart from the modulation of central drive, the shift of the MPF towards lower frequencies may be caused by an accumulation of metabolites and a consequent decrease in pH, resulting in the slowing down of the muscle fiber conduction velocity [9]. In this study, negative correlation of the lactate concentration with the changes in MPF of individual QF showed that the shift of MPF might result from derecruitment of fast-twitch fibres as fatigue progressed.

Non-uniform EMG activities among quadriceps components: The results of our study are in line with previous studies which have shown that SEMG fatigue patterns accompanying isometric fatiguing knee-extensions were different in mono- and bi-articular muscles [1,2,12,15]. During seated KEE, movement about the hip joint is restricted, thus force generated by the RF at the knee joint cannot be effectively transferred to the hip, which cause the bi-articular muscles to function "similarly" to the mono-articular muscles. However, our result shows that the different roles of mono- and bi-articular muscles will still manifest themselves when bi-articular muscles functions as "purely" mono-articular muscles. In set 1, significant increase in aEMG occurred earlier in RF than in VL and VM. Noticeably, significant reduction of aEMG between sets and greater decrease of MPF within set and between sets through KEE in RF indicates that RF was more susceptible to fatigue than VL and VM. SEMG activities during MVC provided additional evidence for this non-uniformity. Our between-set comparison have similar results with Ebenbichler *et al.* [2] who reported that isometric, fatiguing KEE against heavy load caused RF's root mean square EMG to drop, whilst it remained stable or even increased for VL and VM. Further, Ebenbichler *et al.* [1] found that the median frequency of RF fatigued at a higher rate than two bi-articular muscles when subjects made isometric KEE until exhaustion. In the present experiment, the non-uniformity of MPF between RF and two vastii is obviously not negligible.

Distinctly different functions have been proposed for mono-articular and bi-articular muscles during a multi-articular movement by Jacobs *et al.* [7] and van Ingen Schenau *et al.* [20] who have suggested that the bi-articular muscle plays a key role in controlling of the force direction of the endpoint of a limb, whereas mono-articular muscle are primarily responsible for the generation of force and work. This notion was challenged by Nozaki *et al.* [17] who concluded that both mono- and bi-articular muscles equally contribute to the control of both direction and magnitude of force. The difference in SEMG activities among the QF during KEE may be due to the specific functions of the mono-articular muscles compared with bi-articular one. The RF provided regulation of the distribution of the net moments about the hip and the knee joint, whereas the VL and VM regulate that about the knee joint. Using muscle functional magnetic resonance imaging, Kinugasa *et al.* [10] found the extent of recruitment among individual QF during 5×10RM KEE were not similar, the relative recruitment of RF was much more than that of VL and VM. They proposed that greater recruitment of the RF resulted from an ineffective transfer of torque from the knee to hip joint during seated KEE, causing the RF to dissipate greater energy than in multi-joint movement and have a different neuromuscular coordination in central nervous system than the mono-articular muscles. Their explanation may partially account for our result. Additionally, Nozaki *et al*. [16] proved that in case of isometric knee extension, as the hip flexion torque was large, the activity of mono- and bi-articular knee extensors decreased and increased, respectively. However, in this protocol, we did not measure hip joint torque during KEE.

Another reason could be that the fiber composition is different among the QF components. It has been reported that the type I fibre ratio in RF is lower than in VL and VM [8]. Thus, the greater portion of type II fibre in RF could make the muscle more susceptible to fatigue. Especially, when performing KEE against heavy load, there is greater recruitment of type II fibres, which likely results in greater recruitment of the RF muscle compared to the two vastii [14,21]. So, we speculate this phenomenon might be load-related.

The precise reason for the non-uniform EMG activities among quadriceps in this study remains unclear. The actual situation seems more complicated. Recently, Hanon *et al*. [5] demonstrated that RF is the muscle that showed the earliest signs of fatigue during an incremental running test. One could infer that the divergence of neuronal coding mechanisms within the quadriceps muscle group may exist in the central nervous system. The present results clearly show that one muscle may not sufficiently represent the activation pattern of the QF muscle group during fatiguing KEE. Limited myoelectrical signs of fatigue in VL/VM had ever been reported with fatiguing task [13,18].

In summary, the present observations provide evidence that myoelectrical manifestations of quadriceps fatigue during dynamic exercise differ in mono- and bi-articular muscles, namely, RF is more fatigable than VL and VM when performing KEE against heavy load. This suggests different neural control mechanisms of mono- and bi-articular muscles during a fatiguing KEE. Because KEE is widely adopted by researchers in the fields of motor control, sports science, and rehabilitation, related future studies should not neglect the influence of hip joint torque on mono- and bi-articular muscles activity.

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