NEUROMUSCULAR FATIGUE AFTER SHORT MAXIMUM CYCLING EXERCISE

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Abstract:

Neuromuscular fatigue during and after short maximally intensive concentric exercise was analyzed. Nine healthy sport students performed the 15s Wingate test. Maximal cycling power decreased by 1.86 W × kg^{-1} ($p<0.001$) during the cycling. After the exercise, a significant increase in the blood lactate concentration was found (1.13 mM × l^{-1}) before the exercise and 6.7 mM × l^{-1} seven minutes after the exercise ($p<0.05$). Electrical stimulation of the *vastus lateralis* muscle resulted in a decreased twitch maximum force by 30 % ($p<0.001$). Contraction time and half relaxation time were shorter, but not significantly ($p<0.05$). Torque at 20 Hz stimulation decreased by 20 % ($p<0.003$), while torque at 100 Hz stimulation was lowered by 10 % ($p<0.000$). The results after the 15s maximally intensive cycling pointed to high and low frequency fatigue, however, it seems that low frequency fatigue prevailed.

Key words: *sport, neuromuscular fatigue, Wingate test, electrical stimulation*

NEUROMUSKULÄRE ERMÜDUNG NACH KURZEM MAXIMAL INTENSIVEM RADFAHREN

Zusammenfassung:

In dieser Studie wurde die neuromuskuläre Ermüdung während und nach kurzem maximal intensivem konzetrischem Radfahren analisiert. Neun gesunde Studenten des Sports führten den Wingate Test, 15 Sekunden der Dauer, durch. Die 1,86 W × kg^{-1} ($p<0.001$)–Verminderung in der maximallen Schnellkraft des Radfahrens wurde bemerkbar. Nach dem Radfahren wurde eine bedeutende Steigerung von Blutlaktatkonzentration bemerkbar – 1,13 mM × l^{-1} vor dem Radfahren im Vergleich zu 6,7 mM × l^{-1} sieben Minuten nach dem Radfahren ($p<0,05$). Das Resultat der elektrischen Stimulation vom Muskel *vastus lateralis* war die dreißigprozentige ($p<0,001$) Verminderung der maximalen Zuckkraft. Die Kontraktionszeit und die Halbentspannungsszeit waren kürzer, aber nicht bedeutend ($p<0,05$). Das Drehmoment bei der Stimulation von 20 Hz hat sich um 20% ($p<0,003$) und das Drehmoment bei der Stimulation von 100 Hz um 10% vermindert. Die Ergebnisse nach dem maximal intensiven Radfahren in der Zeit von 15 Sekunden zeigte die Hoch- und Niederfrequenzermüdung. Es scheint, dass die Niederfrequenzermüdung dominant war.

Schlüsselwörter: *Sport, neuromuskuläre Ermüdung, Wingate-Test, elektrische Stimulation*

Introduction

In sports, fatigue is a negative sign. To control it, we need the appropriate diagnostic tools, which should be simple, valid and reliable for execution. During maximally intensive exercise, many events may contribute to fatigue. Some of them may be present in the neuromuscular system and depend on the conditions in which the exercise is performed and on the subject's ability to perform the exercise (Bigland-Ritchie, 1984). Two types of peripheral fatigue are of particular interest for the present study: high and low frequency fatigue. High-frequency fatigue has been observed in the stretch-shortening cycle (SSC) exercises performed with maximum intensity (Strojnik & Komi, 1998), while during submaximal intensive exercises low-frequency fatigue dominates (Strojnik & Komi, 2000). High-frequency fatigue has been shown in the selective loss of muscle force with high electrical stimulation (ES) frequencies. It appears because of the impaired action potential propagation along the muscle fiber (Edwards, 1981). In the study, where maximum hopping, drop jumping and cycling for 60s were compared, Jereb and Strojnik (1995, 2001) found high frequency fatigue in hopping and drop jumping, which represented the SSC type exercises. In cycling with the same execution time, where the muscle contractions were predominantly concentric, low-frequency fatigue appeared. Therefore, it can be concluded that hops performed at maximal intensity are more appropriate for observing high-frequency fatigue, and cycling for observing low-frequency fatigue.

From the viewpoint of exercise control and simplicity of execution, cycling is much more accurate and controlled than hopping. Cycling (the Wingate test) is also placed among the standardized anaerobic exercise tests (Vandewalle, Peres, & Monod, 1987). It is used as a test load in many studies and it ensures an accurate comparison between results. All these advantages, e.g. as exhibited by the Wingate test, in comparison to other exercises, make it interesting to see whether it is possible to use cycling for assessing high-frequency fatigue. The answer to this question may lie in a Wingate test shorter than 60 seconds. This assumption is based on the work of Strojnik and Komi (1996) who demonstrated that, during the maximum SSC exercises, chronologically it is the high-frequency fatigue that appeared first, moving then slowly to low-frequency fatigue. It is expected that similar fatigue development can be observed in the concentric exercise. The aim of this experiment was to determine the type of neuro-muscular fatigue in the 15s Wingate test to see if this test may be appropriate for a high-frequency fatigue assessment.

Methods

Subjects. 9 students of physical education participated in the study (age = 23.4 ± 2.7 yrs, body height = 176.9 ± 3.3 cm, body mass = 70.4 ± 4.9 kg). The subjects were well informed about the procedures of the experiment. They signed a written informed consent, stating they were aware of the demands, goals and possible risks of the experiment. The experiment was conducted in accordance with the Helsinki-Tokyo Declaration and was approved by the National Medical-Ethic Committee.

Experimental design. The experiment consisted of a fatigue exercise accompanied by measurements performed before and after the exercise. Measurements before the exercise were proceeded by a standardized warm-up. The time between the warm-up and the first measurement was set at 2.5 minutes, while the exercise started 10 minutes after the warm-up. The second measurements followed one minute after the end of the exercise.

Warm-up. Subjects performed a warm-up, which consisted of 10 min of stepping on a 20-cm high bench with a frequency of 0.5 Hz, and with a change of the step-on leg each minute.

Exercise. The Wingate test was performed in a laboratory environment on a bicycle-ergometer (Monark-model 818E). The height of the seat was adjusted, so that the knee was slightly bent in the lowest pedal position. Body inclination during the pedalling was kept constant by the arms stretched. The subjects had to cycle for 15 seconds with maximal intensity against resistance equal to 7.5% of body weight. The cycling started with a running start, so that the subject reached 60 turns per minute just before the actual start of the exercise. The bicycle was fixed to the floor to ensure stable pedalling. A power-time curve was plotted on-line on a computer display in front of the subjects. They were also encouraged by the staff. The whole cycling protocol was performed in accord with the instructions of the manufacturer (Ayalon, Inbar, & Bar-Or, 1974). Maximum power, minimal power, and the pedalling power during the 15s exercise were calculated based on a sensor which measured the speed of the cycling wheel and took into account the given resistance (SMI, model 1000, St. Cloud, USA). Power was normalized to the body mass. A fatigue index was calculated as a ratio between the maximum power (P_{max}) and the minimum power (P_{min}):

$$FI = 100 - \left(\frac{P_{min}}{P_{max}} \cdot 100 \right) \qquad (1)$$

Electrical stimulation. Measurements with electrical stimulation started 2.5 min after the warm-up and 1 minute after the exercise. Measurements were performed on an isometric knee measurement device at a 45° knee joint angle. During the exercise, the subject lay dorsally on the table with hips blocked and lumbar spine supported to prevent pelvic movements. The distal part of the shank was fixed to the force transducer, which had a constant lever arm to the knee joint axis. The self adhesive 5x5 cm electrodes (Axelgaard, Falbrook, CA), were placed in pairs on the *m. vastus lateralis* (VL): the anode over the distal part of the muscle's belly and the cathode over the middle part of the muscle's belly. A computer controlling the current-constant stimulator was used for muscle stimulation. On all occasions, symmetric square biphasic impulses were employed.

Twitch. The torque-time relationship of the relaxed VL due to a single supramaximal electrical impulse of 0.3 ms duration was measured (Figure 1). Maximal knee torque (F_{TW}), time to reach maximum torque (CT), and half relaxation time ($RT_{1/2}$) were analyzed. Torque was measured on the right knee.

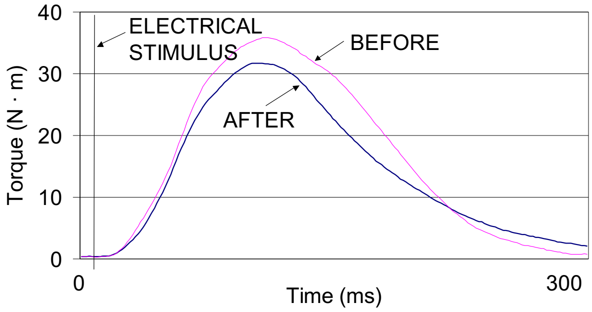
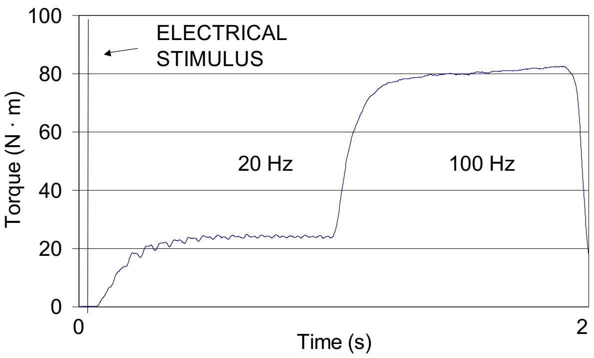


Figure 1. Typical response of an electrical stimulated vastus lateralis muscle in one subject to a single supramaximal stimulus as measured after the warm-up and in the 1st min after the exercise was finished.

High- and low-frequency fatigue test. The maximum torque of the electrically stimulated *vastus lateralis* muscle was measured. The trains of electrical impulses were delivered with 20 Hz and 100 Hz frequency, respectively. Each train lasted for 0.8 seconds (Figure 2). The duration of a single stimulus was 0.3 ms. The measurement was performed on the right leg. The level of the electrical stimulation was three times the motor threshold. The motor threshold was defined as the smallest electrical current that caused the first visually observable VL muscle response at 100 Hz stimulation. All the measuring procedures were done by a personal computer (PC) and the adequate software which allowed the calculation of the above-mentioned parameters.

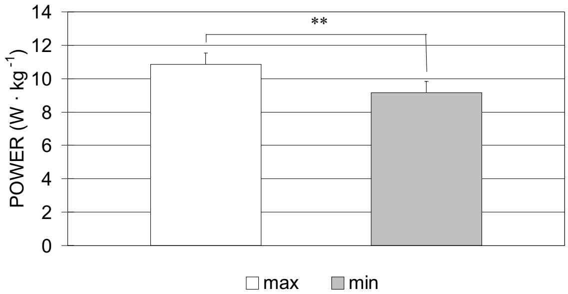


Blood analysis. Blood samples (20 ml) for the blood lactate concentration analysis were taken from the hyperemic ear. Blood lactate concentration was measured with Kontron 640 Lactate Analyser (Kontron, Vienna, Austria) immediately after the sample had been taken, which was done 2.5 minutes after the warm-up, and at 1, 3, 5, 7 and 10 minutes after the exercise.

Statistical methods. The differences in the results measured before and after the exercise were tested using the paired Student's *t*-test. Statistical significance was accepted at 5% alpha error. SPSS statistical package (SPSS Inc., Chicago, IL) was used for analysis.

Results

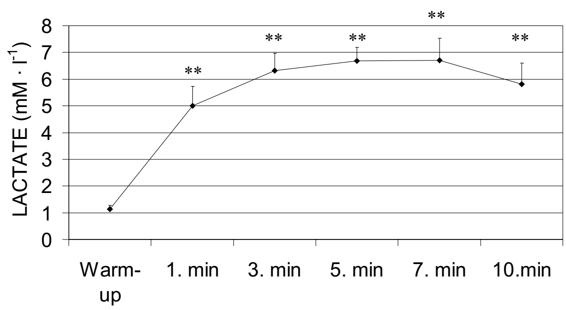
The highest mean relative cycling power was 10.84 W × kg^{-1} and at the end of the exercise it decreased to 9.16 W × kg^{-1} (P=0.002) (Figure 3).



** - statistical significance (p<0.01).

Figure 3. Relative power during the 15s cycling. Vertical lines represent SD.

Blood lactate concentration (LA) increased after the exercise in comparison to the warm-up (Figure 4).



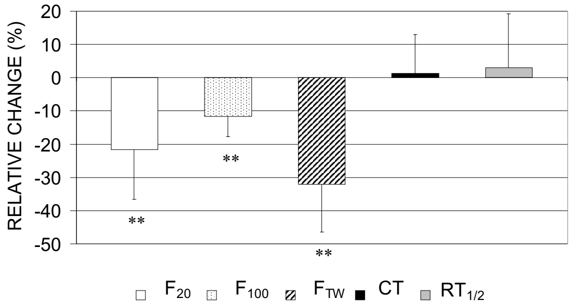
** - statistical significance (p<0.01). Warm-up five minutes before the test. 1, 3, 5, 7 and 10 min after the test.

Figure 4. LA concentration in blood. Vertical lines show SD.

Figure 2. Typical torque response of an electrical stimulated vastus lateralis muscle in one subject to low- and high-frequency electrical stimulation. Bottom of the curve: stimulation with 20 Hz; top of the curve: stimulation with 100 Hz.

The highest LA level was recorded in the seventh minute after the end of the exercise (6.7 mM × l^{-1}) which was significantly higher than after the warm-up ($p<0.001$). After that, the blood LA concentration started to decrease.

Mean F_{TW} values decreased by about 30% (Figure 5) which was statistically significant ($p<0.001$). The results of CT and $RT_{1/2}$ measurement are presented in the same figure and did not change after the exercise.



F_{TW} - twitch torque, CT - contraction time, $RT_{1/2}$ - half reaction time, F_{20} - torque at 20 Hz ES, and F_{100} - torque at 100 Hz ES. Vertical lines show SD. ** - statistical significance ($p<0.01$).

Figure 5. Relative changes in knee torque during electrical stimulation.

Knee torque at 20 Hz as well as at 100 Hz electrical stimulation decreased (Figure 5). At 20 Hz ES a decrease of 20% was measured which was statistically significant ($p<0.003$). At 100 Hz ES, the muscle responded by 10% decrease in torque which was statistically significant as well ($p<0.000$) (Figure 5).

Discussion and conclusions

Power was reduced by 15.5% during the maximally intensive 15s-long cycling. This was accompanied by an increase in the blood lactate concentration. However, since LA values were relatively low (6.7 mM × l^{-1}), they might not necessarily point to a significant change in H^+ content in the muscle (Vøllestad & Sejersted, 1988). In a study by Jones and associates (1985), much higher values in LA (14.1 mM × l^{-1}) were observed in students after 30 seconds of maximum-intensity isokinetic cycling. Furthermore, they did not observe any statistically significant changes in adenosine triphosphate (ATP) concentration in wet muscle with respect to its value before the exercise, while the creatine phosphate (CrP) decreased. From these results, it can be deduced that in the present study fatigue was probably not a result of reduced ATP concentration, but the reasons for fatigue should be sought elsewhere.

Changes in the contractile characteristics of the *vastus lateralis* muscle, which were measured through the changes in twitch parameters, were found only in reduced maximal torque. The reason for this reduction may be found in the increased demand for Ca^{2+} in the contraction process (Donaldson, Hermansen, & Bolles, 1978). The reduction in torque may be attributed to a lower release of Ca^{2+} from the sarcoplasmic reticulum (Rousseau & Pinkos, 1990), which could lead to a reduced number of active cross-bridges. On the other hand, the decrease in the twitch torque could also be a consequence of reduced torque of individual cross-bridges. Since no statistically significant changes were observed in the contraction time and half relaxation time, the reduction of torque during 15 seconds of cycling was more likely a result of the reduced number of active cross-bridges and not a consequence of reduced torque of a single cross-bridge. This explanation is consistent with the results of Metzger, Greaser and Moss (1989), who have reported a reduced twitch torque after exercise, with no changes in contraction and relaxation times.

The most interesting results of the present study are the changes during 20 Hz and 100 Hz electrical stimulation since they are directly connected to a definition of high- and low-frequency fatigue. Muscle force was reduced during the stimulation with both frequencies. Reduced torque at 20 Hz electric stimulation is a consequence of weakened excitation-contraction relation (Edwards et al., 1977). Low-frequency fatigue is accompanied by impaired release of Ca^{2+} from the sarcoplasmic reticulum (Rousseau & Pinkos, 1990) and/or the reduced binding of Ca^{2+} to troponin (Blanchard, Pan, & Solaro, 1984), which may be reflected in the reduced number of active cross-bridges. The reasons for reduced torque during 20 Hz stimulation in the present study were probably in consonance with the causes of the reduced twitch torque (impaired excitation-contraction coupling). The reduced torque at 100 Hz electrical stimulation in the present study was most likely a consequence of impaired action potential propagation along the muscle (Edwards et al., 1977; Stokes, Edwards & Cooper, 1989; Gibson & Edwards, 1985). High frequency of pedalling at the beginning of cycling requires high-frequency activation of motor units to enable explosive contractions (Enoka, 1994, 2002), which probably causes changes in Na^+ and K^+ concentrations in intracellular and extracellular fluids. These were also observed in the loaded muscles subjected to high-frequency electrical stimulation and in fatigued human muscles (Sahlin, Palmskog, & Hultman, 1978; Sjøgard, Adams, & Saltin, 1985), as is evident from the accompanying depolarization of the cell membrane (Sejersted et al., 1984). An imbalance in the Na^+ and K^+ concentrations may occur due to an insufficient number of Na-K pumps, thus leading to a depolarization block, and consequently to a substantially reduced frequency of action potential propagation along the cell membrane and t-tubules during high-frequency stimulation (Balog, Thompson, & Fitts, 1992). In turn, the reduced frequency of action potential reduces the ability to activate the contraction process. Due to a parallel decrease in 20 Hz and 100 Hz force, the results in the present study pointed to a simultaneous occurrence of low- and high--frequency fatigue after the 15-second maximum cycling. However, it seems that low-frequency fatigue prevailed. Simultaneous occurrence of both fatigue types was observed also in the prolonged maximally intensive SSC exercise (Strojnik & Komi, 1996) and when sledge jumps were performed submaximally (80% and 60% of maximal jumping height) until the subjects were unable to maintain the prescribed level (Strojnik & Komi, 1997; 2000).

Results of 15-second maximally intensive cycling pointed to a simultaneous development of both types of peripheral muscle fatigue. It may be concluded that 15 seconds of maximum intensity cycling did not cause any extensive high-frequency fatigue and, consequently, that even the short maximally intensive cycling is not an appropriate exercise for observing high-frequency fatigue. Considering the findings of other studies referred to in the introduction (Strojnik & Komi, 1998; Jereb & Strojnik, 1995; 2001), the development of high-frequency fatigue obviously depends strongly on the type of muscle contraction during exercise. The question arises whether a high-frequency fatigue is predominantly linked to SSC type exercises or may solely occur in exercises performed concentrically as well.

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NEUROMUSKULARNI UMOR NAKON KRATKOG MAKSIMALNOG CIKLIČKOG VJEŽBANJA

Sažetak

Uvod

U sportu je umor nepoželjan. Da bismo ga kontrolirali, potreban nam je prikladan dijagnostički alat koji će biti jednostavan, valjan i pouzdan. Za vrijeme maksimalno intenzivnog vježbanja mnogi faktori mogu pridonijeti nastanku umora. Neki od njih mogu biti prisutni i u neuromuskularnom sustavu i ovisiti o uvjetima samog vježbanja, kao i o vježbačevoj sposobnosti izvođenja vježbe. Istraživanje je usmjereno na dva tipa perifernog umora: na visoko- i na niskofrekventni umor. Visokofrekventni umor pojavljuje se pri izvođenju vježbi ekscentrično-koncentričnog tipa (SSC - *stretch-shortening cycle*), koje se izvode maksimalnim intenzitetom, dok se niskofrekventni umor javlja kod submaksimalno intenzivnog vježbanja. Visokofrekventni umor javlja se pri selektivnom gubitku mišićne sile kod visokofrekventne električne stimulacije. Pojavljuje se zbog reduciranog širenja akcijskog potencijala duž mišićnog vlakna. U istraživanju su Jereb i Strojnik (1995, 2001), uspoređujući maksimalne poskoke, dubinske skokove i vožnju bicikla u trajanju od 60 s, utvrdili pojavljivanje visokofrekventnog umora kod poskoka i dubinskih skokova koji su SSC tip vježbi. Tijekom vožnje bicikla u istom zadanom vremenu izvedbe, kod koje su mišićne kontrakcije dominantno koncentrične, pojavljuje se niskofrekventni umor. Na temelju svega toga može se zaključiti da su skokovi, izvedeni maksimalnim intenzitetom, pogodniji za opažanje visokofrekventnog umora, dok je vožnja bicikla pogodna za opažanje niskofrekventnog umora.

S gledišta kontrole izvođenja vježbe i jednostavnosti izvedbe, vožnja bicikla preciznija je i lakše se kontrolira od skakanja. Vožnja bicikla (Wingate test) također je jedan od standardiziranih anaerobnih testova. Koristi se u mnogim istraživanjima i osigurava precizno uspoređivanje rezultata. Zbog svih prednosti Wingate testa pred ostalim vježbama, činilo se zanimljivim ispitati je li moguće koristiti vožnju bicikla za ispitivanje visokofrekventnog umora. Odgovor na to pitanje mogao bi ponuditi Wingate test kraći od 60 sekunda. Pretpostavka je utemeljena na radu Strojnika i Komija (1996) koji su pokazali da se za vrijeme izvođenja maksimalnih SSC vježbi visokofrekventni umor kronološki javlja prije niskofrekventnoga. Očekuje se da će se sličan obrazac umora moći opaziti i u vježbama koncentričnog tipa. Cilj ovog istraživanja bio je odrediti vrstu neuromuskularnog umora nakon primjene Wingate testa u trajanju od 15 s kako bi se utvrdilo je li u takvom obliku Wingate test prikladan za procjenu visokofrekventnog umora.

Metode

Devet zdravih studenata Fakultete za šport dobrovoljno je sudjelovalo u istraživanju (dob = 23.4 ± 2.7 god., visina = 176.9 ± 3.3 cm, tjelesna masa = 70.4 ± 4.9 kg). Svi su ispitanici dali pristanak za sudjelovanje. Njihovo je ispitivanje odobrila Nacionalna medicinsko-etička komisija. Eksperiment je uključivao zagrijavanje, Wingate test, uzimanje uzorka krvi iz ušne resice za određenje koncentacije laktata u krvi (LA), električnu stimulaciju mišića *m. vastus lateralis* visokofrekventnim (100 Hz) i niskofrekventnim (20 Hz) električnim impulsima. Osim toga, mjeren je i pojedinačni odgovor na supramaksimalni električni podražaj (tzv. mišićni trzaj). Maksimalni obrtni moment u koljenu uz kut od 45 stupnjeva mjeren je za vrijeme električne stimulacije frekvencijama od 100 Hz i 20 Hz. Mišićni trzaj je analiziran za maksimalni obrtni moment (F_{TW}), vrijeme kontrakcije (CT) i pola od ukupnog vremena relaksacije ($R_{1/2}$). Mjerenja su obavljena prije i nakon (15 sekundi) Wingate testa.

Rezultati

Najviša prosječna snaga u vožnji bicikla bila je 10.84 $W \cdot kg^{-1}$ koja je na kraju vježbe u prosjeku padala na 9.16$W \cdot kg^{-1}$ (P=0.002). Koncentracija laktata (LA) u krvi povećala se nakon vježbanja u odnosu na razinu laktata nakon zagrijavanja. Najviša koncentracija LA izmjerena je u sedmoj minuti nakon završetka vježbe (6.7 $mM \cdot l^{-1}$), što je bilo statistički značajno više od one nakon zagrijavanja (p<0.001). Nakon toga koncentracija laktata u krvi počela bi opadati. Prosječna F_{TW} vrijednost pala je za oko 30%, što je bilo statistički značajno različito (p<0.001). Rezultati mjerenja CT i $RT_{1/2}$ nisu se mijenjali nakon provedene vježbe. Obrtni se moment koljena pri električnoj stimulaciji od 20 Hz, kao i pri 100 Hz smanjio. Kod električne stimulacije od 20 Hz izmjereno je smanjenje za 20%, što je bilo statisstički značajno (p<0.003). Kod ES od 100 Hz mišić je reagirao 10%-tnim smanjenjem obrtnog momenta, što je također bila satistički značajna promjena (p<0.000).

Rasprava i zaključak

Za vrijeme maksimalno intenzivne vožnje bicikla u trajanju od 15 s snaga se smanjila za 15.5%. To je bilo popraćeno povećanjem koncentracije laktata u krvi (6.7 mM · l^{-1}). Promjene u kontraktilnim karakteristikama *m. vastus lateralis*, koje su mjerene pomoću promjena parametara mišićnog trzaja, manifestirale su se u vidu smanjenja maksimalnog obrtnog momenta koljena bez promjena u vremenu kontrakcije i relaksacije mišića. Najzanimljiviji rezultat ovog istraživanja jesu promjene koje su dobivene pri električnoj stimulaciji od 20 i od 100 Hz, što se izravno povezuje s definicijom visoko- i niskofrekventnog umora. Mišićna sila smanjila se za vrijeme električne stimulacije na objema frekvencijama.

Rezultati maksimalno intenzivne vožnje bicikla u trajanju od 15 s pridonijeli su simultanom razvoju oba tipa perifernog mišićnog umora. Može se zaključiti da maksimalno intenzivna vožnja bicikla u trajanju od 15 sekunda nije uzrokovala ekstenzivan visokofrekventni umor i, posljedično, čak i kratka maksimalno intenzivna vožnja bicikla ne može se smatrati prikladnom vježbom za praćenje visokofrekventnog umora. Prema nalazima ostalih istraživanja koja se spominju u uvodu (Strojnik i Komi, 1998; Jereb i Strojnik, 1995 i 2001), razvoj visoko frekventnog umora očigledno dominantno ovisi o tipu mišićne kontrakcije za vrijeme vježbanja. Pitanje koje se javlja jest je li visokofrekventni umor dominantno povezan s ekscentrično-koncentričnom vrstom vježbi ili se može javiti jedino u vježbama koncentričnog tipa.