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# DIFFERENCES IN NEUROMUSCULAR FATIGUE AFTER AEROBIC AND ANAEROBIC RUNNING LOADS

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**Abstract.** The aim of the research was to establish some characteristics and differences in neuromuscular fatigue after different running loads. Seven well-trained runners performed two running tasks: an interval run of 5 x 300 m at sub-maximum speed with a one-min rest (100 m jogging) between individual runs, and a continuous 6-km run at the anaerobic threshold speed (criterion $V_{OBLA}$). To measure the contractile characteristics of the femuris muscle quadriceps before and after a running load the following electrical stimulation (ES) tests were used: single twitch, low - and high-frequency stimulation, the maximum voluntary knee extension test and the muscle activation level test. The anaerobic interval runs caused a greater decline in maximum torque twitch ($p<0.05$) and a greater decline in maximum muscular relaxation rate ($p<0.05$) compared to the longer continuous run. The anaerobic interval load reduced muscle contraction at both low and high frequencies of ES, while the aerobic continuous run led to a lowering of muscle contraction force but only at low frequencies of stimulation. After both charges the decrease in ES-evoked muscle contraction was bigger than the decrease in torque at MVC. Both running loads caused peripheral fatigue. The lowering of muscular contractile ability after both loads was mainly the consequence of disturbance in the Ca transport system mechanism, while after the intensive interval runs this was also a result of disturbance in the spreading action potential across the sarcomere.

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*Key words:* Fatigue - Anaerobic interval running - Continuous aerobic running - Electrical stimulation

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## Introduction

All long-lasting and sufficiently intensive muscular activity causes fatigue, leading to a drop in the neuromuscular system's ability to produce force [5,12]. Muscular function decline may cause a reduction of the central neural drive (central fatigue) or disturbances in the neuromuscular junction and in different excitation-contractile couplings (peripheral fatigue) [1,12,15]. According to origin, peripheral fatigue can be divided into high- and low-frequency fatigue [12,14].

Given fatigue's characteristics and the factors causing it, is the key element in establishing effective methodical training in individual sport disciplines. Competition success in most sports disciplines requires the significant development of aerobic and/or anaerobic athletic capacity.

Loads within the range of the maximum blood lactate steady state (80%-90% in $VO_{2max}$) in a continuous or interval form play a very important role in methodical training seeking to develop athletes' aerobic capacity. A typical exercise session within the range of maximum blood lactate involves one to two 15-30 min loads (80 - 90% in $VO_{2max}$). The maximum blood lactate steady state is 3-7 $mmol \cdot l^{-1}$ [6,17].

The most important method of improving athletes' anaerobic lactate capacity is the anaerobic-intensive-interval method. It involves short intervals of effort (30-60 s), of maximum intensity (above 70% $v_{max}$ that is 130–160% in $VO_{2max}$) and often with short rests (15-60 s). In comparison with long and low intensive loads, these exercises cause a high increase in blood lactate (12-20 and more mmol $l^{-1}$) [6,17] and other biochemical changes.

The type of fatigue and its intensity depend on the intensity, extent, type of muscular contraction, and chosen load method [4,5,7,16,28-30].

Most researches on fatigue after dynamic loads focus on the study of long-lasting (more than 30 min), lower- or middle-intensive loads (65%–75% $VO_2max$) [7,10,23]. These loads cause a decline of abilities to generate voluntary muscular force, despite an increase in the EMG amplitude and drop in selective force at lower stimulation frequencies. These are the main characteristics of low-frequency fatigue. Contractive and relaxation times of muscular contraction become shorter or stay the same. The cause of muscular fatigue after long-lasting loads are the coupling of disturbances between muscular fibre excitation and cross-bridge activity reinstatement [12], which are the consequence of lower relaxation and restoration of $Ca^{2+}$ in and out from SR.

Yet, intensive aerobic and anaerobic dynamic loads on the neuromuscular function of well-trained athletes are less well investigated.

The aim of this study is to identify some important neuromuscular fatigue characteristics and muscle fatigue differences following two different running loads:

a) 5 x 300 m (to develop anaerobic lactic capacity); and
b) a continuous 6-km run (to develop aerobic condition).

## Materials and Methods

*Sample of subjects:* Seven well-trained middle - and long-distance runners participated in the study. Their average age was 25.3 years ± 1 years (mean ±SE), the average body weight 62.5 kg±2.2 kg, and average body height 176 cm±2.6 cm. The average length of their competition engagement was 9±0.5 years.

Subjects were well-informed of possible risks associated with the experiment and gave their informed consent before it began. The study was approved by the National Committee for Medical Ethics.

*Experimental design:* All subjects participated in one or two pre-test measurements to familiarise themselves with the percutaneous electrical stimulation procedures. This was followed by a test to determine the maximum speed and the speed of experimental running tasks.

Interval run speed was determined on the basis of a 400-m test run at maximum possible speed. The interval run speed was 5% lower than for the 400-m test.

The intensity of the continuous running test was determined on the basis of a treadmill test. This test comprised six to eight runs, each lasting five min. Individual run speed was steady and constant and was increasing by 0.2 m $s^{-1}$ every following run. Between individual runs the subjects stopped for 45 s to give a blood sample. On the basis of blood lactate kinetics, the running anaerobic threshold speed (OBLA criterion) was calculated [3].

The 400-m run test and treadmill test were carried out over two consecutive days.

Four or five days elapsed between the tests, namely the speed-run determination and the first experimental task (6-km run). After three days, the subjects performed interval training. They were asked not to carry out any intensive training loads at least two days before the experimental task.

The subjects performed a warm-up before both experimental running tasks: 10 min of easy running and stretching.

Muscular contractile properties were measured, and blood samples taken before the exercise (after the warm-up), after running loads (start 50-60 s after completion

of the exercise with the last test ending 3 min after the completed running load) and after 10,20,30,40,60 and 120 min of recovery.

Measurements were performed in the following order: taking a blood sample, the response of a relaxed vastus lateralis muscle (VL) to five individual electrical impulses (twitches), followed by 2 and 3 s responses of the VL to electrical stimulation (ES) at 20 Hz and 100 Hz and thirty seconds after stimulation at 100 Hz the subjects performed a 5-second maximum voluntary knee extension.

*Exercise procedures:* The experimental protocol comprised two different running loads:

1. Interval runs of 5 x 300 m (INT) at sub-maximum speed (5% lower than the 400-m test) with a recovery period of one min (100-m easy run) between each run.
2. Continuous run at a steady pace over 6 km (CON) at anaerobic threshold speed (criterion $V_{OBLA}$).

The runs were performed on an athletic track.

**Measurement of the muscular contractile function**

*Electrical stimulation:* During measurements with electrical stimulation and maximum voluntary knee extension (right leg only), the subjects were in a lying position fixed at the pelvis and over the distal part of the thigh to prevent any trunk and thigh 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 angle of the knee of the fixed leg was 45° (Fig. 1). A force transducer (MES, Maribor, Slovenia) was used with linear properties inside 0–5000 N, with hysteresis less than 1%.

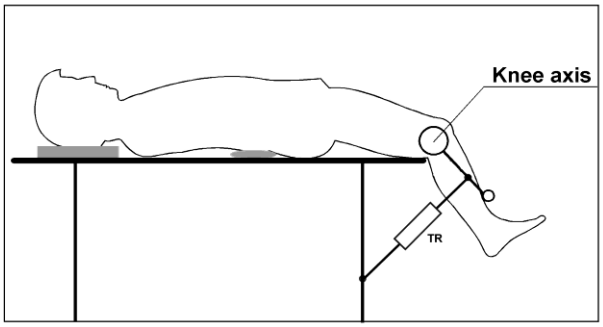



**Fig. 1**
Position of the subject during the measurement (TR: strain-gauge transducer)

The self-adhering neurostimulation electrodes (5 x 6 cm; Axelgaard Manufacturing Co, Fallbrook, CA) were placed over the vastus lateralis, vastus medialis and rectus femoris muscles. The distal electrodes were placed over the distal part and proximal ones over the middle part of the muscle belly. Electrodes remained fixed for the whole time of the experimental procedure.

Each pair of electrodes was connected to its own stimulation channel that was galvanically separated from the others. On all occasions, constant current square biphasic impulses of 0-3 ms duration were employed. A custom-made computer-controlled electrical stimulator was used. Data was sampled at 1 kHz using a 12-bit AD converter (Burr-Brown, USA) and stored in a computer.

*Single twitch test*: Five supra-maximum stimuli were delivered consecutively (one per second) to the relaxed VL muscle. The current used to elicit the maximum twitch was determined in each individual by increasing the stimulation current until no further increase in tension was observed, despite further increments in current. The current at the maximum twitch torque was further increased by 50%. This procedure ensured that each twitch was truly maximum for each individual. The torque signals from the twitch responses were smoothed (moving average; n=5) and averaged with a trigger point at stimulus delivery. Maximum twitch torque ($T_{TW}$), electromechanical delay (EMD), contraction time (CT) and half relaxation time ($RT_{1/2}$), peak rate of torque development (MCR) - measured during the rising of the torque of muscle contraction ($MCR=dT_{TW} \cdot dt^{-1}$) and maximum relaxation torque rate (MRR) measured during the falling of the twitch torque ($MRR=dT_{TW} \cdot dt^{-1}$) were calculated [4,30].

*Low-and high-frequency stimulation test:* The relaxed VL muscle was stimulated with two connected trains (0.8 s duration) of impulses with a frequency of 20Hz and 100Hz. For the 20- and 100-Hz stimulation procedures, the current was increased to the highest tolerable level determined by the subject and was maintained during all measurements. The mean torque during the last 50 ms of stimulation for each frequency ($T_{F20}$ in $T_{F100}$) was obtained [28,29].

*Maximum voluntary knee extension test and muscle activation level test*: The subjects tried to achieve their maximum isometric knee extension torque (MVC) and to maintain it for 5 s. The torque signal was smoothed and analysed for maximum torque ($T_{MVC}$).

The activation level (AL) was assessed during maximum isometric knee extension with additionally stimulated VL, VM and RF muscles with a short 0.8 s long train of electrical impulse of a frequency of 100 Hz [27]. The train of impulse was triggered after three seconds after the start of voluntary concentric muscle contraction, when maximum voluntary contraction was established.

Maximum torque during maximum voluntary contraction ($T_{MVC}$), torque during maximum voluntary muscle contraction with additional electrical stimulation ($T_{MVC + ES}$), and activation level (AL); ($AL=T_{MVC} \cdot T_{MVC+ES}^{-1}$) were established from the time-torque relationship.

*Heart rate*. The heart rate (HR) was measured continuously during both exercise tests with heart rate meters Polar PE 3000 (Oulu, Finland).

*Blood lactate*. The lactate concentration in blood was measured using the Kontron 640 lactate analyser (Vienna, Austria). A sample of 20µl blood was taken from the hyperemic ear lobe before and in the third min after the running loads. The accuracy of measuring the lactate concentration in fresh blood was $\pm$ 0.1 mmol$\cdot l^{-1}$.

*Statistical methods:* T-tests for paired samples were used to calculate the statistical significance of the differences in the individual parameters between initial measurement and after workout. The differences in the effects of the two protocols were statistically tested through an analysis of covariance, where the initial measurement represented the covariate. To calculate the correlation between changes in parameters after workouts, Pearson's correlation coefficient was used.

Statistical significance was accepted at $p<0.05$ (two-tailed).

## Results

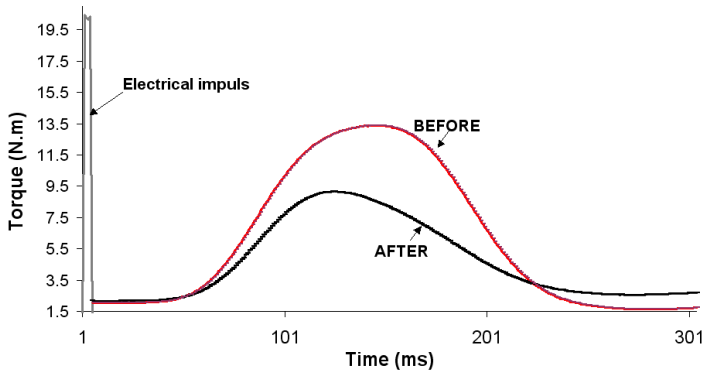
Average speed of interval runs was 6.69±0.02 (SE) m $s^{-1}$ or 77% of their maximum speed. Velocity in the first 300m run was 6.72±0.03m $s^{-1}$, in the second 6.65±0.03m $s^{-1}$, in the third 6.68± 0.02 m $s^{-1}$, in the fourth 6.67±0.03 m $s^{-1}$ and in the fifth 6.70±0,03 m $s^{-1}$. According to the first blood lactate (LA) sample (2.0±0.4 mmol $l^{-1}$) before the test, the result increased to 12.9±1 mmol $l^{-1}$. After the fifth run, HR was 194±4 beats $min^{-1}$ or 96% of the value at the exhausting test load.

Subjects ran 6 km in a steady rate in 20 min and 15 s. The average speed was 4.94±0.29m $s^{-1}$ or 56% of their maximum speed. LA increased from 1.6±0.2mmol $l^{-1}$ to 6.2±0.6mmol $l^{-1}$. At the end of the run, HR was 196±4 beats $min^{-1}$ or 97% of the maximum value.

Interval running velocity was statistically significant higher ($P<0.000$) than the 6-km running velocity. Likewise, after interval runs LA was statistically significant higher ($p<0.000$) than the 6-km run value.

*Muscular contracting function:* Fig. 2 shows muscular responses to a single supra-maximum stimulus and to an electrical impulse train with low- stimulation frequency before and after the 5 x 300 m running load of one subject.

**A**

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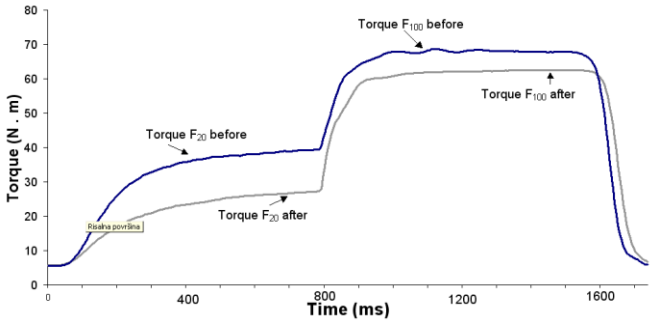


**Fig. 2**
Tipical sample responses of relaxed vastus lateralis (VL) muscle of 1 subject as measured after warm-up and 2.5 min after end of interval runs
A: response to single supramaximal stimulus
B: response to low- and high- frequency electrical stimulation

Table 1 presents the influences of an individual running load on stimulated and voluntary muscular contraction.

**Table 1**
Parameters of voluntary and electrically stimulated muscle contraction before and after interval and continuous running load. Data is shown as mean ± standard error

| | 5 x 300 m | | 6 km | | p |
|---|---|---|---|---|---|
| | Before | After | Before | After | |
| Ttw (Nm) | 10.8±0.9 | 7.9±0.9*** | 12.8±1.6 | 11.0±1.4* | + |
| CT (ms) | 94±2.3 | 86±2.1* | 92±2 | 85±3.1** | NS |
| RT1/2 (ms) | 52±1.7 | 53±2.4 | 54±2.5 | 52±1.6 | NS |
| MCR (Nm/s) | 195±17 | 156±21*** | 220±17 | 207±17 | NS |
| MRR (Nm/s) | 172±18 | 108±14*** | 204±23 | 156±13 | + |
| TF20 (Nm) | 31.4±4 | 25.4±4.6** | 35.8±5.5 | 28.5±5.7* | NS |
| TF100 (Nm) | 49.2±5.7 | 46.3±6.5* | 54±7.2 | 49.7±8.3 | NS |
| MVC (Nm) | 168±15.9 | 159±16.5 | 165.1±14.5 | 154.9±16.7 | NS |
| AL (%) | 73±6 | 74±6 | 71±5 | 74±5 | NS |

$T_{TW}$=twitch peak torque; CT=contraction time; RT ½=half relaxation time; MCR=maximal contraction rate; MRR=maximal relaxation rate; $T_{F20}$=torque during 20-Hz ES; $T_{F100}$=torque during 100-Hz ES; $T_{MVC}$=maximal torque during explosive isometric MVC; AL=activation level.
Asteriks denote significant differences (*p<0.05,**p<0.01,***p<0.001) compared to the value before the workout ); p value - testing of differences between interval and continuous running load; +p<0.05; N.S: statistically non-significant differences

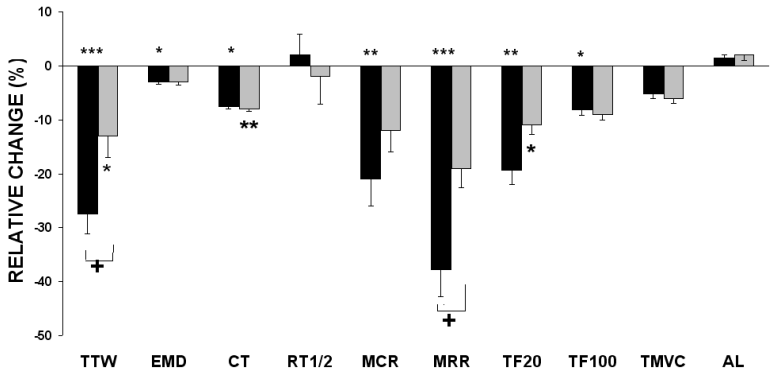


**Fig. 3**
Relative changes in mechanical MVC and ES parameters
Vertical lines, SE; *p<0.05; **p<0.01; ***p<0.001

*Anaerobic load:* Interval runs of 5 x 300 m cause a torque decline by ES-caused muscular contractions and, at same time, a decline in muscular contraction velocity. The torque of voluntary muscular force stayed the same.

In the single twitch test the average maximum torque $T_{TW}$ dropped by 27.5±3.8%. EMD and CT became shorter by 5.1±1.1% ($p<0.05$) or 7.6±3.3% ($p<0.05$), while $RT_{1/2}$ stayed unchanged.

Maximum velocity of torque twitch development (MCR) declined by 20.6±4.8% ($p<0.01$) after the interval runs. After the interval runs, muscular relaxation velocity (MRR) was only 62.6% ($p<0.001$) of the value before the load.

In the low- and high-frequency stimulation test, torque F20 (31.4±4 N·m) in rest declined to 25.4±4.6 N·m ($p<0.01$) after the interval load, while torque F100 dropped by 6.5±1.8%: from 49.2±5.7 N·m to 46.3±6.5 N·m ($p<0.05$). The findings of MVC lowering and AL increasing after the interval runs are not statistically significant.

Subjects with greater LA increment after interval training had a significantly higher decline in torque F20 ($r=-0.80$; $p<0.05$) and torque $T_{TW}$ ($r= -0.92$; $p<0.01$). This higher LA rise was also connected with greater MCR ($r= - 0.95$; $p<0.001$).

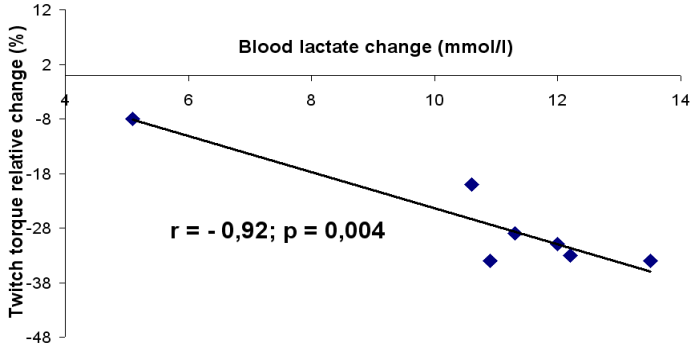


**Fig. 4**
Relationship between changes in lactate and relative changes in twitch torque

*Aerobic load:* The 6-km run also influenced the lowering of stimulated muscular contraction torque and the lowering of voluntary isometric contraction. But it did not cause any statistically significant changes in muscular contraction velocity.

In the single twitch test the torque $T_{TW}$ after the continuous run became 16% lower: from 12.8±1.6 N·m to 11.0±1.4 N·m ($p<0.05$), while EMD became shorter by 46.5±1.9 ms to 44.3±2.1 ms ($p<0.05$) as did CT by 7 ms ($p<0.01$). Torque at 20

Hz of electrical stimulation also fell from 35.8±5.5 N·m to 28.5±5.7 N·m ($p<0.05$). There were no statistically significant differences between LA and changes in the contracting parameters after the 6-km run.

Compared to the 6-km run, the interval runs of 5 x 300 m caused a higher decline in single twitch torque ($p<0.05$) and a greater decline in muscular relaxation velocity ($p<0.05$).

## Discussion

The influence of intensive and long-lasting continuous running loads on some biomechanical parameters of quadriceps is the same, yet on others it is very different.

*The type of fatigue:* The main characteristic of fatigue is a lowering of muscular force. Fatigue is a result of lowering the number of active cross-bridges and/or lower force, which is developed by a single active cross-bridge.

Muscular contractions caused by electrical stimulation are independent of the central nervous system. Therefore, the decline of torque twitch and decline of maximum torque at 20 Hz shows that the reasons for fatigue after both running loads were peripheral mechanisms. The dominance of peripheral fatigue in the present study was also confirmed by the increase (although not statistically significant) in the level of muscle activation. After both running loads, the torque of maximum voluntary isometric contraction with additional electrical stimulation decreased more than the torque of MVC. This confirms that the reasons for fatigue lay in the muscular and not in the central mechanisms.

The large torque decline found during low-frequency stimulation ($T_{F20}$) and small decline of $T_{F100}$ and $T_{MVC}$ (statistically non-significant) after both running loads points to the presence of low-frequency fatigue (LFF) which has been connected to the excitation-contraction coupling failure [12,15]. Low-frequency fatigue implies a smaller $Ca^{2+}$ released from SR and/or the inhibition of $Ca^{2+}$ binding to troponin [5] resulting in fewer active cross-bridges.

Besides extreme torque, the $T_{F20}$ decline also became lower at high-frequency stimulation ($T_{F100}$) after the interval runs. This means that fatigue after highly-intensive anaerobic interval runs is probably not only the consequence of lower $Ca^{2+}$ transport system efficiency (like in the 6-km run), but also the consequence of the lower efficiency of AP transport across sarkolema and T-tubes system (high-frequency fatigue – HFF) [2,26]. A highly-intensive load causes the destruction of electrolytic balance of $Na^{+}$ in $K^{+}$ ions in intra- and extra-cellular fluid [8]. Electrolytic unbalance may cause a depolarisation blockade which significantly

lowers action potential frequency during high-frequency stimulation [2] and consequently has an influence on lowering muscular force.

*Differences in fatigue:* The interval load of 5x300 m at a sub-maximum speed with a one-min rest between each run caused – in comparison with the prolonged continuous 6-km run at the anaerobic threshold speed ($V_{OBLA}$ criterion) – a significantly larger decline in $T_{TW}$ and fall in the maximum rate of muscle relaxation (MRR).

Differences in influences of different running loads on the muscle contractile characteristics indicate that the magnitude of these changes is connected with the speed of running – the intensity of activity. The average speed of the 5x300 m interval runs was 6.69 m $s^{-1}$ or 77% of the subject's maximum speed, while the speed of continuous running was 4.94 $m \cdot s^{-1}$ or 56% of their maximum speed.

The continuous 6-km run and 5x300-m-interval run at sub-maximum speed with a 1-min active intermediate rest belong to different physiological-biochemical load categories. The continuous 6-km run at anaerobic threshold OBLA speed represents mostly an intensive aerobic load in the maximum steady state of the blood lactate zone. On the other hand, the 5x300-m runs represent a typical anaerobic lactate load [6,17].

The high speed of the interval runs demands the more distinctive recruiting of fast (IIa and IIb) muscular fibres and higher proportion of anaerobic lactate metabolic processes in covering energy needs. After the interval runs, LA rose to 12.9 mmol/l and reached twice the value of the 6-km run. Therefore, the differences in pH in muscular cell and blood (after different loads) are logical and expected.

The role of acidosis during the influence of both running loads on some contractile characteristics proves the connections between a change of LA and changes in the contractile parameters. Subjects with a higher LA increment after interval training had a significantly higher decline in torque F20 and $T_{TW}$. This higher LA increment was also connected with a greater decline in MCR and $RT_{1/2}$.

Acidosis reduces the contractile efficiency of the muscle in several ways.

Decreased pH causes the inhibition of Ca2+ release in the sarcoplasmatic reticulum and a decrease in maximum tension [7,13,19,23].

$H^+$ ions occupy the active sites on the actin filaments and thereby limit the formation of cross-bridges [18]. If acidosis is increased, the affinity of $Ca^{2+}$ for binding with troponin [13] decreases. Increased concentrations of ADP, Pi and $H^+$ reduce the activity of Na-K-ATPase, $Ca^{2+}$ ATPase and actomyosin ATPase [13,20]. Simultaneously, the production of free radicals depends on the intensity of the load [10,19].

For fatigue of the skeletal muscles after maximum isometric contraction is not characteristical only the decline of contractile force, but slowdown of contraction also [5,11]. On the other hand, after both running loads the contractile twitch time shortened by 7 ms (on average) and the half relaxation time stayed unchanged. A shortening of twitch time parameters was also noticed after prolonged (more than 30 min) low-intensive loads [1,7,23,30].

Muscular temperature rise is probably the most important reason for the shortening of twitch time parameters. The increase in muscular temperature by 3.1°C caused the decline of CT and $RT_{1/2}$ by 7% and 22%, respectively [9]. This increased muscular temperature not only had a direct but also an indirect influence on the contractile muscular mechanism [24,25]. Higher muscular temperature has an inhibitory influence on decreased pH and other metabolic changes in the muscular cell [7].

The increase (although not significant) of half the relaxation time was only measured after the interval training. After the long-distance run the relaxation time shortened, but the muscular relaxation velocity decline was not significant. Other studies confirm these findings [7,28]. They indicate that, after low-intensive dynamic loads, muscular relaxation time shortens and after a very-intensive load (isometric or excentric-concentric load) the muscular relaxation time extends [4,11,16,30].

The process of muscle relaxation is primarily regulated by the Ca-transport enzymes ATP-ase and myosin ATP-ase which regulate the pumping back of $Ca^{2+}$ into the sarcoplasmatic reticulum - in other words, the efficiency of the dissociation of cross-bridges [18,20].

Despite lowering the efficiency of the $Ca^{2+}$ pump by 17% and $Ca^{2+}$ ATPase by 21% (after prolonged cycling at 75% VO2max) HRT was not extended [7]. Researchers believe the relaxation muscular time begins to increase after lowering the efficiency of the $Ca^{2+}$ pump by more than 40% that is at a higher-load intensity. The result of this study also shows the $HR_{1/2}$ extending is connected to the level of acidosis. Subjects with a higher blood lactate increase (after interval training) had significantly higher $HR_{1/2}$. Higher LA (after interval runs) decreases re-phosforilisation ADP efficiency, which has an influence on slowing of the cross-bridges cycle and consequently on the extending of $RT_{1/2}$ [15,21,22].

## Conclusion

Both running loads caused peripheral fatigue. The lowering of muscle contractile ability after both loads is mostly the consequence of disturbances in the

Ca transport system mechanisms. At the same time, after the intensive interval loads the lowering of muscle contractile ability is also a consequence of disturbances in the extension of active potential across sarcomere and T-tube system.

The intensive interval runs caused bigger and numerous changes in muscular contractile characteristics compared with the less-intensive prolonged run. The results indicate a higher level of blood lactate and consequently lower muscular pH are the most important reasons for the greater neuromuscular fatigue seen after the interval runs.

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