HIGH FREQUENCY FATIGUE APPEARING AFTER MAXIMAL HOPPING

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Abstract:

Neuromuscular fatigue after stretch-shortening cycle (SSC) exercise was analysed. Eleven healthy sport students performed maximal hops for 60 secs on a force plate. After the workout, a statistically significant increase in the blood lactate concentration was found (before workout 0.73 mmol/l, three minutes after workout 6.41 mmol/l, ($P<0.001$)). During the hopping, maximal height was decreased for 3 cm ($P<0.002$). Contact times were shortened statistically significant, too ($P<0.001$). There were no statistically significantly changes in power or in fatigue index. Electrical stimulation of the vastus lateralis muscle resulted in a decreased twitch force (12%), contraction time and half relaxation time were also shorter, but the changes were not statistically significant. Torque during 20 Hz stimulation showed a trend of increase. Torque during 100 Hz stimulation was significantly lower ($P<0.001$). Results showed that a high frequency fatigue was present after the hopping, noting that fatigue appeared in the conductory part of the muscle while the muscle contractile activity was not impaired.

Key words: *neuromuscular fatigue, stretch-shortening cycle (SSC) exercise, electrical stimulation.*

INTRODUCTION

Fatigue is a complex phenomenon influenced by various physiological and psychological factors. Physiologically, fatigue is often defined as a reversible muscle force decline (Edwards, 1981, 1983), or as an inability to maintain the needed or expected strength or power. In a voluntary isometric muscle contraction (MVC), the muscle force is a result of various events in the chain of command from the brain to the muscle (Edwards, 1978). Fatigue is manifested through different symptoms (one or more) depending on one or more physiological mechanisms. The above mentioned authors distinguish between central and peripheral fatigue. Peripheral fatigue includes events peripheral to the neuromuscular junction and is further divided into high- and low-frequency muscular fatigue. High-frequency fatigue occurs as a result of he impairment of the action potential propagation along a muscular fibre (Edwards et al., 1977), whereas the problem of low-frequency fatigue lies in excitation-contraction coupling (Bigland-Ritchie et al., 1978; Edwards, 1981).

The type of muscle fatigue in isotonic muscle contractions depends on the intensity and duration of the load and on the type of muscle contraction used to overcome the load. High-frequency fatigue has been reported in maximum stretch-shortening cycle (SSC) exercise (Jereb and Strojnik, 1995; Strojnik and Komi, 1998). Low-frequency fatigue pervaded in maximum concentric muscle contractions exercises (Jereb and Strojnik, 1995; Jereb and Strojnik, 1998) and a submaximal SSC workout (Strojnik and Komi, 2000). In a study conducted by Strojnik and Komi (1998), the subjects performed maximal SSC exercise for a short time (jumping height dropped to 90%). High frequency fatigue was observed suggesting the problem was in the action potential propagation along the sarcolemma. On the other hand, an improvement in the contractile mechanism occurred. The contractile mechanism seemed to be potentiated through a shorter Ca^{2+} transient from the sarcoplasmic reticulum and shorter cross-bridge cycle. The execution of submaximal hops (60% of the maximal jump) leads to a decline in torque with 20 Hz electric stimulation (Strojnik and Komi, 2000).

The jumps in the above mentioned studies (Strojnik and Komi, 1998; 2000) were conducted on a special sledge apparatus, which enabled long contact times and high knee amplitudes during the contact (up to 90° in the low position). In practice, hops with much shorter contact time and smaller knee amplitude are performed for improving take-off power. These differences may have an important impact on a neuromuscular function (Bosco et al., 1982; Kyrolainen and Komi, 1995). It is possible to expect greater muscle pre-activation and reflex potentiation resulting in higher firing frequencies in hopping than in sledge jumps. Therefore, it is possible to expect that hopping would develop high frequency fatigue. The aim of the present study was to determine the type of muscle fatigue after performing maximally intensive vertical hops with short contact times.

METHODS

Subjects. 11 students (Faculty of Sport) participated in the study (age = 22.9 ± 3.9 yr, height = 176.1 ±4.1 cm, body mass = 71.8 ± 3.7 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 Helsinki-Tokyo Declaration and was approved by The National Medical-Ethic Committee.

Experimental design. After familiarising themselves with the experimental procedures, the subjects learned the execution of the tests. They were acquainted with all the measuring protocols. The experiment included a warm-up, hopping performance, and blood sample taken to record blood lactate concentration (LA).

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

Exercise. Consecutive hops were conducted in a laboratory environment on a force plate (Kistler, model 9278 Winterthur, Switzerland). Hopping started 5 mins. after the warm-up period. Hands on the hips were obligatory (Figure 1). The subjects started with a squat jump followed by successive vertical hops, which had to be performed with the maximum jumping height and with the shortest possible contact time. The whole jumping exercise lasted 60 seconds (Bosco et al., 1983). On the basis of the force-time curve, the following parameters were calculated: work per hop, power per hop, relative power per hop, contact time, flight time, and hop height. An average load in all these parameters in each quarter of the test (Bosco et al., 1983) was also calculated. The total number of hops divided into four equal parts defined the quarters. A fatigue index (FI) was calculated from the relative force results of the first and the last quarter of the hopping:

$$FI = 100 - \left(\frac{\overline{P}_F}{\overline{P}_L} * 100 \right)$$

$\overline{P}_F$ = average power of the first quarter

$\overline{P}_L$ = average power of the last quarter

Electrical stimulation. The electrical stimulation measurements began 2.5 mins. after warm-up and 1 min after the test. All measurements with electric stimulation were performed on an isometric knee torque measuring device at a 45° knee joint angle. During the measurements, the subject lay dorsally on the table with hips stopped and lumbar spine supported to prevent pelvic movements (Figure 2). 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

***Figure 2.** Position of the subject during the measurement.*

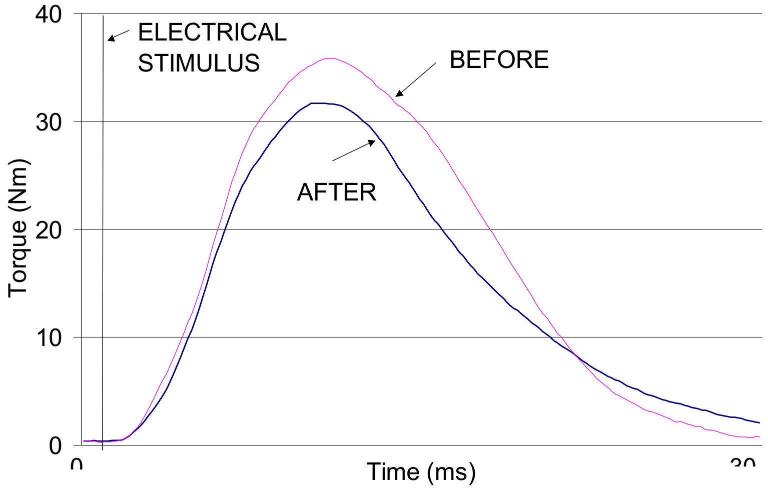

Figure 3. *Typical response of a relaxed vastus lateralis muscle in one subject to single supramaximal stimulus as measured after warm-up and 1st min after the end of workout.*

over the vastus lateralis muscle: anode over the distal part of the muscle's belly and cathode over the middle part of the muscle's belly. On all occasions, constant current square biphasic impulses of 0.3 ms duration were employed.

Twitch. The torque-time relationship of the relaxed vastus lateralis muscle (VL) as a result of the single supramaximal electrical stimulus of 0.3 ms impulse duration was observed. Maximal muscle torque (F_{TW}), time to maximum torque (CT), and half relaxation time ($RT_{1/2}$) were analysed. TW was measured on the right leg (Figure 3).

High and low frequency fatigue test. The maximum torque of the relaxed vastus lateralis muscle during a 0.8 s duration of sequences electrical impulses delivered with 20 Hz and 100 Hz frequency was observed. Duration of a single stimulus was 0.3 ms (Figure 4). The measurement was performed on the right leg. The level of electrical stimulus 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 PC and adequate software which allowed the calculation of the above-mentioned parameters.

Blood analysis. Blood samples for blood lactate concentration analysis (20 ml) were taken

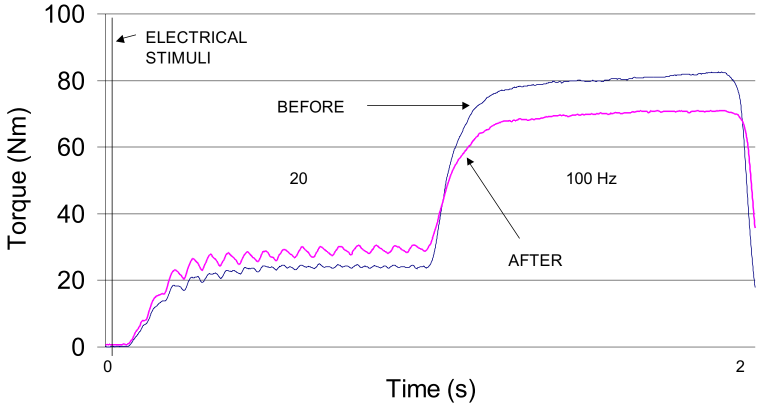

Figure 4. *Typical torque response of a relaxed vastus lateralis muscle in one subject to low- and high-frequency electrical stimulation subject as measured after warm-up and 1st min after the end of workout.*

from the hyperaemic ear. Lactate concentration was measured with Kontron 640 Lactate Analyser (Kontron, Austria) immediately after being taken, which was done 2.5 min after warm-up, and 1, 3, 5, 7 and 10 min after the test.

Statistical methods. The differences in results measured before and after the test were tested using paired students t-test (SPSS Inc., Chicago, IL). Statistical significance was accepted at 5% alpha error.

RESULTS

The results of hopping are shown in Figure 5. Hops showed a trend of increased power, while the hopping height decreased from 35 to 32 cm (P=0.002). During the hopping, contact times changed as well. They showed statistically significant shorter times (P=0.000). However, there were no significant changes in the FI.

Mean F_{TW} values decreased approximately 12% (Figure 6). Contraction times were shortened by 5%, which did not prove to be statistically significant. Relaxation times were shortened by

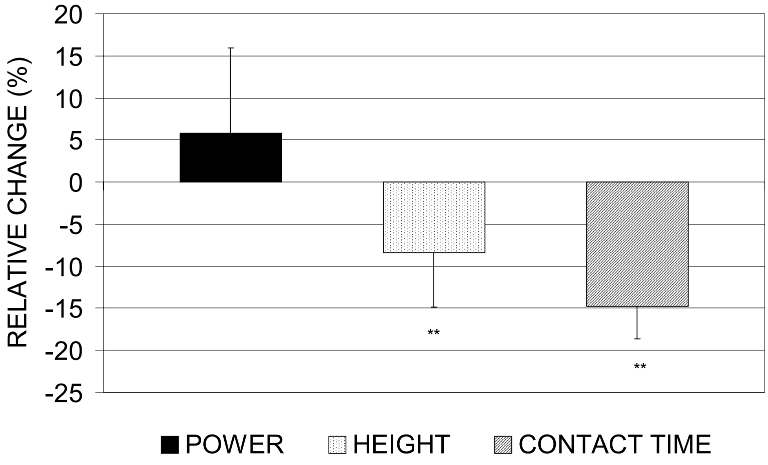

Figure 5. *Relative changes of hopping parameters during the workout. Vertical lines represent SD. **-statistical significance (P<0.01).*

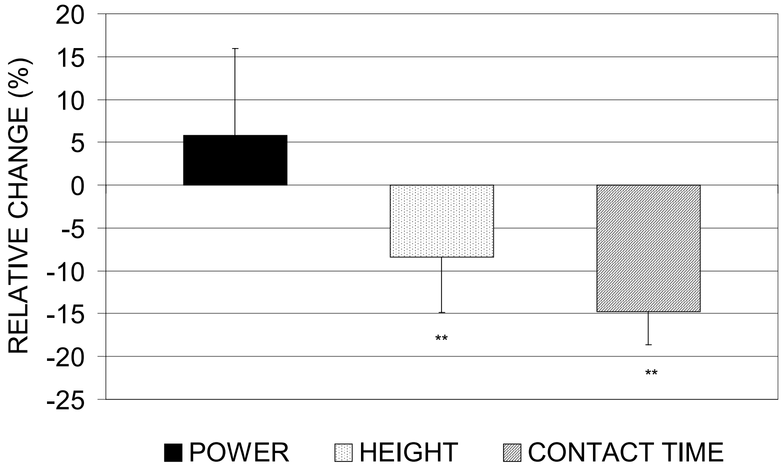

Figure 6. *Relative changes in muscle torque during electrical stimulation. F_{TW} - twitch force, CT - contraction time, $RT_{1/2}$ - half relaxation time, F_{20} - force at 20 Hz ES, and F_{100} - force at 100 Hz ES. Vertical lines show SD. **-statistical significance (P<0.01).*

7%, again not statistically significant.

There was a trend of increasing force at 20 Hz stimulation (Figure 6), but these changes were too small to be statistically significant. At 100 Hz stimulation, the muscle responded with a decrease in force (Figure 6) that was statistically significant (P=0.01).

Blood LA concentration increased after the workout in comparison to the warm up (Figure 7). The highest LA level was recorded in the third minute after the end of the workout (6.4 mmol/l) and was significantly higher than the level after the warm up (P=0.000).

where the subjects performed movements with predetermined amplitudes, muscular stiffness decreased with fatigue at higher amplitudes and increased at lower amplitudes. Fatigue related increase in muscle stiffness during hopping was also observed by Gollhofer et al. (1987). In another study, Gollhofer et al. (1989) observed a fatigue conditioned decrease in stiffness, which probably results from increased knee angle amplitudes. Muscle stiffness and joint amplitude depend on preactivation before performing a movement and the reflex activation during the movement, which ensures a good hopping performance. Relative power did not fall during the hopping. We could even observe a trend of the increased power, which may be an indication of increased elastic energy use in the concentric part of the hop. This type of hopping is, as far as energy turnover is concerned, very efficient. Low LA concentrations (6.4 mmol/l), which were obtained after the load, show that there were no dramatical biochemical changes in the muscles probably because of the use of the elastic energy of the tendons and muscles during the hopping.

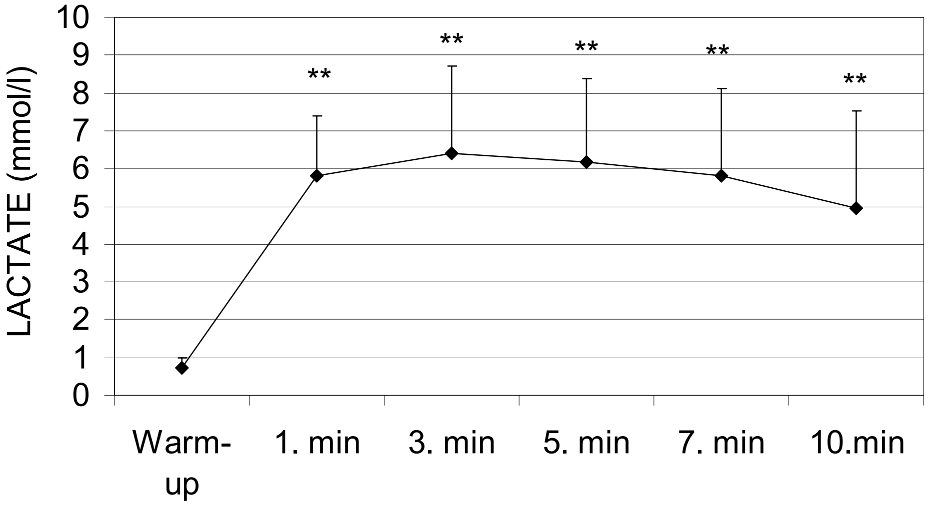

Figure 7. *LA concentration in blood. Vertical lines show SD. **-statistical significance (P<0.01). Warm up-five min before the load. 1, 3, 5, 7 and 10 min after the load.*

DISCUSSION

The main findings in this study were only minimal changes in certain dynamic parameters such as hopping power, hopping height, ground contact time and the fatigue ratio. Small changes were also observed in muscle contractile characteristics where F_{TW} decreased slightly, while CT and $RT_{1/2}$ slightly shortened. The most significant changes were observed in stimulation with 20 Hz and 100 Hz. 20 Hz force did not change significantly, but the greatest effect was seen in the decreased force during 100 Hz stimulation.

Ground contact times during the hopping became shorter which proved to be statistically significant. This change may be connected mostly to the changes in muscle stiffness and reduced joint angle amplitudes. These two parameters are closely related to fatigue. In a study by Kim (1988)

In this study, almost no change in twitch parameters occurred, which showed that muscle contractile characteristics did not change significantly. Actually, shortened CT and $RH_{1/2}$ make it possible to speak about a slight improvement in the contractile muscle characteristics. Even more pronounced changes in the muscle contractile characteristics were observed by Strojnik and Komi (1998). An improvement in muscle contractile characteristics occurred after maximal stretch-shortening cycle exercise, which was slightly shorter than in the present study. The improvement was attributed to the shorter Ca^{2+} release and reabsorption cycle from the sarcoplasmic reticulum and faster cross bridges activity. In isometric condition, F_{TW} depends on the number of active cross bridges and/or the amount of force generated by one cross bridge (Metzger et al., 1989). As there were no significant changes in F_{TW} after the activity, we can conclude that the cross bridge binding after the load remained at generally the same level as before the load. Cross bridge binding is influenced by intracellular pH (Metzger and Moss, 1990). Lowered intracellular pH lowers the cross bridge binding and thus lowers the F_{TW}. It is possible to assume that this did not occur in the present study despite the slight increased blood LA concentration. Muscle temperature increased as a result of activity and may have been the cause of shorter CT and $RT_{1/2}$. Davies and Young (1983) reported that a 3.1°C increase in temperature shortens CT by 7%, and $RT_{1/2}$ by 22%. In this study the subjects performed a warm up before the test and thus it can be assumed that rather constant muscle temperature is mentioned during the whole workout. The small changes in twitch parameters may therefore be mainly attributed to the shorter Ca^{2+} release and re-absorption cycle from the sarcoplasma, which can be denoted as a sign of promotion of muscle contractile characteristics.

F20 decrease can be defined as low frequency fatigue (Edwards et al., 1977). An impairment in the contractile system is often caused by higher muscle and blood acidosis (Stokes et al., 1989), which influences excitation-contraction coupling (Bigland-Ritchie et al., 1983; Edwards et al., 1977). Low-frequency fatigue is accompanied by a shorter Ca^{2+} release from sarcoplasmic reticulum (Rousseau and Pinkos, 1990) and/or lower Ca^{2+} binding on troponin (Blanchard et al., 1984) which results in a smaller number of active cross bridges. In our study F20 has not changed, so it is not possible to talk about low-frequency fatigue. The decline in 100 Hz force is a result of an impairment in the action potential propagation (Edwards et al., 1977; Stokes et al., 1989; Gibson et al., 1985). In explosive contractions (Enoka, 1994), a demand for high frequency action potential delivery to the motor units probably causes shifts in Na^+ and K^+ concentrations in intracellular and extracellular fluids. This has also been observed in muscles receiving high frequency ES and in fatiqued human muscles (Sahlin et al., 1978; Sjřgard et al., 1985), resulting in membrane depolarisation (Sejersted et al., 1984). Such a disproportion in Na^+ and K^+ may appear because of an inadequate number of Na-K pumps or lack of energy. A depolarisation block may occur, which may reduce the action potential frequency during high-frequency stimulation (Balog et al., 1992). Reduced action potential propagation over cellular membrane lowers the activation of the contractile part of the muscle. Although it is possible to suspect that high-frequency fatigue was present after maximal hopping for 60 secs, it was still not possible to observe any substantial changes in the mechanical parameters of the hopping. This might be due to a reactive nature of the hops relying much on the use of the elastic energy of muscles and tendons and may therefore be not so sensitive to changes in the muscles' force production as during pure concentric ballistic action.

From the studies analysing muscular fatigue with stretch-shortening cycle exercises, we can conclude that: (1) in submaximal SSC exercises with longer execution time (Strojnik and Komi, 2000) low-frequency fatigue appears and (2) in the SSC exercise with the maximal intensity and short duration (Strojnik and Komi, 1998) high-frequency fatigue prevails. The results from this study fall into the second group. After 60 secs of successive maximal hopping, high-frequency fatigue appeared. The most interesting thing was that a small potentiation in the muscle contractile characteristics was observed while at the same time a conductive block prevented the muscle from being efficiently activated. From this we can see that the reactions of the same muscle to the load may be very different: while fatigue appeared in the conductory part of the muscle, the muscle contractile apparatus seemed improved.

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VISOKOFREKVENTNI UMOR NAKON SKOKOVA MAKSIMALNE SNAGE

SAŽETAK

UVOD

Umor je složena pojava na koju utječu brojni fiziološki i psihološki faktori. Fiziološki, umor se obično definira kao reverzibilni pad mišićne sile, ili kao nemogućnost održanja potrebne ili očekivane mišićne jakosti ili snage. Pri voljnoj izometričnoj mišićnoj kontrakciji (MVC), mišićna sila je rezultat različitih zbivanja u lancu prijenosa naredbi iz mozga u mišić. Umor se javlja kada se jedno ili više različitih zbivanja događa istovremeno, a moguće je razlikovati centralni i periferni umor. Periferni umor uključuje ona zbivanja koja se nalaze ispod razine neuromuskularne sinapse, a može se podijeliti na visoko ili nisko frekventni mišićni umor. Visoko frekventni mišićni umor javlja se kao rezultat slabljenja širenja akcijskog potencijala duž mišićnog vlakna, dok problem mišićnog zamora niske frekvencije leži u ekscitacijsko-kontrakcijskom mehanizmu.

Tip mišićnog napora u izotoničkoj mišićnoj kontrakciji ovisi o intenzitetu i trajanju opterećenja, kao i o tipu mišićne kontrakcije koja se koristi za savladavanje tog opterećenja. Visoko-frekventni umor javlja se nakon vježbi koje uključuju ciklus kontrakcije i opuštanja mišića (stretch-shortening cycle - SSC). Nisko-frekventni umor prevladava u vježbama maksimalne koncentrične mišićne kontrakcije i kod submaksimalnog SSC treninga. Visoko frekventni mišićni umor može uzrokovati smanjenje širenja akcijskog potencijala duž sarkoleme. S druge strane, javlja se poboljšanje svojstava kontraktilnog mehanizma mišića, koje se očituje ubrzanjem otpuštanja Ca^{2+} iz sarkoplazmatskog retikuluma te ubrzanjem ciklusa kretanja poprečnih mostića.

U prethodnim su istraživanjima skokovi izvođeni na posebnom sledge-aparatu, koji je omogućavao duže vrijeme kontakta i veću amplitudu savijanja koljena za vrijeme kontakta (do 90° u donjoj poziciji). U praksi (stvarnim uvjetima), skokovi s kraćim kontaktnim vremenom i manjom amplitudom koljena izvode se u cilju poboljšanja snage odraza. Te bi razlike mogle imati značajan utjecaj na neuromišićnu funkciju. Zato je moguće očekivati višu razinu mišićne preaktivacije i viši potencijal refleksa što može rezultirati višom frekvencijom *okidanja živčanih impulsa* kod odraza nego kod skokova na sledge-aparatu. Također je moguće očekivati da će skokovi izazvati pojavu visoko frekventnog umora. Cilj ovog istraživanja bio je utvrditi tip mišićnog umora koji se javlja nakon maksimalno intenzivnog izvođenja vertikalnih skokova uz kratkotrajni kontakt s podlogom.

METODE

Jedanaest zdravih studenata fizičke kulture (dob=22.9 +/- 3.9 god., visina = 176.1 +/- 4.1 cm, tjelesna masa= 71.8 +/- 3.7 kg) dobrovoljno je, uz osobni pristanak, sudjelovalo u istraživanju. Istraživanje je odobrio Nacionalni medicinski etički odbor. Eksperiment je sadržavao zagrijavanje, izvođenje maksimalnih skokova u trajanju 60 sekundi na tenziometričkoj ploči, uzimanje uzoraka krvi iz ušne resice kako bi se dobio uvid u koncentraciju laktata (LA), te električnu stimulaciju relaksiranog *m. vastusa lateralisa* s nizom električnih impulsa visoke (100 Hz) i niske (20 Hz) frekvencije. Također je dodatno mjerena i reakcija na jedan supramaksimalni električni trzaj. Maksimalni moment sile pri 45 stupnjeva u koljenskom zglobu mjeren je za vrijeme električnog podraživanja sa 100 Hz i sa 20 Hz. Trzaj je analiziran za maksimalnu vrijednost momenta sile (F_{TW}), vrijeme kontrakcije (CT) te na poluvremenu oporavka ($RT_{1/2}$). Mjerenja su provedena prije i nakon izvođenja skokova (60 sec.).

REZULTATI

Skokovi su pokazali trend povećanja mehaničke snage na kraju zadatka, dok je visina skoka pala sa 35 na 32 cm (P=0.002). U toku izvođenja skokova vrijeme kontakta s podlogom također se je promijenilo. Dobiveno je statistički značajno skraćenje vremena kontakta (P=0.000). Međutim, nije bilo statistički značajnih promjena u pokazateljima umora, što je iskazano kao omjer između prosječne snage za vrijeme prvih i zadnjih 15 sekundi odražavanja.

Srednja vrijednost F_{TW} u prosjeku se smanjila za 12%. Vrijeme kontrakcije smanjilo se za 5%, što se nije pokazalo statistički značajnim. Poluvrijeme oporavka smanjilo se je za 7%, što također nije bilo statistički značajno.

Vidljiv je bio trend povećanja snage pri podraživanju sa 20 Hz, ali su i te promjene bile preniske da bi bile statistički značajne. Pri podraživanju sa 100 Hz, mišić je reagirao smanjenjem sile, što se pokazalo statistički značajnim (P=0.01).

Koncentracija laktata u krvi (LA) povećala se je nakon vježbanja u odnosu na period zagrijavanja. Najviša koncentracija laktata u krvi primijećena je u trećoj minuti nakon prestanka izvođenja skokova (6.4 mmol/l), što je bilo statistički značajno različito od koncentracije laktata u krvi u fazi zagrijavanja (P=0.000).

RASPRAVA

Glavni rezultati ovog istraživanja očituju se u minimalnim promjenama mehaničkih parametara pri izvođenju skokova, kao što su snaga skoka, visina skoka, vrijeme kontakta s podlogom i količina umora. Dobivene su i manje promjene u kontraktilnim karakteristikama mišića, gdje je dobiveno malo smanjenje F_{TW}, dok je vrijeme CT i $RT_{1/2}$ također neznatno skraćeno. Najznačajnije promjene dobivene su pri podraživanju mišića električnim impulsima frekvencije 20 i 100 Hz. Pri podraživanju sa 20 Hz promjene mišićne sile nisu statistički značajne, dok je najznačajniji učinak dobiven pri podraživanju frekvencijom 100 Hz, a očitovao se u smanjenju mišićne sile.

ZAKLJUČAK

Na temelju istraživanja mišićnog umora u ciklusima kontrakcija-opuštanje (Strojnik i Komi, 2000), možemo zaključiti da: (1) pri submaksimalnom SSC vježbanju s dužim vremenom izvođenja javlja se niskofrekventni umor, i (2) kod SSC vježbi maksimalnog intenziteta i kratkog trajanja prevladava visoko frekventni umor. Rezultati ovog istraživanja pripadaju ovoj drugoj grupi. Nakon 60 s maksimalnog uzastopnog izvođenja skokova, javlja se visoko frekventni umor. Najzanimljivija je uočena niska učinkovitost kontraktilnih karakteristika mišića, dok je u isto vrijeme blok provođenja impulsa sprečavao učinkovitu aktivaciju mišića. Iz ovog je vidljivo da reakcija istog mišića na opterećenje može biti vrlo različita: ako se umor javlja u provodnom dijelu mišića, kontrakcijski aparat istog mišića biti će neiskorišten.

Ključne riječi: *neuromišićni umor, SSC vježba, električno podraživanje.*