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The Effect of Two Warm-Up Protocols on Some Biomechanical Parameters of the Neuromuscular System of Middle Distance Runners

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Abstract. Škof, B., and V. Strojnik. The effect of two warm-up protocols on some biomechanical parameters of the neuromuscular system of middle distance runners. *J. Strength Cond. Res. 21(2):394–399. 2007.*—The objective of this study was to determine the effect of 2 different warm-up protocols on the neuromuscular system of well-trained middle distance runners. Seven runners performed 2 different warm-up protocols, one of which included slow running, stretching, and bounding and sprinting exercises, while the other consisted of slow running and stretching only. Before and after warm-up, contractile properties of the vastus lateralis and quadriceps femoris were monitored with a single twitch test, maximal torque, and the level of muscle activation during maximal voluntary extension. The 2 types of warm-up protocols showed statistically significant differences in the increase of peak knee extension torque and muscle activation level. After warm-up 1 maximal twitch torque was increased and twitch contraction time (CT) was shortened. Both maximal torque and the level of activation were increased. Parameter changes after warm-up 2 were similar to those after warm-up 1 but not statistically significant. Sprinting and bounding as part of athletes' warm-up improve muscle activation.

Key Words. warm up, muscle contractile functions, electrical stimulation

Introduction

A runner's efficiency depends on different combinations of aerobic and anaerobic power and capacity, running economy, neuromuscular characteristics, and muscular strength. Warm-up is used by athletes to activate their biological and psychological potential and achieve such a physiological and psychological state as to ensure optimum competitive efficiency. Several studies (1, 21, 24, 25, 28, 32) confirm the connection between different physiological and biochemical changes in the body after warming up, and enhanced competitive efficiency. Competitive loads of different intensity require different, i.e., specific, preparation. Different techniques of warm-up protocols (active, passive) as well as different intensity and duration result in different physiological-biochemical changes in the body (8, 9, 13, 26, 28).

In addition to optimal metabolic circumstances, racing velocity in middle distance running (i.e., 800–3,000 meters; 6.5 to 8 $m \cdot s^{-1}$) and other intensive short-term workloads requires a suitable preparation of the neuromuscular system that enhances the mechanical efficiency of work (29).

The effects of warm-up on the neuromuscular system can be observed on 2 levels:

- The effectiveness of peripheral mechanisms is increased. Raised muscle temperature and other factors trigger different biochemical and electrophysiological changes in the muscle which increase muscle function. Changes included enhanced ATPase activity, shortened cross-bridge cycle (6), increased action potential (AP) transfer velocity and, as a result, increased muscle contraction velocity and increased strength (10, 36), reduced muscle viscosity, and lowered passive muscle and joint stiffness (11).
- The effectiveness of the central mechanisms (neural drive) of the neuromuscular system is increased (22, 39).

It is known that different types of muscular activity (isometric, concentric, stretch-shortening cycle [SSC]), as well as different levels of intensity and volume, have a different effect on the function of the neuromuscular system (19, 23, 34). Therefore, it is likely that different content and, as a result, different intensity of warm-up will influence different mechanisms of the neuromuscular function.

Stewart et al. (36) found that a 15-minute low-intensity warm-up on a bicycle ergometer increased muscle temperature by 3%. As a result, the frequency of surface EMG was increased by 11% and this, in turn, caused an increase in the velocity of action potential. Because of the shift of the force-velocity ratio, power output during squat jump increased by 7%.

It is assumed that intensive sprinting and bounding warm-up exercises stimulate the activity of the central mechanisms of neuromuscular function and muscle activation to a higher degree than just jogging or slow running. Strojnik and Komi (39) found that maximal intensity bounding influences the potentiation of the contractile system via 2 mechanisms: (a) a faster Ca^{2+} transport, which causes cross-bridge cycle shortening and (b) a higher conduction velocity of AP. Intensive bounding along with high frequency AP activate fast twitch fibers too. Temperature influence of the complex warm-up on the periphery is likely to be similar to the effects of low-intensity warm-up with jogging.

The aim of this study is to investigate the influence (and the likely differences between the 2 warm-up protocols) on some biomechanical parameters of the middle distance runners' neuromuscular system. One of the protocols consisted of jogging and stretching only while the other also included different bounding and sprinting exercises.

Methods

Experimental Approach to the Problem

To determine the influence of 2 different warm-up protocols on specific biomechanical parameters of neuromuscular function of middle distance runners and the differences between these protocols, we used repeated measures design. A group of runners first completed warm-up protocol 1 and after 4–6 days completed protocol 2. Measuring of selected parameters was done before and after the protocol. Protocols were always completed at the same time of day. Runners did not do any hard exercise 2 days before testing. All the warm-up parameters were time-controlled to precise performance, length, and intensity.

Subjects

The subjects were 7 well-trained middle distance runners. Their average age was 25.3 ± 4.1 years, their weight was 62.5 ± 4.1 kg, and their height was 176 ± 3.6 cm. On average they competed for 9 ± 3 years. Their average result on 1,500 meters was 3:54.12. Selected runners have trained in precompetition 6–8 sessions weekly. Their average mileage was 80 km per week.

Prior to testing they were all acquainted with the details of the experimental protocol, the possible risks, and the inconveniences involved. They had all given informed consent. The study was also approved by the National Commission for Medical Ethics and was carried out in accordance with the Declaration of Helsinki.

Experimental Protocol

The experiment was conducted in the precompetition cycle and did not disturb the regular training program of the subjects. Prior to the experiment, the subjects took part in laboratory testing to become familiar with the testing protocols with percutaneous electrical stimulation. Subjects first performed a graded test on a treadmill. Lactate threshold velocity (V_{LT}) was calculated from blood lactate kinetics (3), and this was how running intensity in different warm-up protocols was determined. The subjects' average and *SD* V_{LT} was 4.42 ± 0.36 $m \cdot s^{-1}$. The average lactate concentration at this velocity was 1.7 ± 0.56 $mmol \cdot L^{-1}$.

Warm-Up Protocols

The experimental protocol included 2 different warm-ups:

- Warm-up 1 (WUP 1): 10-minute continuous run at 80% V_{LT}, 5-minute stretching (flexibility exercises involving legs), 6 × 50 meter bounding exercises (2 × skipping, 2 × hopping, 2 × strides), and 5 × 80 meter acceleration runs. The warm-up took 25–27 minutes.
- Warm-up 2 (WUP 2): 10-minute continuous run at 80% V_{LT} and 5-minute stretching (flexibility exercises involving the legs). The warm-up took 15 minutes.

There was a 3-day interval between the treadmill test and the first warm-up protocol. The subjects first performed WUP 1; 4–6 days later they performed WUP 2. They were asked not to do any strenuous training during the last 2 days before the experimental task.

Prior to each WUP protocol, the subjects were administered electrodes for electrical stimulation and temperature measurement, and a heart rate monitor. After this they rested in a seated position for 20 minutes. To determine the initial state (after 20 minutes of rest), the following tests were administered (in order): blood sampling, the surface temperature of the vastus lateralis muscle, the relaxed vastus lateralis response to a single electrical impulse (twitch), and maximal voluntary isometric extension in the knee with added quadriceps femoris electrical stimulation. The same protocol was used after the warm-up. The post warm-up measurements were performed 60–90 seconds after the last warm-up task.

Measurements of Muscle Contractile Function

Electrical Stimulation. During the measurements involving electrical stimulation and maximal voluntary knee extension (right leg only), the subjects lay supine and were fixed at the pelvis and over the distal part of the thigh to prevent trunk and thigh movements. The distal part of the lower leg was fixed to the force transducer which had a constant lever arm to the knee joint axis. The angle at the knee of the fixed leg was 45°. We used a force transducer (MES, Maribor, Slovenia) with linear properties inside 0–5,000 N. Self-adhering neurostimulation electrodes (5 × 8 cm; Axelgaard Manufacturing Co., Fallbrook, CA) were placed over the vastus lateralis (VL), vastus medialis (VM), and rectus femoris (RF) muscles. The distal electrodes were placed over the distal part of the muscle belly and the proximal ones were placed over its middle part. The electrodes remained fixed during the experimental procedure. Each pair of electrodes was connected to its own stimulation channel that was galvanically separated from the others. On all occasions the constant current square biphasic impulses of 0.3 ms duration were employed. We used a custom-made computer-controlled electrical stimulator. Data were sampled at 1 kHz using a 12-bit AD converter (Burr-Brown, Dallas, TX) and stored in a computer.

Single Twitch Test. Five supramaximal stimuli were delivered consecutively (1 per second) to the relaxed VL muscle. The current used to elicit a maximal twitch was determined in each individual by increasing the stimulation current until no further increase in tension was observed despite further increments in current. This procedure ensured that each twitch was truly maximal for each individual. The torque signals from the twitch responses were smoothed (moving average) and averaged with a trigger point at stimulus delivery. Maximum twitch torque (T_{TW}), electromechanical delay (EMD), contraction time (CT), and relaxation half-time ($RT_{1/2}$) were calculated (7, 41).

Maximal Voluntary Knee Extension Test and Muscle Activation Level Test. The subjects tried to achieve their maximum isometric knee extension torque (MVC) and maintain it for 3 seconds. The torque signal was smoothed and analyzed for maximum torque (T_{MVC}). Muscle activation level (AL) was assessed during maximal isometric knee extension with additionally stimulated VL, VM, and RF muscles with a 0.8-second train of electrical impulse with the frequency of 100 Hz. The impulse was triggered after 2 seconds of voluntary concentric muscle contraction. From the analysis of the torque at the knee, the following biomechanical parameters were selected: maximum torque during maximal voluntary contraction (T_{MVC}), torque during maximal voluntary muscle contraction with additional electrical stimulation (T_{MVC+ES}), and AL ($AL = T_{MVC} \cdot T_{MVC+ES}{}^{-1}$) (38).

Blood Lactate. Blood lactate concentration was measured using the Kontron 640 lactate analyzer (Vienna, Austria). A sample of 20 μl of blood was taken from the hyperaemic earlobe before and 2 minutes after the warm-up. The accuracy of the measurement of the fresh blood lactate concentration was ±0.1 $mmol \cdot L^{-1}$.

Skin Temperature on the Surface of the VL Muscle. The measurement of the surface temperature of the vastus lateralis muscle (TS_{VL}) was taken with a digital thermom-

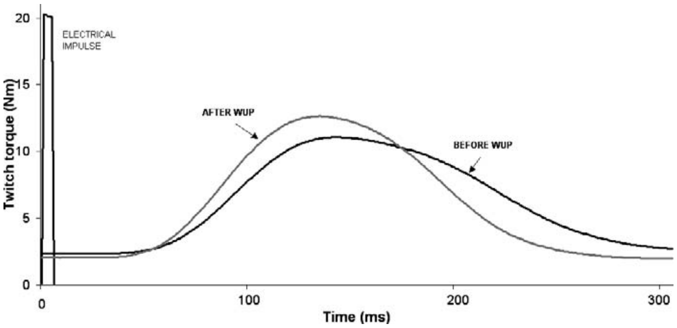

FIGURE 1. Typical responses of relaxed vastus lateralis muscle in a single subject as measured before and after warm-up 1 (WUP).

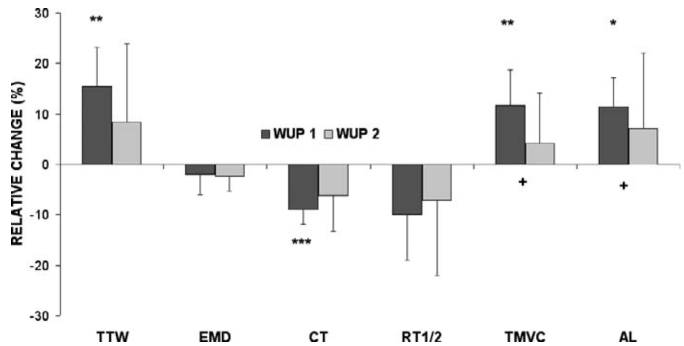

FIGURE 2. Relative changes in voluntary and evoked muscle contractions (mean ± *SE*). T_{TW} = maximal twitch torque; EMD = electromechanical delay; CT = contraction time; $RT_{1/2}$ = half relaxation time; T_{MVC} = torque during maximum isometric knee extension torque (MVC); AL = activation level; $T_{MVC\,+\,ES}$ = torque during MVC with added electrical stimulation. * statistically significant differences from values before warm-up (WUP); * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; + $p < 0.05$ on testing of differences of the influence between WUP 1 and WUP 2.

eter (Yokogawa EW 2572, Tokyo, Japan) and Cu Constant Type T thermoelements (Yokogawa). Electrodes were administered on the skin, i.e., on the surface of the middle and distal parts (up and down) of the muscle. The accuracy of the measurement was 0.1° C.

Statistical Analyses

A 2-way (before/after × WUP 1/WUP 2) analysis of variance for repeated measurements (protocol effects and interaction) followed by a post hoc test (Bonferroni test) were used. Statistical significance was accepted at $p \leq 0.05$ (2-tailed).

RESULTS

The velocity of warm-up runs was 3.6 $m \cdot s^{-1}$ or 4:40 $min \cdot km^{-1}$, which represented 80% of lactate threshold velocity. Subjects covered about 2,200 meters in 10 minutes.

Blood lactate concentration after WUP 1 rose from 1.1 ± 0.06 $mmol \cdot L^{-1}$ to 2 ± 0.5 $mmol \cdot L^{-1}$ ($p = 0.094$), while after WUP 2 it only increased by 0.1 $mmol \cdot L^{-1}$ from the resting value of 1.2 ± 0.24 $mmol \cdot L^{-1}$ ($p = 0.756$). The difference in the change of lactate concentration after the 2 warm-up protocols was 0.7 $mmol \cdot L^{-1}$ ± 0.06 $mmol \cdot L^{-1}$ ($p = 0.098$).

Skin Temperature on the Surface of the VL Muscle. The average temperature at 3 measurement points on the surface of the VL muscle was increased after both warm-up protocols. After the sprints and bounding warm-up (WUP 1), TS_{VL} increased by 1.3° C (from 32.5 ± 0.3° C to 33.8 ± 0.4° C; $p < 0.05$); the TS_{VL} increase of 1.2° C after WUP 2 was not statistically significant.

Contractile Characteristics of Electrically Stimulated Muscle. Figure 1 shows a sample of 1 subject's response of a relaxed VL muscle to a single electrical impulse at rest and after WUP 1. The effects of 2 different types of warm-up on biomechanical parameters of electrically stimulated muscle contraction are shown in Table 1. Relative changes of the different parameters of the stimulated and voluntary muscle contraction (with regard to the resting values) are shown in Figure 2.

Following the warm-up involving sprinting and bounding, T_{TW} increased by 16.5% (from 9.7 ± 2.6 N·m to 11.3 ± 0.9 N·m; $p < 0.01$), while T_{TW} after WUP 2 did not increase significantly. The differences in T_{TW} after both warm-up protocols were not significant either. Both warm-up protocols had a very similar effect on the twitch time parameters. Both protocols caused a significant shortening of CT (by 8.7 ± 4.8 ms after WUP 1, $p < 0.001$ and by 6.7 ± 5.2 ms after WUP 2, $p = 0.053$), while the shortening of $RT_{1/2}$ in both cases was on the borderline of statistical significance ($p = 0.052$ and 0.096).

Despite the fact that after WUP 1 changes in the biomechanical parameters of muscular contraction were more pronounced, the differences in the effect of both warm-up protocols on the twitch parameters were not statistically significant.

Voluntary Muscular Contraction and Muscle AL. The effect of the 2 different types of warm-up on maximal voluntary muscular contraction and muscle activation level is shown in Table 2. Following WUP 1, MVC (T_{MVC}) torque increased by 11.7 ± 7.1% ($p < 0.01$) and was significantly higher ($p < 0.05$) than T_{MVC} value after WUP 2. There were no differences between the amount of torque at the knee joint during $T_{MVC\,+\,ES}$ prior to and following the 2 different types of warm-up. Muscle activation level follow-

TABLE 1. Influence of 2 different protocols of warm-up on biomechanical parameters of electrically stimulated muscle contraction (mean ± *SD* for 7 subjects).*

	WUP 1		WUP 2	
	Before	After	Before	After
T_{TW}, (N·m)	9.7 ± 2.6	11.3 ± 0.9††	11.8 ± 1.3	12.8 ± 1.6
EMD (ms)	47 ± 1.2	46 ± 0.9	48 ± 0.9	47 ± 0.7
CT (ms)	100 ± 2.7	91 ± 2.3†††	99 ± 3.3	92 ± 2
$RT_{1/2}$ (ms)	59 ± 4.2	51 ± 1.7	59 ± 4.8	53 ± 2.4

* WUP 1 = warm-up 1; WUP 2 = warm-up 2; T_{TW} = maximal torque; EMD = electromechanical delay; CT = contraction time; $RT_{1/2}$ = half relaxation time.

† Indicates level of statistically significant difference from values before warm-up; difference of the influence between WUP 1 and WUP 2 not statistically significant.

TABLE 2. Influence of warm-up on biomechanical parameters of voluntary muscle contraction (mean ± *SD* for 7 subjects).*

	WUP 1		WUP 2		
	Before	After	Before	After	*p*
T_{MVC} (N·m)	150.1 ± 13.4	167.7 ± 15.9††	147.9 ± 15.2	155.5 ± 15.4	< 0.05
T_{MVC+ES} (N·m)	215.1 ± 33.6	219.7 ± 36.3	210.8 ± 35.2	211.3 ± 40.7	N.S.
AL (%)	70 ± 6.2	78 ± 6.4†	70 ± 5.9	75 ± 6.2	< 0.05

* WUP 1 = warm-up 1; WUP 2 = warm-up 2; T_{MVC} = maximal torque of voluntary muscle contraction; T_{MVC+ES} = maximal torque of voluntary muscle contraction with additional electrical stimulation; AL = activation level; N.S. = statistically not significant.

† Level of statistically significant differences from values before warm-up; *p* value includes differences of the influence between WUP 1 and WUP 2.

ing WUP 1 increased by 9.1 ± 5.8% ($p < 0.05$), which is significantly higher ($p < 0.05$) than following WUP 2.

DISCUSSION

The two most important findings of the study were:

- The changes in the contractile response of the VL muscle were only recorded after a more complex and intensive warm-up. A more intensive warm-up resulted in posttetanic potentiation—the torque of voluntary and electrically stimulated muscle contraction increased. The speed of contraction was also increased.
- In comparison to a lower intensity warm-up, a more intensive and complex warm-up resulted in a more significant increase of the MVC torque and in an enhanced muscle activation.

Only a more complex and intensive warm-up (WUP 1) caused a change (increase) in the muscle contractile efficiency. Low-intensity running and stretching (WUP 2) caused similar changes in the biomechanical parameters of the muscle contraction (T_{TW}, EMD, CT, and $RT_{1/2}$), but they did not reach the threshold of statistical significance. As part one of both protocols was the same (a 10-minute run at 80% lactate threshold velocity, and stretching) and muscle surface temperature after both protocols did not differ, we can conclude that the changes in the muscle contractile capacity are primarily a result of the application of horizontal bounding and sprinting.

The ability to produce force during running at maximal and submaximal velocity is closely related to middle distance runners' competitive efficiency (29). The speed of muscle contraction is defined with the duration of the cross-bridge cycle (6). Cross-bridge cycle is also influenced by the speed of muscle activation. The higher the speed of activation (the speed of AP transfer) of a single sarcomere of the muscle fiber, the higher the speed of muscle contraction (42). The shortening of the CT for an average of 9 ms ($p = 0.001$) and $RT_{1/2}$ for 8 ms ($p = 0.052$) or the increase of the muscle contraction speed and relaxation of the twitch after WUP 1 is a result of the increased muscle temperature as well as other physiological mechanisms triggered by warming up. The speed of AP increases along with the rise in muscle temperature (36, 37). This can be explained by a faster opening and closing of the Na^+ channels in the muscle, which shortens the time for Na^+ diffusion into the muscle and causes an increase in the speed of AP spreading along the muscle fiber (33). With the rising muscle temperature the activity of ATPase is increased (35), and inner passive muscle stiffness is reduced (11, 31), which also causes a change in the speed of muscle contraction. Because of technical restrictions we only measured muscle surface temperature (skin). Muscle surface temperature and deep muscle temperature cannot be compared directly as skin and muscle fascia are efficient insulators. This is the reason the 2 temperatures differ, and the difference is further increased with the production of temperature in the muscle (8). With regard to the muscle surface temperature increase by 1.3° C after WUP 1 and 1.2° C after WUP 2, if we take into account the laws about the difference in skin and deep muscle temperature (8), we can assume that during the 2 warm-up procedures muscle temperature increased similarly. The shortening of the time parameters of muscle contraction (CT, $RT_{1/2}$) and an increase in torque (T_{TW}) after WUP 1 is also a result of other physiological processes in the muscle cell which are not connected with temperature change (the release of Ca^+, its bond with troponin, and the speed of Ca^+ return to sarcoplasmatic reticulum [16]). We can conclude that the intensive components of WUP 1 contribute to the desired muscle characteristic changes. This is further confirmed in studies (6, 10, 14, 30) that found that after passive warm-up of the thigh, vertical jump/power output during vertical jump increased by 3.1% per 1° C rise in temperature, while after active warm-up muscle power parameters during vertical jump improved by 4.2–4.4% per each °C of increased muscle temperature.

After WUP 1 maximal twitch torque was increased by 17% ($p < 0.001$), while MVC torque was increased by 12% ($p < 0.01$). WUP 2 caused a similar trend of T_{TW} and T_{MVC} change, but it was not statistically significant. Similar values of postactivation potentiation (PAP) after active warm-up which included sprinting and voluntary muscle contractions were also recorded by Gullich and Schmidtbleicher (18), Young et al. (44), Hamada et al. (20), and Gossen and Sale (15). A higher speed of developing muscular force and a greater muscle force contribute to the runner's efficiency in several ways. Muscle power and force-time ratio influence the time and dynamic parameters of the support phase of the running stride. Greater power facilitates a shorter braking phase during support and thus a more economical running action (43). The force-time ratio depends on the muscle fiber ratios in a particular muscle (40). How the neuromuscular potential of a runner will be used during workload also depends on preparation (warm-up). Bounding and sprinting as part of a warm-up are not only important in the improvement of the contractile characteristics of the peripheral muscle system, their influence is also seen in the complex of the neuromuscular connection.

Studies (2, 27) show that motor unit activation during eccentric and eccentric-concentric (SCC) activity differs from the muscle activation during concentric and isometric muscular work. At SCC a smaller number of motor units is activated, but they are mostly type II muscle fibers. A significantly higher MVC torque increase after WUP 1 than after WUP 2 means that explosive strength exercises of SCC muscle type after WUP 1 activated large motor units to a higher degree than slow running. After WUP 1 the level of muscle activation increased by 12%, while after WUP 2 AL was not changed at all. An increase in muscle activation is above all a result of the increase of the torque after voluntary muscle contraction. After both types of warm-ups, torque at maximal isometric muscular contraction with added electrical stimulation remained unchanged. This is the reason we can conclude that the central nervous system's efficiency is enhanced. It is not yet clear whether the reason for the improvement is improved central input or enhanced excitation of the α-motor neuron. Stretching was a constitutive part of both warm-up protocols; however, in 1 protocol it was the final activity and in the other protocol it was followed by bounding and ballistic exercises. It has been shown (17) that stretching reduces alpha motor neuron pool excitability but only for a very short period after the end of stretching (12). It appears that an acute bout of stretching did not impair the warm-up effect related to maximal voluntary strength but reduced balance and prolongated reaction/movement time (4). If stretching is prolonged, it will impair muscle activation as well (5). The way the stretching was performed in the present study corresponded to regular praxis of athletes. It is possible to assume that such stretching affects maximal voluntary activation (observed in the present study) as well as other sensor motor functions which were not analyzed here and thus reduces warm-up effects. Adding bounding and ballistic actions after stretching may restore voluntary activation.

Practical Applications

A middle distance runner's efficiency depends on different combinations of aerobic and anaerobic power and capacity, running economy, neuromuscular characteristics, and muscular strength. Explosive-strength training (horizontal and vertical bounding and hopping, strength training with weights, and sprinting) improve anaerobic efficiency and mechanical efficiency of running (economy) and, as a result, the level of a middle distance runner's competitive efficiency (29). In events requiring high movement velocity (power), it is of vital importance to ensure, along with a suitable biochemical and physiological state, that before the start the runner's neuromuscular system is as efficient as possible.

Our study shows that warming-up with dynamic explosive-strength exercises such as bounding and sprinting contributes to the acute improvement of the neuromuscular system and leads to a better performance in training and competition. A more complex and intensive warm-up resulted in the potentiation of the contractile complex of the skeletal muscle and in the enhancement of muscle activation, which means that the neuromuscular system has improved in efficiency. Horizontal bounding and sprinting, which follows a more general warm-up with jogging, can be a form of successful precompetition preparation (warm-up) in longer sprints and middle distance events.

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