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Optimization of Training: New Developments in Safe Strength Training

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Abstract—The hypertrophic effect of strength training is known to be due to mechanical and metabolic stimuli. During exercises with the restricted blood supply of working muscles, i.e., under the conditions of intensified metabolic stress, the training effect may be achieved with much lower external loads (20% of one repetition maximum). The effects of 8 weeks of high-intensity (80–85% of one repetition maximum) strength training were compared to low-intensity (50% of one repetition maximum) training without relaxation. The high-intensity strength training resulted in higher increases in strength and size of the exercised muscles than training without relaxation. During high-intensity training, at the muscle cross section, an increase in the area occupied by type II fibers prevails; while, during training without relaxation, an increase in the area occupied by type I fibers prevails. An exercise session without relaxation leads to a more pronounced increase in the secretion of the growth hormone, insulin-like growth factor-1, and cortisol. The expression of gene regulating myogenesis (*Myostatin*) is changed in different ways after a high-intensity strength exercise session and after an exercise session without relaxation. Low-intensity strength training (50% of one repetition maximum) without relaxation is an efficient way for inducing increases of the strength and size of the trained muscles. This low-intensive type of training may be used in rehabilitation medicine, sports, and fitness.

Keywords: strength training, skeletal muscle, muscle fibers, anabolic hormones, gene expression

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Health-enhancing physical activity is a potent natural drug-free way to improve the state of the human body. Aerobic exercises, which have been intensively studied, are practiced to improve the cardiovascular and respiratory systems. However, training in the anaerobic mode (strength training) has a more pronounced effect on the musculoskeletal system. Strength training is an effective method to prevent decreases in the volume of skeletal muscles and their strength, as well as to prevent regulatory disorders that are related to these decreases. To date, it has been proved that the use of strength training can slow the progression of age-related osteopenia and sarcopenia, as well as the metabolic syndrome and the related obesity, hyperlipidemia, and hypertension; it can also reduce the development of rheumatoid myopathy and other kinds of myopathy [1].

Widespread use of strength training in prevention and rehabilitation is hampered by the absence of a scientific approach to the optimization of training loads. It is obvious that excessively small training loads are ineffective, whereas excessive muscular contractions, in addition to the risk of injuries of the musculoskeletal system, may cause pronounced changes in the functioning of the autonomic vicseral systems (e.g., high blood pressure, which increases the load on the heart). In this respect, there is an obvious need for safe weight training modes, which do not cause undesirable changes at the system level but provide the changes in the metabolic processes in working muscles sufficient to activate the growth of the muscle cells, i.e., the activation of intracellular signaling pathways and increasing the expression of genes-regulator of myogenesis. The solution to this problem should be based on a scientifically substantiated system of creating specific loads on the muscular system in order to correct irregularities in the functioning of both the muscle and systemic regulatory mechanisms.

In this study, a method of low-intensity strength training is described. This method involves training without full muscle relaxation. It allows the strength of the trained muscles to be increased compared to traditional strength training, and, at the same time, the method is injury-free.

The hypertrophic effect of strength exercises is related to the influence of both mechanical and metabolic stimuli. It is well known that strength exercises impair cell membranes, which is confirmed by the significant increase in the activity of creatine kinase (CK)

in the blood 15–20 h after high-intensity strength training [2]. Mechanical stress, which is transmitted to the extracellular matrix of the muscle cell, can influence the expression of gene that regulate myogenesis, intracellular signaling, and control the rate of protein synthesis in muscle cells [3]. Such changes should be expected, firstly, in strength training using high-intensity loads. This approach to strength training is very widespread; thus, hereinafter, it is called the traditional strength training. The main disadvantage strength training is the high risk of injury of the musculoskeletal system in connection with the use of high training loads (75–90% of one repetition maximum (1 RM)).

However, it is well known that strength exercises are accompanied by the accumulation of metabolites in muscles. The energy supply of the working muscle is mainly due to anaerobic metabolism, including the pronounced activation of glycolysis. Due to the degradation of creatine phosphate, in the muscle, there is a marked increase in the content of creatine [4, 5], which is the factor that stimulates anabolic processes [6, 7]. In muscles and blood, there is a significant increase in the content of lactate, which, in turn, stimulates the secretion of anabolic hormones [8–10]. There is an increase in the content of the somatotropic hormone, testosterone, and insulin-like growth factor 1 in the blood [11–14]. These metabolic changes may alter signaling and the expression of genes regulating myogenesis in muscle fibers [15–17]; and they may be related to an increase in the muscle mass and strength [5]. Based on these considerations, there were a number of attempts to potentiate the effects of strength training using exercises under the conditions of the restricted blood supply of the working muscles, when metabolic changes are intensified, and, hence, the training effect could be achieved by using lighter external loads. Limiting the blood supply was achieved with the help of occlusive cuffs [18–20] or by creating high pressure on the lower half of the body when a subject was placed in the pressure chamber [10, 21, 22]. However, the practical use of this approach is related to significant inconvenience to the subjects. Therefore, attempts were made to achieve similar effects by using more convenient and accessible approaches.

It is well known that, during the static tension, blood flow in a working muscle is reduced, and sometimes completely absent; i.e., the conditions are similar to occlusion. It is well known that exercises in a static (isometric) mode are not very efficient for increasing the dynamic strength [23]. However, during the traditional strength training, continuous restriction of the local blood flow cannot be achieved. This contradiction was successfully resolved by developing a hybrid method of strength training, including static and dynamic components [24]. The method is based on the absence of relaxation of the working muscles in the final phase of the training movement. This mode of training is called the low-intensity method of strength training without relaxation.

It was shown using nuclear magnetic resonance spectroscopy in vivo that, during low-intensity exercises with a restricted blood flow (30–40% 1 RM), metabolic changes in the working muscle are comparable with the changes that occur during traditional high-intensity strength training [25]. The authors conclude that, in order to achieve significant metabolic changes during exercises with restricted blood flow, the load should be at least 30–40% of 1 RM. Note that, in the vast majority of studies on the effects of strength training with restricted blood flow, the loads were 20% of 1 RM. These studies involving untrained people or elderly subjects have shown the efficiency of the training programs used to increase their strength and muscle mass [5, 17, 20, 26, 27]. It is likely that exercises with such loads are suitable for rehabilitation; however, we assume that these loads will be insufficient for the activation of protein synthesis in the muscles of physically active people. Also note that there are few studies comparing the efficiency of exercises with a restricted blood flow and traditional strength training [17, 27].

In this paper, we consider various modes for using the method of strength training without muscle relaxation with loads that are 50–70% of 1 RM, as well as regulatory changes resulting from this training, both at the level of the whole body and within the working muscles, including the changes in the expression of the gene-regulating myogenesis. In addition, we present a comparison of the effects of strength training without muscle relaxation and traditional high-intensity strength training.

MATERIALS AND METHODS

We compared the effects of 8- to 10-week traditional strength training (80–85% of 1 RM) and training without relaxation with various loads (50–70% 1 RM) in leg and knee extensions (L series and K series) on the strength and morphological characteristics of the working muscles, as well as on the biochemical parameters of blood and the hormonal status. We also studied the effect of a single training session described above on the expression of genes regulating myogenesis.

L series. Young, physically active male subjects trained their leg extensor muscles (leg extension, L series) for 8 weeks. Nine subjects from the control group (LC group) trained according to the traditional strength training routine; the remaining nine subjects constituted an experimental group (LE group) and performed low-intensity strength training without relaxation. The developing training for the LC group included seven sets with 10-min rest periods between them. During each set, the training with a load of 80–85% of 1 RM was performed to exhaustion (6–12 reps). The training movements (leg extension) were performed with the greatest speed possible for them. The time ratio of muscle tension and relaxation in this group was about 50% to 50%. For the LE group, the training session included 4 supersets for 3 sets, each with a load

of 50% of 1 RM. The duration of the set was 50–60 s, the rest intervals between them were 30 s, and the intervals between the series were 10 min. The training movement was slower approximately by 3.5 times than during the traditional strength training, at a constant speed. In this group, continuous maintenance of muscle tension was achieved because the subjects did not carry the working platform to the extreme position and immediately began to move in the opposite direction. During this training, the amplitude of movements was approximately 15% smaller than the amplitude during traditional strength training. Thus, in this group, the ratio of the times of muscle tension and relaxation was 100% to 0%.

In order to evaluate the effect of two types of training on the size and strength of the muscles involved in the movement, before and after the experiment, the 1RM for the trained movement was measured. We additionally tested the force-velocity characteristics of the two main muscle groups involved in this movement, the extensors of the hip and knee joints, in the isokinetic mode, at the angular velocities of 30, 180, and 300 deg/s. In addition, we estimated the local performance of the knee extensor muscles. The volumes of m. quadriceps femoris and m. gluteus maximus were calculated based on magnetic resonance imaging (MRI); the area occupied by the muscle fibers of the first and second types (MFI and MFII) on a cross section of m. vastus lateralis, as the product of the percentage composition of the fibers of this type in the muscle by the average muscle fiber cross-sectional area of this type.

K series. Thirteen young, physically active men trained the knee extensors (K series) for 10 weeks. Nine subjects (KC group) used the traditional strength training, and four subjects (KE group) used the low-intensity strength training without relaxation. Training protocols were the same as in the L series.

The 1 RM of the knee extensor muscles were measured before and after 10 weeks of training in the isokinetic mode, with the angular velocities of 30, 120, 180, 240, and 300 deg/s.

The cross sectional area of the muscle fibers of the two types and the area that they occupy were determined in the same way as in the L series.

During the *M series*, the experimental group trained with middle intensity. The experiment was organized according to the following scheme: two groups of ten subjects each were compared to each other. For the control group (MC group), the subjects of which trained in the usual way of traditional strength training, each session consisted of seven sets with 5-min rest periods between them. During each set, the work with a load of 85–90% of 1 RM was performed to exhaustion (6–10 reps). In the experimental group (medium intensity training without relaxation, ME group) a session consisted of five supersets, each of which had four sets. The loads were 65–70% of 1 RM; the duration of one set was 40–50 s; the rest intervals between them were 30 s; and the rest periods between the series were 5 min.

As can be seen from the above, the workload for the E group was increased in comparison to the series described previously due to the greater intensity of exercising (65–70% vs. 50% of 1 RM in the previous experiment), and an increase in the number of sets. This allowed us to equalize the total amount of training performed by the MC group and the ME group. In addition, the duration of the rest periods in this group was reduced from 10 min to 5 min.

Before and after the training cycle, the strength of the trained muscles, as well as the size of the muscles and muscle fibers of two types, were measured.

Evaluation of hormonal adaptation during the eight-week strength training. The exercises and training protocol were the same as in the series with leg extension (L series). Leg press 1 RM, the strength of the knee extensor muscles in the isokinetic mode, and the size of the m. quadriceps femoris and the two types of muscle fibers in its lateral head were evaluated before and after the eight-week training.

The effect of strength training of varying intensity on the biochemical and hormonal blood parameters was evaluated by the acute response to a traditional training session (comparison of the parameters after a single training session with the baseline levels at rest) at the beginning (in the second week) and at the end (seventh week) of the training cycle. The lactate concentration, the content of growth hormone (GH), insulin-like growth factor 1 (IGF-1), testosterone, and cortisol were determined in the blood. Before and 18 h after the training session, the total activity of creatine kinase (CK) and the activity of its cardiac isoform (MB CK) were determined in the blood. The activity of CK from the striated muscle fibers (MM CK) was calculated.

Changes in the expression of genes regulating myogenesis in response to a single training session. The effects of a training session with the knee extension according to the traditional strength exercise scheme (75% of 1 RM_{tr}) was compared to the normal low-intensity exercise (50% of 1 RM_{tr}) and to low-intensity strength exercise without relaxation (50% of 1 $RM_{no\ relax}$) that were equal in terms of the time of muscle tension and the range of motion. The study involved young men adapted to strength training. The changes in gene expression in the muscle sample were determined before, 5 h after, and 22 h after a single training session using the real-time polymerase chain reaction.

On the day of the experiment, the subjects had a standard breakfast; and 1 h after the completion of training session, they had a standard lunch. Before training session and 15 min after the completion of exrcise, samples of venous blood were taken to determine the levels of the hormones. During session after the third, fifth, and eighth sets, finger samples of the capillary blood were taken (20 μL) to determine the concentrations of lactate and glucose. Before the training, as

well as 5 h, and 22 h after the training, using the microbiopsy technique [28], a sample of the muscle tissue was taken from the m. vastus lateralis.

The strength gain and fatiguability of the trained muscles, the sizes of the muscles and the sizes of muscle fibers of the two types and the biochemical changes in the blood were determined before and after the training cycle.

Evaluation of the force-velocity characteristics and fatigueability. In order to evaluate the effect of two types of training on the strength gain, before and after the experiment, one repetition maximum (1 RM) was determined by the maximum weight that the subject could lift once. An additional testing of the force-velocity characteristics of the two main muscle groups that take part in the movement, the hip and knee extensors, was performed using a Pro System 3 dynamometer (Biodex, United States) in isokinetic mode, at the angular velocities of 30, 120, 180, 240, and 300 deg/s.

The assessment of local performance (fatigueability) of knee extensors was carried out in a 45-s test with the maximum isometric force. The dynamics of a decrease in the torque, normalized to 1 RM, was evaluated during the test.

The estimation of the morphometric parameters of the muscles and muscle fibers. The volumes of m. quadriceps femoris and m. gluteus maximus were calculated on the basis of MRI. The MRI study was carried out using a Magnetom 63SP tomograph (Siemens, Germany; magnetic field, 1.5 T) by the spin-echo method in the transverse plane. On each of the images obtained, the cross-sectional areas of m. quadriceps femoris and m. gluteus maximus were determined; then, taking into consideration the distances between the shots (17 mm), the volume of the muscle was calculated. The results contain the averages of the volume of the muscles of both legs.

The cross-sectional areas of the muscle fibers of types I and II were evaluated on the transverse sections of the biopsy samples (m. vastus lateralis), taken using a needle biopsy technique [29]. Muscle tissue samples were frozen in liquid nitrogen and stored at −70°C. Prior to the analysis, serial sections perpendicular to the muscle fibers, with a thickness of 5 μm were made of frozen (−20°C) tissue samples using a microtome (Leica, Germany). Muscle fibers of types I and II were detected by immunohistochemistry using NCL-MHCf (a + b) and NCL-MHCs monoclonal antibodies (Novocastra Laboratories). Then, secondary antibodies labeled with FITS were used. The measurements were made using an Axiovert-200 microscope (Carl Zeiss, Germany). For each of the tissue samples, the values of at least 100 fibers of each type were taken in the counting.

The area occupied by the muscle fibers of the first and second types (MFI and MFII) in the cross section of m. vastus lateralis, was evaluated as the product of the percentage of fibers of this type in the average muscle fiber cross-sectional area of this type.

Estimation of hormones and metabolites in the blood and gene expression in the muscle tissue. The concentrations of lactate, somatotropic hormone, insulin-like growth factor 1 (IGF-I), testosterone, and cortisol were determined in the blood. Before and 18 h after the workout, the total activity of creatine kinase and its cardiac isoenzyme (CK and MB CK, respectively) in the blood were determined. The activity of CK from the striated muscle fibers (MM CK) was calculated as the difference between CK and MB CK. The concentrations of hormones and enzymes were determined by ELISA using DSL (United States) test kits.

RNA isolation. RNA isolation from the muscle tissue samples was performed using a TRIZOL set (Invitrogen, United States). The complementary DNA was obtained using the Sileks set (Russia).

Polymerase chain reaction. The real-time PCR was carried out with a RotorGene Q thermocycler (Qiagen, Germany), using a Sybr Green set (Synthol, Russia). In the samples, the expression of insulin-like growth factor 1 (IGF-1Ea) and myostatin genes was determined. The genes of the large ribosomal protein P_0 and β-actin were used as reference genes. The changes in the expression of the target gene were determined according to [30], with the calculation of the efficiency of the reaction for the target and reference genes by the standard curve.

RESULTS AND DISCUSSION

Strength training of the leg extensors (L series). The effect of traditional training on the strength of the working muscles and the size of their muscle fibers (MFs) was compared to the effect of low-intensity strength training without muscle relaxation [31]. Strength training in both modes resulted in an increase in 1 RM of the leg press. However, in the LC group, where the subjects trained according to the traditional strength training protocol, the increase in 1 RM was 34% of the original level; while in the LE group, the increase in 1 RM was 21% (Table 1). We assume that the greater increase in 1 RM was related to the larger training loads. Indeed, the total work performed during the entire training cycle during traditional strength training was approximately twice as much as the total work performed during the low-intensity strength training without relaxation (Table 1). This difference was due to both the exercise intensity and the amplitude of leg extension; as in the LE group, each of these parameters was lower than the respective parameter in the LC group.

The maximum strength of the individual muscle groups involved in the movement trained were determined by isokinetic dynamometry. No differences were recorded in the gain of the torque of the knee extensor muscles; whereas, in the LC group, the gain in the torque of the hip extensor muscles was greater compared to that in the LE group in the wide range of angu-

Table 1. The comparison of the effects the traditional high-intensive strength training (control groups, C) and training without muscle relaxation (experimental groups, E) during leg extension series (L series), knee extension series (K series), and leg extension series, when the group trained with middle intensity (M series)

Group	Work, kJ	1 RM gain, %	Area of MFI, gain, %	Area of MFII, gain, %
		L series		
LC group (80% 1 RM)	1604 ± 62	34 ± 3.1*	9.4 ± 3.9	23.4 ± 8.3*
LE group (50% 1 RM)	834 ± 44§	21 ± 2.5*§	17.7 ± 6.8*	8.2 ± 3.59
		K series		
KC group (80% 1 RM)	951 ± 60	29 ± 5.8*	6.5 ± 4.3	19.4 ± 5.3*
KE group (50% 1 RM)	400 ± 27§	24 ± 3.6*	17.7 ± 5.3*	5.6 ± 4.3
		M series		
MC group (85% 1 RM)	2100 ± 31	33.5 ± 3.9*	5.7 ± 4.5	33.0 ± 5.1*
ME group (65% 1 RM)	2188 ± 33	30.1 ± 4.8*	18.1 ± 6.9*	6.2 ± 3.8

Note: The total work for the entire training cycle; the gains in one repetition maximum (1 RM), and the areas occupied by the muscle fibers of the first and second types (MFI and MFII) on a cross section of m. vastus lateralis are shown. * Significant gain compared from the baseline ($p \le 0.05$); § significant difference from this parameter in the control group.

lar velocities (Figs. 1a and 1b). Therefore, we assume that the increase in leg press 1 RM in the LE group was mainly due to the gain in the strength of the knee extensor muscles, rather than to the gain in the strength of the hip extensors.

The difference in the gain of the 1 RM of the individual muscle groups is consistent with the MRI data (Fig. 1c). The eight-week training resulted in a comparable increase (by 10–15%) in the volume of m. quadriceps femoris in both groups. However, an increase in the volume of m. gluteus maximus was recorded only in the LC group; in addition, this increase was greater than the respective increase in the LE group (Fig. 1c).

Apparently, the differences in the gains in strength and volume of the muscles are related to the redistribution of the load between the muscles during leg extension. As noted above, the amplitude of movement in the groups performing low-intensity strength training was approximately 15% less than in the group that trained according to the traditional scheme. It is well known that the strength of the skeletal muscles depends on their length (the strength–length relationship). For the hip extensors, the optimal muscle length (the length at which a given muscle develops the maximum force) is recorded in the position of a flexed hip [31]. In the LE group, the extensor muscles of the hip did not achieve their optimal length during exercising due to the lower amplitudes of their movement. As a result, during low-intensity strength training without relaxation, in the L series, the hip extensors developed smaller strength, and, consequently, they obtained a smaller training effect than during the traditional training. For the knee extensors, the decrease in the amplitude did not affect the biomechanics of contraction, as the optimal length of this muscle group corresponds to 110 degrees [31], i.e., to the middle position between full leg flexion and full leg extension in the knee joint.

Both types of muscle fibers are involved in the high-intensity muscle contraction [32]. At the same time, it is well known that the traditional strength training leads to more severe hypertrophy of type II muscle fibers than of type I muscle fibers [33–36]. Probably, the reason is that high-intensity muscular work causes more pronounced metabolic changes in the type II muscle fibers than in type I fibers. This leads to greater activation of the mTORC1 and ERK1/2 signal pathways, which control protein synthesis [37, 38]. In our study [39], in the LC group, the area occupied by type II muscle fibers in the cross section of the working muscle m. vatus lateralis was increased by 23%, while for type I fibers, it did not change, which is consistent with the data in the literature. However, after a low-intensity strength training without relaxation, qualitatively different changes in these parameters were found: the area occupied by type II muscle fibers did not change, while the area occupied by type I muscle fibers increased by 18% (Table 1). We hypothesized that the marked metabolic stress in the muscle fibers could be one of the factors that initiate the process of hypertrophy. It is difficult to achieve the marked metabolic shifts in type I muscle fibers [40], since the fibers of this type have a high oxidation potential. However, it was shown that, during isometric contractions (under the conditions of the restricted blood flow caused by muscle tension) with intensities of 25, 50, and 75% of 1 RM, the maximal lactate concentration in m. vastus lateralis at the exhaustion was recorded when the intensity was 50% of 1 RM, with the largest concentration of lactate found in type I muscle fibers [41, 42]. Apparently, this is due to the fact that, according to the principle of dimension, work of this character

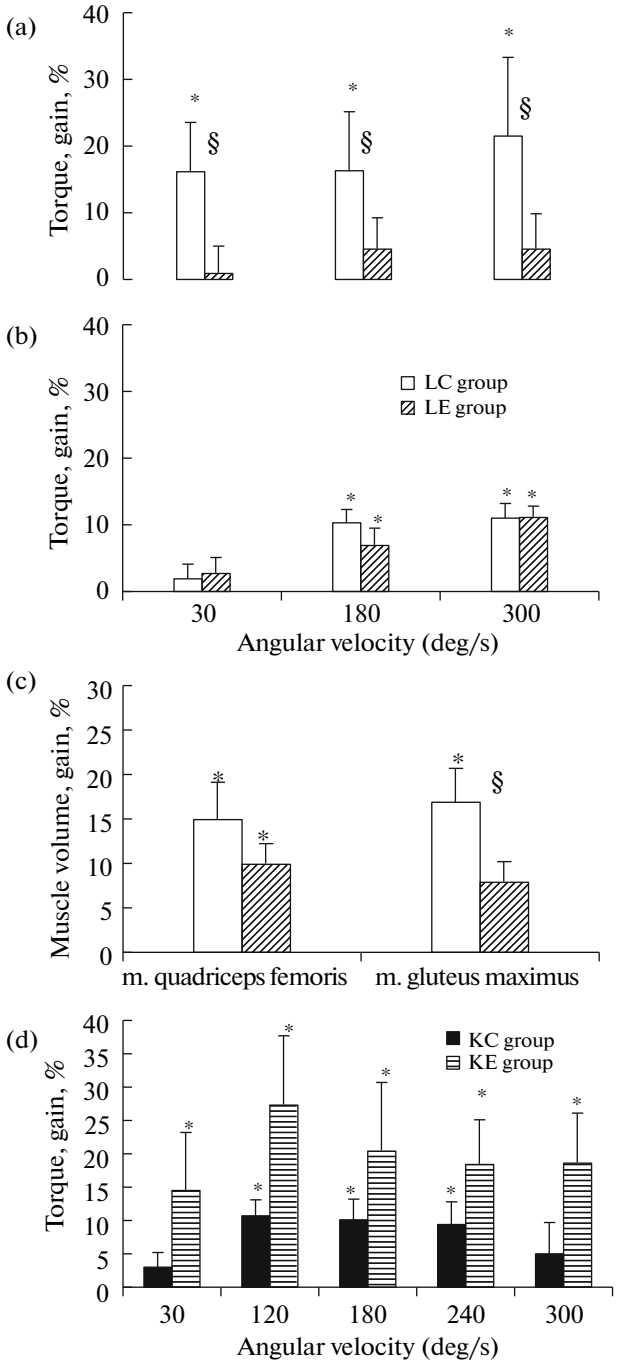

Fig. 1. The changes in the torque at different angular velocities of the hip (a) and knee (b) extensor muscles; (c) the cross-sectional areas of m. quadriceps femoris and m. gluteus maximus estimated by MRI in the L series; and (d) the changes in the torque at different angular velocities in the K series. * Significant ($p \le 0.05$) gains compared to the baseline levels; § significant ($p \le 0.05$) difference of experimental (E) group from the respective parameter in the control (C) group. For the abbreviations here and in Fig. 2, see the text.

should primarily engage type I muscle fibers [32], in which, due to the limited blood flow, the activation of glycolysis occurs. This provides grounds to assume that, during the low-intensity strength training without relaxation, with an intensity of 50% of 1 RM, as well as during isometric exercises, primarily, type I muscle fibers are involved in the performance, which allows the marked metabolic shifts in them to be achieved at exhaustion. Note that, in the LE group, the termination of each set was accompanied by severe subjective fatigue of the working muscles. At the same time, the concentration of blood lactate, which is the marker of the activation of glycolysis, during the training session in the LE group was higher than that in the LC group (see below).

The increase in the resistance of the trained muscles to fatigue in the 45-s maximal isometric test compared to the traditional strength training is one of the expected effects of the low-intensity strength training without relaxation. In assessing the resistance to fatigue in the static test, it was found that, in the LC group, there was a decrease in this parameter after the eight-week training cycle, while in the LE group, it did not change compared to the baseline levels before the training [39].

Thus, it has been shown that there was an increase in the muscle mass and strength after eight weeks of low-intensity (50% of 1 RM) strength training without relaxation. Note that the increase in the muscle mass after eight weeks of low-intensity strength training without relaxation is related to the hypertrophy firstly of type I muscle fibers, while the traditional strength training leads to the hypertrophy preferentially of type II muscle fibers. In the this study, the effects of exercises in the L and K series were compared. Note that studying leg extension is associated with a number of methodological restrictions for analysis, which is due to the specifics of biomechanics and the control over complex motor actions, with the redistribution of efforts between different muscle groups, etc. With this kind of training, the objective assessment of a variety of physiological and morphological responses at the level of individual muscle groups may be difficult. Therefore, the data obtained during a 10-week training of a knee extensors are of particular interest.

Strength training of the knee extensors; K series. The effects of the traditional strength training with an intensity of 80–85% of 1 RM (control group, KC group) were compared to the effects of low-intensity strength training without relaxation, with an intensity of 50% of 1 RM (experimental group, KE group). The total work done during a 10-week training cycle differed in the KC group and KE group by more than two fold (Table 1). At the same time, the gains in 1 RM of the knee extensor muscles in the trained exercise did not differ, being 29 and 24% in the KC group and KE group, respectively (Table 1).

Analysis of the gains in 1 RM during training in the L series and K series showed significant differences. In the K series, the gain in 1 RM after traditional strength training is greater than that after low-intensity training without relaxation (35% vs. 21%); while in the K series, no differences between the groups were recorded (29%

vs. 24%). Apparently, these differences are related to the features described above of the biomechanics of the muscles during leg and knee extension, namely, the redistribution of the load between the muscles.

Assessing the effect of a 10-week training of the knee extensors on the area occupied by muscle fibers of different types in the cross section of m. vastus lateralis showed similar gains in type II muscle fibers in the KC group and type I muscle fibers in the KE group (Table 1), which is in good agreement with the results obtained during training in L series.

Thus, based on the comparison of the effects of the prolonged training of the knee and leg extensor muscles, we conclude that (1) the degree of hypertrophy of the knee and hip extensors during training in leg extensors depends on the biomechanics of the exercise; (2) as a result of the redistribution of the load between the muscles, the strength gain of the knee extensor muscles during leg extension low-intensity training without relaxation is lower than that during traditional strength training; (3) in the case of training of knee extensors, low-intensity strength training without relaxation can result in the same increase in strength of knee extensors muscle as the traditional strength training; (4) low-intensity training without relaxation of the knee extensor muscles, as well as training of the leg extensors, results in an increase in muscle strength, mainly due to the hypertrophy of type I muscle fibers.

So far, we compared the effects of traditional strength training (80–85% of 1 RM) and low-intensity training (50% of 1 RM) without relaxation. In the LE group, the increase in the strength was smaller than in the group that trained with a high intensity, which could be due to lower intensity and volume of the work performed. We assume that, during training with incomplete relaxation, a slight increase in the intensity (from 50% of 1 RM to 65–70% of 1 RM) and an increase in the work performed during a training session (to the levels of traditional strength training) could provide an increase in strength comparable to their increase during traditional high-intensity strength training.

Strength training of medium-intensity without relaxation (M series). The scheme of the experiment comparing two groups of subjects was described above. The subjects trained leg extension. In the control group (MC group), which practiced traditional strength training, the load was 85–90% of 1 RM. In the experimental group (medium intensity training without relaxation, ME group), the load was 65–70% of 1 RM. The workout of the ME group was increased compared to the series previously described due to the greater intensity of the load (65–70% of 1 RM versus 50% of 1 RM in the preceding experiment) and the increase in the number of sets. This allowed us to equalize the total work performed by the MC group and ME group. Furthermore, in the ME group, the duration of the rest periods was reduced from 10 min to 5 min.

The total work performed during the 8-week training period was 2100 ± 31 kJ for the MC group and 2188 ± 33 kJ for the ME group, so it did not differ between the groups (Table 1). Gains in the leg press 1 RM over 8 weeks in the MC group and ME groups were 34% and 30%, respectively, i.e., no differences between the groups were recorded (Table 1).

Assessing the physiological and morphological parameters of the knee extensor muscles showed the same gains in 1 RM in isometric mode (8.0 ± 3.2% in the ME group and 7.2 ± 3.5% in the MC group) and the same gains in the volume of m. quadriceps femoris evaluated by MRI (9.8 ± 1.6% in the ME group and 6.8 ± 2.4% in the MC group).

As in the group that trained with low intensity without relaxation, in the group that trained with middle intensity without relaxation, an increase (18.1 ± 6.9%) was found in the area occupied by type I muscle fibers in the cross section of m. vastus lateralis, and no increase was found in the area occupied by type II muscle fibers (Table 1). In contrast, in the group that used traditional strength training, there was an increase in the area occupied by type II muscle fibers (by 33.0 ± 5.1%), and no changes were found in the area occupied by type I muscle fibers. Thus, training without relaxation with an intensity of about 65–70% of 1 RM can increase the strength to the same extent as traditional high-intensity strength training.

When comparing the effects of strength training and low-intensity training without relaxation, the question about the mechanisms of the gain in the muscle mass naturally arises.

An increase in the muscle mass and strength during low-intensity training without relaxation is related to hormonal adaptation. As noted above, muscle hypertrophy can be activated by mechanical and metabolic factors. Both kinds of factors can activate protein synthesis either directly, by affecting the muscle fiber, or indirectly, through increased secretion of anabolic hormones. We attempted to answer the question on which of these factors (mechanical or metabolic) is more important for triggering the hormonal response to muscle activity, and determine the mechanisms of hypertrophic changes in the muscle tissue when using different types of training.

There is evidence that an increase in the concentration of the growth hormone is related to the activity of Ia muscle afferents [43]. However, many authors attribute the increased concentrations of anabolic hormones to metabolic changes in the working muscles [8, 9, 44, 45]. Indeed, it is shown that limb ischemia potentiates the hormonal response when performing strength [20] and aerobic exercise [10, 20].

In our study [46], we hypothesized that the restriction of the blood supply of the working muscles during low-intensity training without relaxation serves as a stimulus for the secretion of anabolic hormones. The

Table 2. The changes in the blood concentrations of lactate, somatotropic hormone (GH), insulin-like growth factor (IGF-1), testosterone, cortisol, and the activity of muscle creatine kinase (MM CK) in response to a single training session in week 2 and week 7 of traditional high-intensive strength training (80% of 1 RM, C group) and low-intensity (50% of 1 RM) training without muscle relaxation (E group)

Parameters	C group				E group			
	week 2		week 7		week 2		week 7	
	before	after	before	after	before	after	before	after
Lactate, mM	2.2 ± 0.2	8.5 ± 0.6*	1.8 ± 0.2	12.3 ± 1.0*	2.4 ± 0.3	13.2 ± 1.8*	2.5 ± 0.3	14.5 ± 1.4*
MM CK, MU/L	176 ± 30	435 ± 76	106 ± 24	255 ± 42	145 ± 32	283 ± 61	123 ± 9	182 ± 11
GH, ng/mL	0.22 ± 0.02	3.47±0.76*	0.20 ± 0.05	6.30 ± 2.82*	0.27 ± 0.03	9.09 ± 1.37*	0.20 ± 0.03	8.29 ± 1.41*
IGF-1, ng/mL	277 ± 39	259 ± 29	276 ± 27	266 ± 30	320 ± 50	350 ± 47*	304 ± 17	372 ± 30*
Testosterone, nmol/L	13.89 ± 2.43	14.24 ± 2.78	12.15 ± 1.74	13.89 ± 2.08*	9.72 ± 1.04	11.81 ± 2.08	7.99 ± 1.74	8.68 ± 2.08
Cortisol, nmol/L	195 ± 19	259 ± 37	253 ± 22	341 ± 53	154 ± 18	264 ± 29*	187 ± 14	358 ± 30*

* Significant ($p \le 0.05$) gains compared to the baseline levels.

training protocols were the same as in the L training in the study described above [39].

It was found that the traditional strength training (85% of 1 RM) and low-intensity training without relaxation (50% of 1 RM) cause different changes in the blood lactate concentration and in the activity of the muscle isoform of creatine kinase (MM CK). Lactate is the final product of glycolysis. Since, during strength exercise, the energy supply is provided mainly by the anaerobic pathway and the level of blood lactate indirectly shows the intensity of metabolic processes in the working muscles. As expected, the restriction of the blood supply of the working muscles was accompanied by a marked increase in the concentration of the lactate in the blood. At the beginning of the eight-week training cycle (during week 2), after the training session, the blood lactate concentration during traditional strength training (C group) increased by 6.3 mmol/L; however, after low-intensity strength training without relaxation (E group), it increased by 10.8 mmol/L (Table 2). In the final period of the training cycle, the differences between the groups became less marked. Thus, the concentration of blood lactate after a session of training with incomplete relaxation, despite the lower volume of work, was greater rather than less than that after the session of training in the traditional way.

It is well known that the release of musclular CK in blood indirectly reflects the extent of damage of the cell membrane of working muscles and depends on the load. For example, during the eccentric exercise, the increase in activity of CK is greater than that during the concentric exercise [47–49]. In our study [46], an increase in the activity of MM CK during week 2 of the training cycle was 73% greater in group C (traditional strength training) than that in group E (low-intensity training without relaxation) (258 ± 69 IU/L vs. 149 ± 36 IU/L), which is likely to be due to the greater training load in group C (85% of 1 RM vs. 50% of 1 RM, respectively). Probably, in the subjects of group E, the restriction of blood flow in the working muscle did not potentiate the damage of the membranes of muscle fibers. This is consistent with the finding that occlusion of the working limb does not increase the activity of CK in the blood: one day after low-intensity strength training (20% of 1 RM) with the occlusion of working muscles (214 mm Hg), the level of CK was the same as in the control group exercising without occlusion [20].

Comparing the changes in the concentrations of lactate and MM CK during two types of training load used in our study [46], we suggest that the traditional strength training causes greater mechanical damage to the muscle fibers, increasing the release of MM CK in the blood. At the same time, after the training session with incomplete relaxation, intensified glycolysis leads to a significant accumulation of lactate in the blood. Thus, traditional training generates predominantly mechanic-related stimuli that can trigger anabolic processes in muscle fibers, whereas after training with incomplete relaxation, metabolic changes develop more intensely. If we assume that the main feature of exercise with incomplete relaxation is the restriction of the blood supply in working muscles, then we should consider the data on training under the conditions of occlusion in our discussion on the mechanisms of hypertrophic response. For example, according to [21, 22], a four-week aerobic exercise (cycling 4 times a

week for 45 min, load ~20% of 1 RM) in a hermetic chamber with extra pressure on the lower half of the body of 50 mm Hg leads to an increase in the cross-sectional area of the trained muscles, and an increase in the cross-sectional area of the muscle fibers predominantly of types I and IIB. The authors attribute hypertrophy to both an increase in contractile proteins, and an increase in glycogen and hyperhydration. Similar results were obtained in the study on elite rugby players performing an eight-week ischemic (cuff pressure, 200 mm Hg) low-intensity strength training (twice a week, 4 sets, 50% of 1 RM) [50]. The gains in the dynamic force, and the cross section (MRI) of the knee extensors in this study were 14 and 15%, respectively. Comparing the data on the changes in the specific force and electromyographic activity, the authors come to the conclusion that the increase in the muscle volume is mainly due to contractile proteins.

The increase in the secretion of GH and insulinlike growth factor 1 (IGF-1) can be considered among the factors responsible for the hypertrophic effect due to training against the restriction of blood supply. In our study [46], the concentration of GH in the blood after a training session with incomplete relaxation was higher; although the mechanical effect on the muscle fibers was much smaller than during the traditional strength training (Table 2). It is important that training without relaxation provided a high GH response throughout the entire training cycle. A significant increase in the blood GH was shown previously during aerobic and strength exercise with venous occlusion [10, 20]. According to the authors, this is due to the activation of afferents III and IV in response to the local accumulation of metabolites in the muscles working with limited blood supply (metaboreflex mechanism).

The main system mediator of the anabolic effects of the growth hormone is the IGF-1. It is well known that it is secreted systemically by the liver cells stimulated by the growth hormone and autocrinically, by the skeletal muscle fibers during their intense contractile activity [51]. Thus, an increase in IGF-1 in the blood was recorded after high-intensity strength exercise [12, 14]. In our study [46], increases in the levels of IGF-I in the blood (during week 2, as well as week 7) were recorded only after the training session with incomplete relaxation. After a traditional strength exrcise (characterized by much greater intensity of mechanical loads) no changes in the concentrations of IGF-1 were detected (Table 2). Note that an increase in IGF-1 after exercise with incomplete relaxation occurred against the background of an increase in the secretion of GH (Table 2).

Low-intensity exercise with restricted blood flow caused no increase in the content of testosterone in the blood (Table 2), which is consistent with the data of other authors [52]. At the same time, we note that low-intensity exercise without relaxation resulted in increased cortisol secretion, which, apparently, indicates the high physiological costs of these types of training (Table 2).

Thus, low-intensity (50% of 1 RM) exercise without relaxation leads to higher levels of secretion of GH and IGF-1 in the blood than exercises with larger external loads (85% of 1 RM) performed in the traditional way. Probably, this phenomenon is caused by more intensive accumulation of metabolites in the muscle during training with incomplete relaxation due to the reduced blood flow, which is inevitable with this type of training, as well as under the conditions of muscle ischemia. Note, however, that the mechanisms of metabolic reflectory posteffect stimulation of the secretion of anabolic hormones require further research. In studies on the hormonal response to strength training, the results are mixed. West et al. studied the effects of different levels of endogenous hormones in the blood on the strength gain and muscle hypertrophy [53]. The authors concluded that an increase in the levels of the growth hormone and IGF-1 in the blood caused by the strength exercise is not the main stimulus for the activation of a hypertrophic process in the working muscles. The regulation of the synthesis of muscular protein, in their view, depends mainly on the intracellular mechanical and metabolic stimuli.

Effects of high-intensity strength training and low-intensity strength training without relaxation of muscles on the expression of genes regulating myogenesis. In the past decade, molecular biological techniques have been widely used to study the mechanisms underlying muscle adaptation to various physical activities and to determine the efficiency of different training programs. Analysis of gene expression in muscle cells enables us to evaluate, individually for each subject, the efficiencies of different training protocols based on the results of a single training session. It was shown that a single session of high-intensity strength training alters the expression of myogenic regulatory genes, such as *IGF-1, MGF, MyoD, Myogenin*, and *Myostatin*, during the day of recovery and longer [54, 55]. It was found that low-intensity training (20% of 1 RM) with limited blood flow leads to changes in the expression of the genes studied; whereas in the control group training of the same intensity, the changes in the expression may be absent [56, 57]. This is due to the fact that, during traditional strength exercise, principally greater external loads are used (70–90% of 1 RM); whereas, in the cited studies, the load of 20% of 1 RM was used in control group, which may be too small to cause the changes in the expression of myogenic regulatory genes in the muscles of physically active people. As mentioned above, in order to achieve marked metabolic stress in the working muscle during exercise with restricted blood flow, the load should be at least 30–40% of 1 RM [25]. Therefore, we attempted to compare the changes in the expression of myogenic regulatory genes after strength exercise performed without muscle relaxation (50% 1 $RM_{no\ relax}$), to the changes after the traditional high-intensity strength exercise.

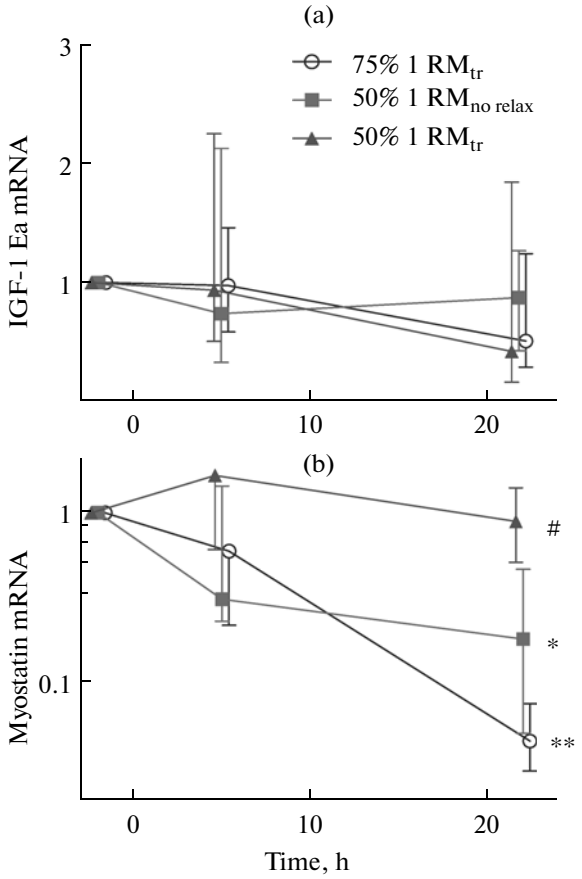

Fig. 2. The expression of mRNA of IGF-1Ea (a) and myostatin (b) normalized to the baseline levels, after a single strength training: traditional high-intensity strength training (75% of 1 RM$_{tr}$), low-intensity training without relaxation (50% of 1 RM$_{no\ relax}$), and traditional low-intensity strength training (50% of 1 RM$_{tr}$). 0 h, the time of the termination of a training session. * Significant changes ($p \le 0.05$) compared to the baseline levels; # significant difference ($p \le 0.05$) from the respective parameter of 75% of 1 RM and 50% of 1 RM

To eliminate the effect of redistribution of the load between different muscle groups during the exercise and the impact of the increased secretion of anabolic hormones on intracellular signaling, the training of knee extensors was chosen. It is well known that strength exercises involving low muscle mass do not lead to increased secretion of anabolic hormones [53, 58]. In the present study, during the training, the concentration of lactate in the capillary blood increased slightly (to 3.1 ± 0.5 mmol/L) during low-intensity training (50% of 1 RM$_{tr}$); and it increased to 6.3 ± 0.6 mmol/L after a high-intensity training session. After low-intensity training without relaxation, the concentration of lactate reached the highest levels (7.4 ± 0.5 mmol/L). As expected, the content of anabolic hormones: testosterone and IGF-1 did not change after the training sessions in either of the exercises. The content of GH increased slightly only after high-intensity strength exercise.

According to the current view, in adult humans, the IGF-1 protein secreted by the skeletal muscles may affect muscle hypertrophy, mainly, due to the regulation of the differentiation and fusion of satellite cells with existing muscle fibers [59, 60]. In addition, the suppressor effect of IGF-1 on the degradation of muscle proteins through signaling pathway Akt-FOXO [61] and its possible role in the regulation of the rate of protein synthesis through activation of Akt-mTORC1 is discussed [60, 62]. In our study the expression of the muscle isoform of the insulin growth factor (IGF-1Ea) in the recovery period did not change (Fig. 2).

The training regimes compared influenced the expression of the Myostatin gene, which is a negative regulator of the muscle growth. Five hours after exercise without relaxation, the content of myostatin mRNA decreased by four-fold; in addition, it remained at that level until 22 h after exercise (Fig. 2). After high-intensity strength exercise, the content of myostatin mRNA continuously decreased for 22 h of the recovery (in total, by 20-fold). Note that, after the low-intensity traditional exercise, this expression of the gene did not change. The decrease in the expression of myostatin is related to the increased activity of signaling kinases of Akt-mTORC1 pathway [63]; on the other hand, the decrease in the expression of myostatin can decrease activity of the FOXO transcription factors, which stimulate the expression of E3 ligases mRNA, and inhibit the differentiation of satellite cells [64, 65].

Thus, it has been shown that different modes of strength exercise result in different changes in the expression of myogenic regulatory genes: high-intensity strength exercise decrease of the myostatin expression higher than low-intensity training without relaxation. Obviously, in order to characterize in detail the effects of different types of strength exercise, we should assess the changes in the rate of myofibrillar protein synthesis and activation of signaling pathways that regulate the rate of protein synthesis. These tasks should be solved in future studies.

CONCLUSIONS

Comparison of the efficiency of different types of strength training showed that, after low intensity (50% of 1 RM) strength training without relaxation of the working muscles, the gains in strength capacities and the size of the trained muscles were not as large as those after traditional high-intensity (80–85% of 1 RM) strength training. Muscular hypertrophy caused by the traditional strength training and by training without relaxation is, apparently, achieved in different ways. During the traditional strength training, mechanically-related stimuli, which trigger anabolic processes within the muscle fibers, are predominantly generated. During training without relaxation, there is more pronounced activation of anaerobic reactions in the muscle, which by the metaboreflex leads to a more pronounced increase in the secretion of GH, IGF-1, and cortisol in

the blood. High-intensity strength exercise and low-intensity strength exercise without muscle relaxation are characterized by different dynamics of the expression of the myogenic regulatory gene *Myostatin*. The differences in the triggering mechanisms are combined with the differences in the features of hypertrophic changes under the influence of two types of training. During traditional strength training, there is a preferential increase in the cross-sectional area occupied by type II muscle fibers; during training without relaxation, there is a preferential increase in the cross-sectional area occupied by type I muscle fibers.

This study can be useful in the practice of sports, especially those with high requirements for the strength and endurance of the working muscle. In addition, training with relatively low loads preserves the ligamentous from injuries. This feature allows this training regime to be used in fitness and rehabilitation medicine as safe strength training and as a way of supporting the functional capacities of muscles after injuries.

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