BIOMARKERS FOR ASSESSING THE MECHANISMS OF RE-ADAPTATION OF SPECIAL UNITS' MILITARY PERSONNEL IN CONDITIONS OF POWER LOADS

БІОМАРКЕРИ ОЦІНКИ МЕХАНІЗМІВ РЕАДАПТАЦІЇ ВІЙСЬКОВОСЛУЖБОВЦІВ СПЕЦІАЛЬНИХ ПІДРОЗДІЛІВ В УМОВАХ СИЛОВИХ НАВАНТАЖЕНЬ

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Abstracts

Purpose – to study the influence of different training models during long-term rehabilitation on the re-adaptation of special units' military personnel (SUMP); to determine the most informative biomarkers for assessing the manifestations of short-term adaptation and compensatory reactions to strength loads during the re-adaptation.

Material and methods. 45 SUMP aged 24–26 years were examined after injuries during long-term rehabilitation. Participants were divided into three groups of 15 servicemen. The duration of the study was 70 days. The first group used classical protocols for rehabilitation classes. The experimental models of classes for re-adaptation using the main components of power fitness were developed for the second and third groups of SUMP. Blood biomarkers were used to determine the features of adaptive and compensatory reactions to loads. Basal levels of CPK, LDH, cortisol, and testosterone in the blood of the SUMP and changes in their parameters in response to the experimental test load (R_a=0.67) were assessed. Measurements were taken at both the start and end of the study.

Results. The study revealed that before the long-term rehabilitation phase the baseline levels of CPK, LDH, and cortisol in the blood of the SUMP were nearly at the upper limit of the reference range. In response to the test load, all participant groups exhibited an increase in LDH levels, a decrease in cortisol concentration, while CPK and testosterone levels remained unchanged. After 70 days of implementing the proposed training protocols, the baseline levels of biomarkers in the SUMP participants of the first group exhibited a slight reduction. The response of biochemical indicators to the test load remained consistent with the observations recorded at the beginning of the study. SUMP of the second and third groups showed a significant decrease in the baseline level of CPK, LDH, and cortisol in the blood against the background of an increase in testosterone, which indicates pronounced re-adaptation processes. In response to the load, participants in the second group exhibited a slight increase in blood levels of CPK and testosterone, whereas LDH and cortisol levels showed a significant rise. In contrast, the third group of SUMP exhibited a several-fold increase in blood levels of CPK and testosterone in response to acute stress compared to the second group. LDH and cortisol levels in the third group showed negligible changes following stress exposure.

Conclusions. The use of CPK, LDH, cortisol, and testosterone in the blood as informative biomarkers is objectively only for monitoring short-term adaptation processes or manifestations of compensatory reactions in response to acute stress. The initial concentrations of these biomarkers did not provide meaningful diagnostic information, considering the previous (before injuries) high resistance to loads. The study showed that the most pronounced re-adaptation processes during long-term rehabilitation were observed under isolated exercises combined with high-intensity loads, particularly when operating within the creatine phosphokinase energy supply mode.

Key words: military personnel, re-adaptation, test load, compensatory reactions, rehabilitation, blood biomarkers.

Мета – вивчити особливості впливу різних моделей занять у період довготривалої реабілітації на процеси реадаптації військовослужбовців спеціальних підрозділів (ВСП); визначити найбільш інформативні біомаркери оцінки проявів короткочасної адаптації та компенсаторних реакцій їх організму на силові навантаження в процесі реадаптації.

Матеріал і методи. Обстежено 45 ВСП віком 24–26 років після поранень у період довготривалої реабілітації. Учасників розділено на три групи по 15 військовослужбовців. Тривалість дослідження становила 70 діб. ВСП першої групи використовували «класичні» протоколи занять з реабілітації. Для військовослужбовців другої та третьої груп були розроблені експериментальні моделі занять для реадаптації з використанням основних компонентів силового фітнесу. Для визначення особливостей адаптаційно-компенсаторних реакцій на навантаження використовували біомаркери крові. Оцінювали базальний рівень КФК, ЛДГ, кортизол, тестостерон у крові ВСП та зміну їх параметрів у відповідь на експериментальне тестове навантаження (R_a=0.67). Контроль відбувався на початку та наприкінці дослідження.

Результати. Встановлено, що перед початком етапу довготривалої реабілітації базальні рівні КФК, ЛДГ та кортизолу в крові ВСП перебували практично у верхніх межах референту. У відповідь на тестове навантаження у обстежених усіх груп підвищуються параметри ЛДГ, знижується кортизол та не змінюється КФК і тестостерон у крові. Встановлено, що після 70 днів використання запропонованих моделей занять у обстежених ВСП першої групи базальні рівні біомаркерів демонструють мінімальне зниження. У відповідь на тестове навантаження виявлено характер змін біохімічних показників, подібний результатам на початку дослідження. Серед ВСП другої та третьої груп виявлено суттєве зниження базального рівня КФК, ЛДГ, кортизолу в крові на тлі підвищення тестостерону, що вказує на виражені процеси реадаптації. У відповідь на навантаження в другій групі мінімально підвищується КФК, тестостерон у крові, але суттєво зростають параметри ЛДГ та кортизолу. Однак у ВСП третьої групи у відповідь на гостре навантаження параметри КФК та тестостерону в крові порівняно з результатами другої групи підвищуються в декілька разів. При цьому ЛДГ та кортизол у крові військовослужбовців третьої групи після навантаження практично не змінюються.

Висновки. Використання КФК, ЛДГ, кортизолу та тестостерону в крові як інформативних біомаркерів об’єктивно лише для контролю за процесами реалізації короткочасної адаптації або проявами компенсаторних реакцій у відповідь на гостре навантаження. Вихідні базальні параметри таких біомаркерів, враховуючи попередній (до поранень) високий рівень резистентності ВСП до навантажень, є малоінформативними. Встановлено, що найбільш виражені процеси реадаптації в організмі ВСП у період довготривалої реабілітації відбуваються за умов використання ізольованих вправ у поєднанні з навантаженнями високої інтенсивності в умовах креатинфосфокіназного енергозабезпечення.

Ключові слова: військовослужбовці, реадаптація, тестове навантаження, компенсаторні реакції, реабілітація, біомаркери крові.

Introduction. Developing an effective system for monitoring the re-adaptation processes in military personnel of special units remains a subject of ongoing debate among many researchers [5; 6; 18]. The complexity of implementing this problem is associated with the previous high resistance of SUMP to various loads, which in most cases eliminates the effectiveness of using classical diagnostic indicators for rehabilitation. At the same time, the absence of a clear mechanism for correcting loads during the post-acute rehabilitation stage based on physiological and biochemical control methods negatively affects the frequency of manifestations of compensatory reactions to the stimulus [2; 7]. A mismatch between the applied loads and the initial resistance levels, and adaptive reserves of the examined SUMP before long-term rehabilitation, is likely to intensify adaptation failure [3; 9]. The study of this problem is to determine the optimal combination of biomarkers for defining the nature of adaptive and compensatory reactions to stress. However, in their works, researchers [1; 8; 9] demonstrate disagreement regarding the effectiveness of using the optimal set of biomarkers to assess adaptation failure, re-adaptation, and adaptation to various loads.

When studying the problem of finding effective ways to accelerate SUMP re-adaptation in different periods of rehabilitation, the issue of the feasibility of using classical protocols is quite controversial [5; 16]. The difference in perspectives can be attributed to the varying levels of practical training among rehabilitation specialists and their understanding of contemporary approaches to diagnosing adaptive failure and guiding the re-adaptation process [1; 4]. One of the key aspects of developing effective models for SUMP during long-term rehabilitation is the analysis of the interaction between the stimulus magnitude and the physiological processes of re-adaptation [11; 15]. The feasibility of using some combinations of load regimes, principles, and innovative means inherent in power fitness for SUMP re-adaptation after injuries is a debatable issue [2; 6; 9]. However, these issues remain unresolved in fundamental scientific research using various physiological and biochemical methods for monitoring re-adaptation processes.

Purpose of the study – to explore the influence of different training models during long-term rehabilitation on the re-adaptation of special units' military personnel; to determine the most informative biomarkers for assessing the manifestations of short-term adaptation and compensatory reactions to strength loads during the re-adaptation.

Material and methods. Forty-five members of special military units, aged 24–26 years, with marked hypokinesia as a result of extended hypodynamia due to neuromuscular system injury, were included in the study. Previously, the participants used classical physical therapy protocols during 43–45 days of acute and post-acute rehabilitation periods after mine and blast injuries. Considering SUMP's high resistance to a stressful stimulus, they were divided into groups (3 groups of 15 people) by random sampling. The research was conducted in 2024 at the branches of the Research Center of Modern Kinesiology "KINEZUS" (Kyiv, Odessa, Chernivtsi, Ukraine). The Bioethics Committee of Lesya Ukrainka Volyn National University, Ukraine, approved the study design. After being informed of the risks and benefits of the study, participants signed an informed consent form prepared following the ethical standards of the Declaration of Helsinki.

Test load. A test load was developed to assess the resistance of the study participants to the stressful physical stimulus. Due to the lack of information about the initial state of hypokinesia of the SUMP, during the development of the test load, one of the specific principles of premature fatigue in power fitness was used [4; 6]. Isolated auxiliary exercises are employed to apply load until the energy reserves of muscle groups synergistic to those requiring re-adaptation are fully depleted. Premature fatigue of mainly synergist muscle groups will allow reducing the parameters of the load value and maximally loading the agonist muscles, taking into account their ability to counteract the stimulus. Under these conditions, the parameters of the load value (dumbbells, exercise machines) for muscle groups that require re-adaptation can be reduced by 25–30% compared to synergists. One of the important aspects in developing test load for this category of SUMP is the need to use a medium-intensity load regime (R_a = 0.65-0.67) [5]. In the given loading conditions, energy production occurs via simultaneous engagement of the creatine phosphate system and intramuscular glycogen stores [15]. That is, to ensure counteraction to an external stress stimulus, a portion of the energy reserves of the creatine phosphokinase mechanism (25%) and anaerobic glycolysis (75%) are sequentially involved [2; 12]. The technique is modified, particularly by adjusting the amplitude and duration of the eccentric phase of movement to minimize the involvement of stabilizer muscle groups during test exercises. During the initial two sets of each of the four exercises, fatigue manifested primarily in the active synergist muscle groups, whereas in the final two sets, it was predominantly observed in the agonist muscles. The number of repetitions under the conditions of this load regime was 8–10, which is sufficient for partial depletion of the reserves of anaerobic energy supply mechanisms in SUMP. The structure of the strength exercises used in the test load depended on the characteristics of the damage to the peripheral parts of the neuromuscular system of the study participants. Rest intervals between test exercises were within 50–60 s.

Biochemical parameters. The biochemical research methods were used to determine the effectiveness of implementing short-term adaptation, or possible manifestations of compensatory reactions to a given stress stimulus [2; 9; 15].

The activity of the lactate dehydrogenase (LDH) and creatine phosphokinase (CPK) in the SUMP's blood serum was determined by the kinetic method on the equipment of the company "High Technology Inc" (USA) with a set of reagents PRESTIGE 24i LQ LDH (Poland). The testosterone and cortisol levels in serum were measured using enzyme-linked immunosorbent assay (ELISA) with the SteroidIFA-Testosterone reagent kit on instrumentation provided by "Alkor Bio". Reference values of the studied biochemical indicators in the blood serum of the participants, taking into account age characteristics, were the following: CPK (40–270 units/l), LDH (195–462 units/l), cortisol (150–660 nmol/l), and testosterone (8.64–29.01 nmol/l). Venous blood collection was conducted by qualified medical laboratory staff within a specialized department of the "KINEZUS" centers, adhering to internationally recognized protocols for medical and biological research. Control blood sampling was carried out at rest before and after the test load. The obtained samples were stored in special refrigerated boxes, and after completion of the sampling, they were immediately sent to the medical laboratory. Comparative analysis was performed at baseline and following a 70-day period during which the SUMP groups engaged in the prescribed exercise models as part of their re-adaptation process.

Organization of research. The research was conducted in several stages during 2024.

At the first stage, a comparative analysis was conducted to evaluate the effectiveness of training programs aimed at the re-adaptation of functional capacities and the neuromuscular system status in SUMP personnel during the acute and post-acute rehabilitation periods. First, attention was paid to analyzing the results of biochemical blood tests conducted in medical institutions during this rehabilitation period. The primary focus was on assessing the dynamics of basal activity levels of key enzymes and the concentrations of steroid hormones in the blood serum of the study participants. The results allowed determining the nature of SUMP re-adaptation with some lesions of the neuromuscular system during these rehabilitation periods. However, studies concerning the changes in key enzymes and hormones in the blood in response to acute stress were not conducted. Data on potential manifestations of short-term adaptation or the activation of compensatory responses to stress stimuli in SUMP are lacking. Therefore, accurately characterizing the dynamics of functional re-adaptation processes in this cohort during the 43–45-day acute and post-acute rehabilitation periods remains practically unfeasible. Evaluating the mechanisms underlying SUMP re-adaptation during prolonged rehabilitation with different strength training models requires a well-founded selection of informative biomarkers.

During the second stage, at the study's onset, changes in biomarkers (CPK, LDH, cortisol, and testosterone) in the blood of the examined SUMP were assessed in response to a stress stimulus and compared to their resting state. A test load was designed and implemented at the study's outset to evaluate the resistance of study participants to a stressful stimulus (power loads). One of the tasks of this stage was to assess the capacity of SUMP, following 45 days of prior rehabilitation, to initiate short-term adaptive responses or exhibit compensatory mechanisms in reaction to a stress stimulus. Accordingly, the main stressful stimulus was the test load we developed. Two experimental models of re-adaptation training sessions were developed based on the findings and SUMP professional profiles and their physiological resistance to power loads. For creating these models, specific principles related to fitness, load regimens, and exercise complexes were applied to facilitate the re-adaptation of functional capabilities throughout the long-term rehabilitation period of SUMP. During the design of the training sessions, key challenges related to the re-adaptation of individuals with peripheral neuromuscular system injuries resulting from mine and blast trauma were carefully considered.

At the third stage, specific exercise models were assigned to each of the three SUMP groups to evaluate the effectiveness of re-adaptation processes during the initial phase of long-term rehabilitation. Participants in the first group followed a classical training regimen during the

70-day rehabilitation period. Participants in the second group underwent the experimental training model 1 throughout the study period. The third SUMP group was assigned experimental model 2 to potentially achieve enhanced re-adaptation during long-term rehabilitation. At the end of this stage, the adaptive and compensatory responses to the stressful stimulus were re-evaluated in participants in all three groups. The baseline levels of the monitored biomarkers were established, and their changes in response to the test load were analyzed. The load parameters were calculated depending on the value of 1 RM, which SUMP could demonstrate while performing isolated exercise for one muscle group. Throughout all stages of the study, a comparative analysis was conducted on the changes in blood biomarkers in SUMP both at rest and following the test load. The results were processed.

Statistical analysis. Using the IBM *SPSS* Statistics 27 software package (StatSoftInc., USA), statistical analysis of the study results was performed. The G-Power 3.1.96 program allowed for determining the smallest sample size for the study (calculation of statistical power). Nonparametric methods of statistical analysis were used. The median (Me) and interquartile range (IQR) were determined. The Kruskal-Wallis test was employed to compare baseline parameters across the groups established at the study's onset. For comparisons between two related samples, the Wilcoxon signed-rank test was applied.

Research results. Fig. 1 presents experimental models of exercises for re-adaptation of the cardiovascular system after prolonged hypodynamia due to damage to the peripheral parts of the neuromuscular system. These models are designed for the initial periods of the long-term rehabilitation. The peculiarity of each of the presented models depends on the content and parameters of its main components: the variability of the combination of physical exercises, the intensity of the load regime, the mechanism of energy supply and the level of adaptive reserves, the periodization of loads, and the mechanism of their correction. A comparative analysis of the sets of exercises used in each of the presented power fitness and MMA training models, varying in complexity and energy expenditure, shows that it is necessary to address multiple tasks at the same time.

Model 1 is characterized by the predominant use of fundamental strength fitness exercises that engage agonist, synergist, and stabilizer muscle groups simultaneously. This approach prioritizes exercises utilizing body weight, dumbbells, and partner resistance. However, in conditions of insufficient re-adaptation of these muscle groups during the previous rehabilitation periods, which are agonists in the basic exercises, it can lead to selective hypertrophy of synergists and complicate the situation [2; 17]. Under these conditions, a new problem arises, which is associated with the need to conduct additional studies using electromyography methods. The study results allow for determining the index of the number of active motor units (MUNIX) in damaged muscle groups, which are primarily agonists. An interesting solution is the simultaneous use of a low (R_a=0.56) and medium intensity (R_a=0.67) exercise regime in combination with the anaerobic glycolysis mechanism, which ensures ATP resynthesis in the energy supply process.

The key feature of model 2 is the use of isolated exercises (subtractive and basic) for the sequential involvement of mainly synergist, stabilizer, and partially agonist muscle groups. Preference is given to a combined complex of special isolated exercises (simulators, exercises with resistance to the efforts of another person) of power fitness and MMA for the re-adaptation of affected muscle groups. It is isolated exercises (with resistance to the efforts of another person), similar to the technical elements of MMA, allowing for loading agonist muscles under conditions of prior fatigue of synergists. Under these conditions, applying a high-intensity load regimen (R_a = 0.74) alongside the creatine phosphokinase energy supply mechanism influences the level of resistance during SUMP re-adaptation.

Figure 2 graphically presents the changes in creatine phosphokinase in the blood of SUMP during a given period of long-term rehabilitation in response to test loads.

Initial findings indicate that baseline CPK activity in the blood of all SUMP participants

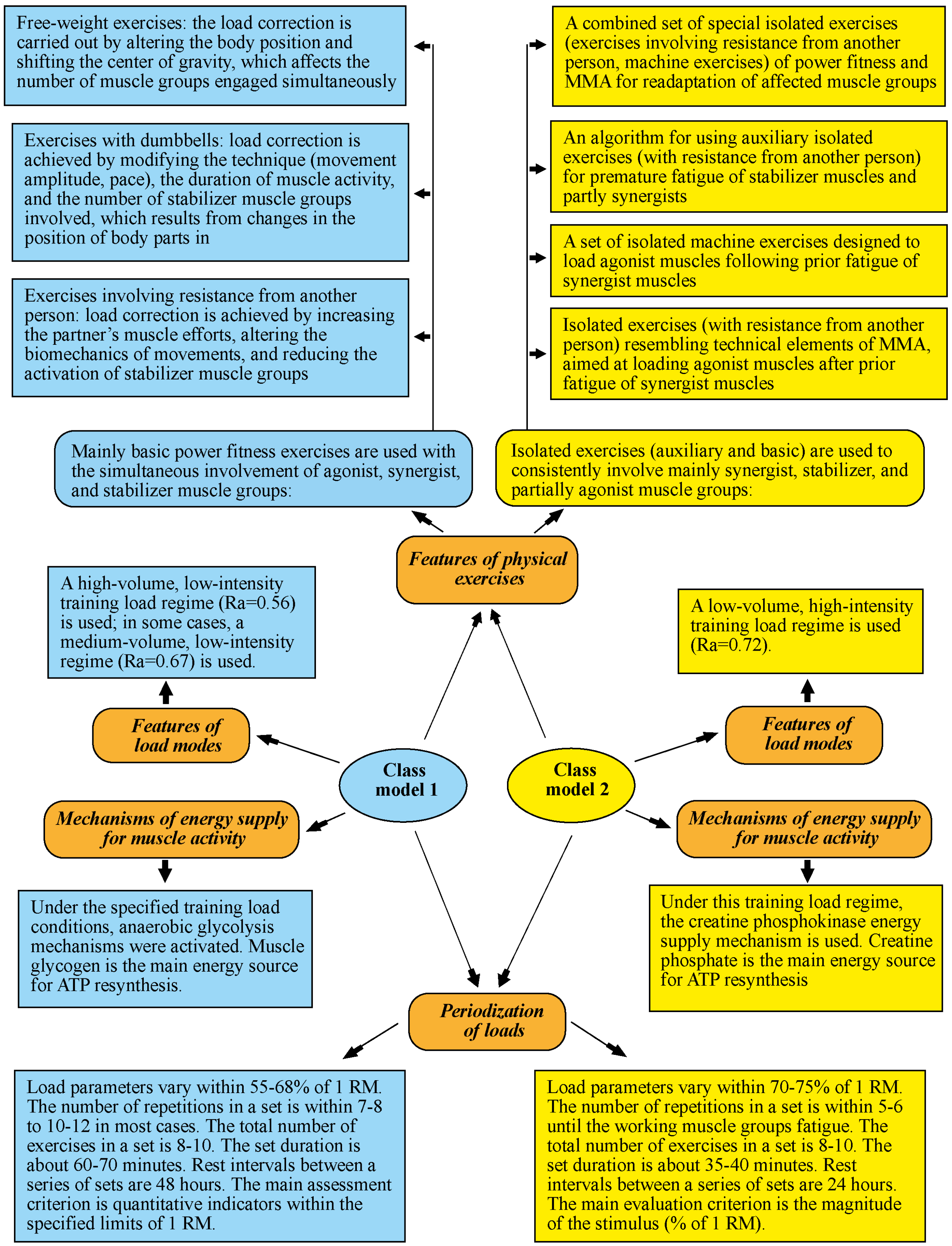

Fig. 1. Experimental training models for SUMP re-adaptation during long-term rehabilitation following damage to the peripheral components of the neuromuscular system

was near the upper level of the reference range. Following the application of the test load, CPK levels remained statistically unchanged across all three groups when compared to their baseline measurements.

After 70 days of implementing these training models, a significant reduction in the baseline levels of CPK activity was observed in the blood of SUMP participants across all groups. The most pronounced decrease in this indicator in the blood by 31.3% was observed among the third group representatives. The smallest, but at the same time significant, decrease in the basal level of this enzyme by 10.1% was recorded in the SUMP of the first group. In response to the test load, the CPK activity in the first group, as at the beginning of the study, did not change. At the same time, CPK activity increased in the blood of the second (+3.1%) and third (+28.8%) groups in response to the given stress stimulus.

The data presented in Figure 3 illustrate changes in lactate dehydrogenase activity in the blood of all SUMP groups during long-term rehabilitation in response to test load.

At the onset of the study, baseline lactate dehydrogenase levels in the participants' blood were within the established reference range and showed no significant differences between the groups. In response to the test load, the activity of this enzyme in the blood increased by an average of 11.8% among representatives of all groups. However, the results obtained after applying a stressful stimulus exceed the upper limits of the reference values.

Analysis of the results recorded after prolonged use of the specified models of re-adaptation classes indicates a decrease in the basal level of LDH in the blood of representatives of all groups. The most pronounced decrease in the basal level of LDH in the blood by 27.7% was observed among the third group of SUMP. Minimal but significant changes in this indicator by 6.7% compared to the initial data were found among the first group participants. The results obtained in response to the test load showed that LDH activity in the blood of SUMP of the first (+10.7%) and second (+8.5%) groups significantly increased.

Figure 4 presents the results illustrating changes in blood cortisol levels among SUMP participants from the examined groups during long-term rehabilitation in response to test loading.

The initial results indicate that baseline cortisol concentrations in the blood of all examined

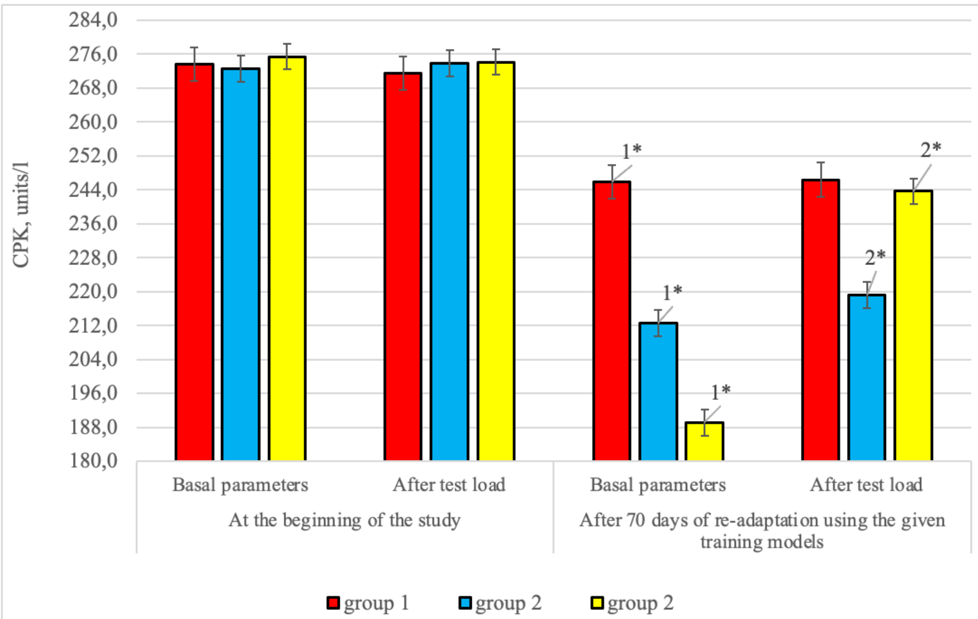

Fig. 2. Changes in the CPK activity in the blood of SUMP during long-term rehabilitation in response to test loads, n=45

Note: 1* – p<0.05 compared to the indicators at the beginning of the study (baseline parameters); 2* – p<0.05 compared to the indicators before the load

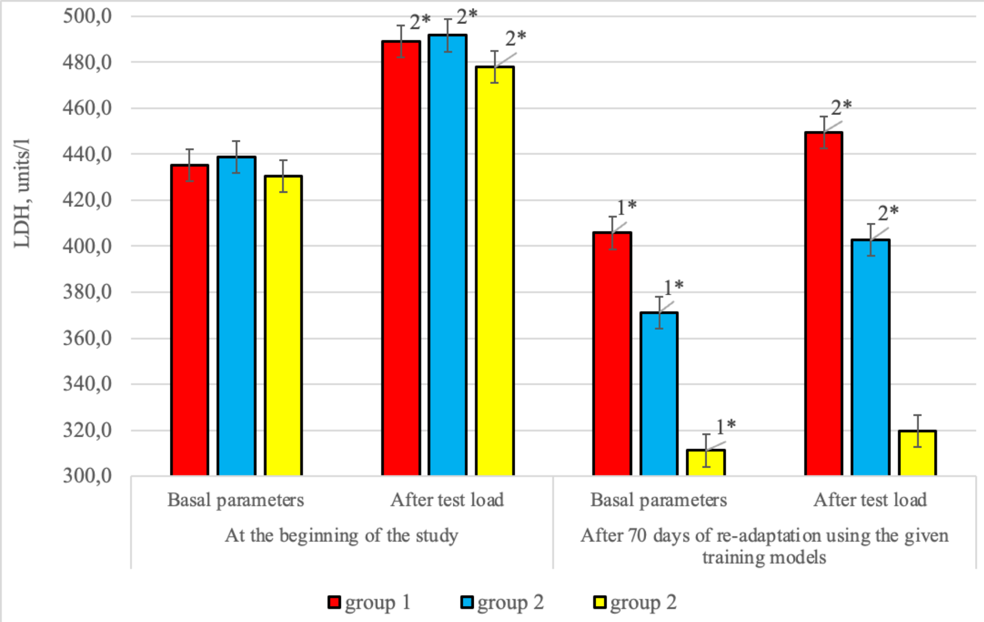

Fig. 3. Changes in lactate dehydrogenase activity in the blood of all SUMP groups during long-term rehabilitation in response to test load, n=45

Note: 1* – $p<0.05$ compared to the indicators at the beginning of the study (baseline parameters); 2* – $p<0.05$ compared to the indicators before the load

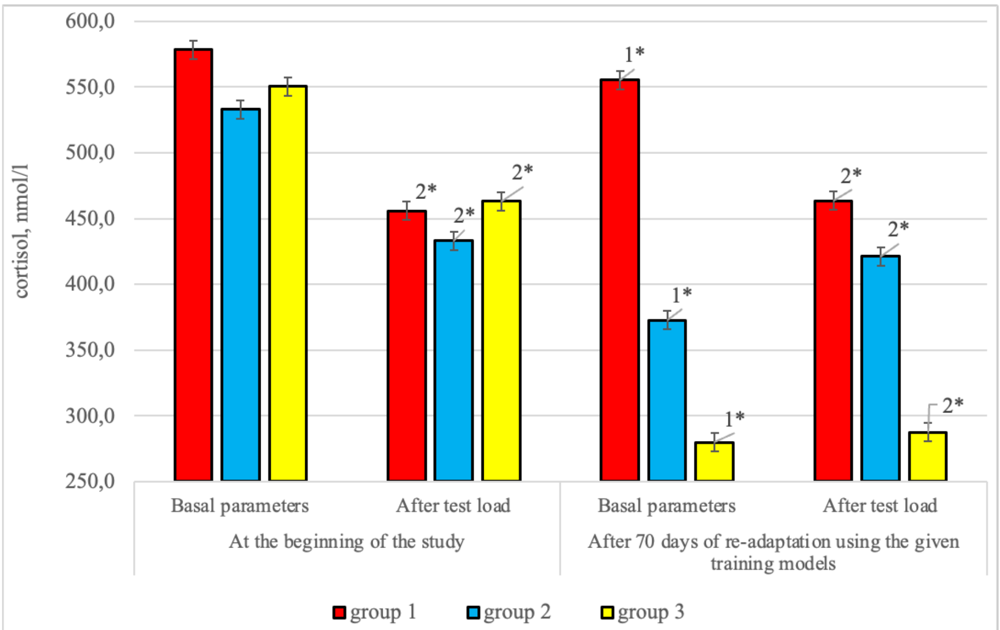

Fig. 4. Changes in cortisol concentration in the blood of all SUMP groups during long-term rehabilitation in response to test load, n=45

Note: 1* – $p<0.05$ compared to the indicators at the beginning of the study (baseline parameters); 2* – $p<0.05$ compared to the indicators before the load

SUMP participants were close to the upper limit of the reference range. In response to the test load, the cortisol concentration in the blood significantly decreased among representatives of all groups within 15.8–21.2%.

Laboratory assessments conducted at the end of the study revealed a distinctly variable pattern of reduction in baseline cortisol concentrations among the SUMP participants across the examined groups. The minimum decrease in the parameters of this indicator by 3.9% was observed among the participants of the first group. At the same time, in the third group of SUMP the basal level of cortisol concentration in the blood serum decreased by 49.2%, compared with the initial data. Analysis of the responses to the test load revealed a 16.5% decrease in blood cortisol concentration in the VSPs of the first group. An increase in blood cortisol levels in response to the stress stimulus was observed in participants of the second (+13.0%) and third (+2.7%) groups.

Figure 5 illustrates the patterns of changes in blood testosterone concentration among SUMP across the examined groups during the specified period of long-term rehabilitation in response to test loads.

At the study's outset, baseline testosterone levels in the blood of the examined subjects were within the reference range and showed no significant differences between the groups. In response to the test load, the concentration of the studied hormone in the blood serum did not exhibit significant changes in SUMP participants across all three groups.

Analysis of the results of prolonged application of the re-adaptation training models revealed an increase in baseline blood testosterone levels in participants of the second (+9.7%) and, notably, the third (+34.5%) groups. There was a significant increase in the blood testosterone concentration of the second (+4.1%) and third (+22.9%) groups of SUMP in response to the test load. Participants in the first group exhibited no changes in baseline blood testosterone levels, nor were any alterations in hormone concentration observed in response to the test load throughout the study.

Discussion. This study highlights research efforts aimed at addressing a critical challenge in long-term rehabilitation: identifying reliable biomarkers for evaluating re-adaptation processes [3; 9; 14]. The complexity of solving this

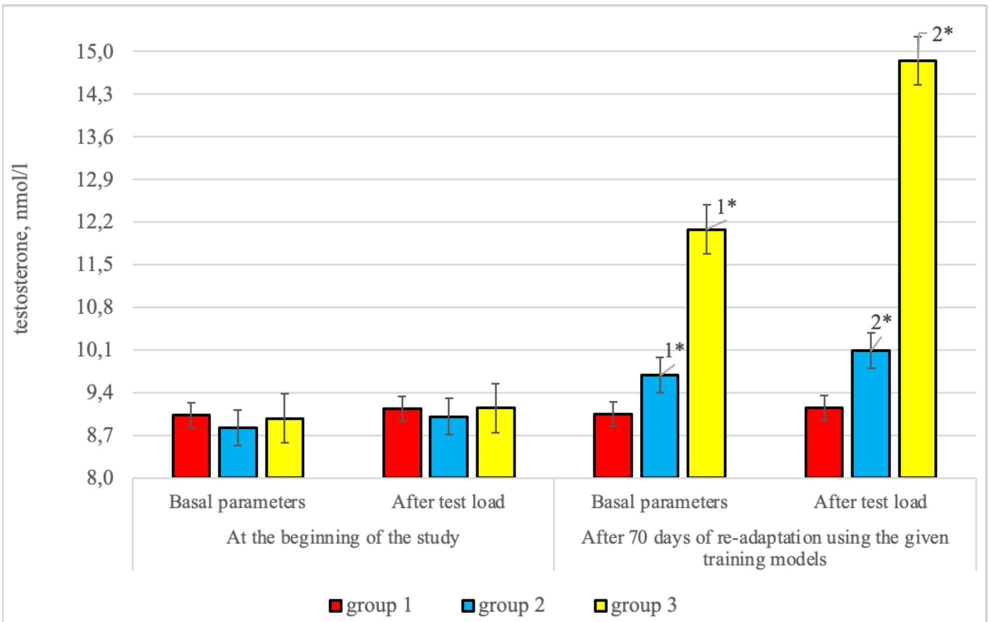

Fig. 5. Changes in testosterone concentration in the blood of all SUMP groups during long-term rehabilitation in response to test load, n=45

Note: 1* – $p<0.05$ compared to the indicators at the beginning of the study (baseline parameters); 2* – $p<0.05$ compared to the indicators before the load problem is associated with the high resistance of SUMP to stressful stimuli, which existed before injuries. We studied the manifestations of short-term adaptation and compensatory reactions of the examined SUMP to acute power loads, using a wide range of biochemical research methods [2; 15]. The experimental class models were designed using power fitness methods, MMA training protocols, and test loads to evaluate adaptive and compensatory responses to stimuli. Re-adaptation processes in SUMP, occurring against the background of pronounced hypokinesia, were investigated under prolonged application of various experimental training models. The results indicate that the initial basal parameters of the most common biomarkers for assessing maladaptation processes [3; 9; 12] only partially reflect the state of hypokinesia in SUMP during the rehabilitation period. The study established that blood biomarkers could detect manifestations of short-term adaptation or compensatory responses in SUMP only following acute test loads. The results obtained will contribute to solving the problem of finding optimal training models to increase the efficiency of SUMP re-adaptation processes during long-term rehabilitation. These findings positively contribute to resolving the question of the viability of using LDH, CPK, cortisol, and testosterone as informative biomarkers for evaluating VSP re-adaptation processes.

The inadequacy of monitoring re-adaptation processes in SUMP body systems during various stages of rehabilitation, particularly in the long-term, complicates the selection of optimal physical activity regimens [5; 17]. Considering the previously high stress resistance in special unit military personnel before the onset of hypokinesia, the application of conventional physical rehabilitation protocols proves to be ineffective [1; 4; 6]. In most cases, this issue arises from a lack of practical understanding of the mechanisms for adjusting load regimes and training models for SUMP, particularly in the context of adaptive failure [9; 18]. The limited number of studies addressing this issue in the global scientific literature [7; 8; 14] further complicates the identification of optimal blood biomarkers for assessing SUMP re-adaptation following prolonged hypodynamia caused by injury.

The study proved that before the start of the long-term rehabilitation stage, the basal blood levels of CPK, LDH, and cortisol were within the upper limits of the reference. These data indicate a stressful state of the examined SUMP and possible manifestations of muscle adaptation failure due to the inadequacy of loads to the adaptive body reserves in previous rehabilitation [5; 6; 9]. In response to test power loads (R_a = 0.65-0.67), the examined participants of all groups showed an increase in LDH activity above the upper limits of the reference against the background of a significant decrease in blood cortisol. During the test load, both anaerobic mechanisms of energy supply were involved, but the CPK activity in the blood did not change. Similar changes in biomarkers in response to a given stimulus indicate low reserves of creatine phosphate and muscle glycogen in the muscles and activation of compensatory mechanisms (gluconeogenesis process) [2; 15].

The changes observed in the studied blood biomarkers in SUMP after 70 days of implementing the proposed training models reflect the heterogeneous nature of their adaptive and compensatory responses. In the first group participants, who used classical protocols for physical rehabilitation, the basal parameters of biomarkers demonstrated a minimal decrease. In response to the test load, the changes in the studied blood parameters of this group were similar to the results recorded at the beginning of the study. Consistent patterns of simultaneous cortisol reduction and LDH elevation in response to physical load suggest sustained activation of compensatory mechanisms, which may contribute to the development of chronic adaptation failure [9; 15, 16]. These results indicate the low effectiveness of classical protocols for physical therapy during long-term rehabilitation on the processes of re-adaptation [4; 12]. This may be due to the lack of an optimal mechanism for correcting load regimes depending on the specifics of changes in SUMP resistance during re-adaptation [11; 14].

Laboratory findings from the other two groups, who followed the experimental training models for 70 days, indicate effective re-adaptation processes, characterized by enhanced adaptive reserves and increased physiological resistance to a stressful stimulus. The detected decrease in the basal level of CPK, LDH, and cortisol in the blood of SUMP of the second and third groups against the background of an increase in testosterone indicates pronounced processes of repeated long-term adaptation [2; 3]. However, in response to the test load, the variations in the analyzed biochemical blood markers among participants of the second and third groups exhibited certain differences. In the second group, who used the load regime (R_a=0.67), there was a minimal increase in CPK and testosterone in the blood, but a significant increase in LDH and cortisol parameters. The obtained data indicate the effectiveness of implementing short-term adaptation mechanisms under moderate intensity loads with anaerobic energy supply due to increasing muscle glycogen reserves [6; 15]. In the third group (R_a=0.72), in response to acute stress, the parameters of CPK and testosterone in the blood increased several times, compared with the results of the second group. Following the test load, LDH activity and blood cortisol concentrations in the third group remained virtually unchanged, indicating a stable physiological response. These changes in the studied blood biomarkers under the specified conditions suggest an enhancement of creatine phosphate reserves and an increased physiological resistance to stress stimuli [2; 12; 14].

Conclusions. The study results demonstrate the feasibility of using CPK, LDH, cortisol, and testosterone blood parameters as informative biomarkers for assessing the SUMP re-adaptation during long-term rehabilitation. However, these blood biomarkers are objective only for monitoring the implementation of short-term adaptation, or manifestations of compensatory reactions in response to acute stress. The initial baseline levels of CPK, LDH, and cortisol in the blood, considering the pre-injury increased resistance of SUMP to stress loads, proved to be non-informative. The most pronounced re-adaptation processes in SUMP during long-term rehabilitation were observed during isolated exercises combined with high-intensity loads utilizing the creatine phosphokinase energy supply regimen. These findings will help in addressing the challenge of identifying effective mechanisms for SUMP re-adaptation during long-term rehabilitation and in developing an integrated monitoring system based on an optimal set of blood biomarkers.

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