

DEVELOPMENT OF A CONCEPTUAL MODEL FOR STUDYING THE REACTIVITY AND ADAPTATION OF THE CIRCULATORY SYSTEM TO DIFFERENT TYPES OF PHYSICAL EXERCISE

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Cardiovascular adjustment to physical exercise is a dynamic process that continues from the onset of muscular activity into the early post-exercise period. Its comprehensive evaluation therefore requires monitoring not only baseline values and acute exercise-induced changes, but also the subsequent return of hemodynamic parameters toward their initial levels. Since different exercise modalities impose distinct demands on the cardiovascular system, the contribution of cardiac, vascular, and autonomic regulatory mechanisms may vary depending on the structure of the exercise and the nature of previous training. The aim is to substantiate a conceptual approach and develop a methodological framework for studying reactive and adaptive changes in the circulatory system depending on the type of physical exercise and the nature of the training stimulus, based on an integrated assessment of central hemodynamics and autonomic regulation. This work is methodological in nature. The proposed study will involve men in early adulthood divided into groups of untrained individuals, individuals engaged in conventional resistance training, and individuals engaged in functional TRX training. The model includes the assessment of stroke volume, cardiac output, cardiac index, total peripheral vascular resistance, and heart rate variability parameters before and after dynamic, static, static-dynamic, and high-intensity interval exercise, followed by repeat assessment after one year. A six-block protocol was developed, comprising baseline morphofunctional assessment, standardized exercise tests, assessment of reactive changes and rapid recovery parameters, control of experimental conditions, and longitudinal assessment of adaptation. The simultaneous analysis of circulatory effector parameters and the mechanisms of autonomic regulation was substantiated. The proposed structure makes it possible to compare the phases of activation, maximal functional strain, and recovery and to identify response patterns depending on the type of exercise and training status. The developed model provides a methodological basis for the comprehensive investigation of circulatory reactivity and long-term adaptation. Its implementation will enable the identification of specific hemodynamic and autonomic adaptations and the assessment of rapid recovery as an informative marker of the body's functional reserves.

Key words: circulatory system, central hemodynamics, physical exercise, functional TRX training, rapid recovery, reactivity, adaptation.

Connection of the publication with planned research work.

The work is being conducted at the Department of Medical Biology and Sports Dietetics of the National University of Ukraine on Physical Education and Sport "Influence of Endogenous and Exogenous Factors on the Course of the Body's Adaptive Responses to Physical Loads of Varying Intensity" (state registration number 012U108187).

Introduction.

The circulatory system matches the metabolic demands of working muscles with systemic oxygen delivery while maintaining arterial blood pressure. The acute response to physical exercise is mediated by interrelated changes in heart rate (HR), stroke volume (SV), cardiac output (CO), total peripheral vascular resistance (TPVR), and autonomic regulation. The magnitude of these changes depends on training status and the mode of muscular activity: young trained and untrained individuals show differences in the blood pressure response to exercise, while higher habitual physical activity and aerobic training are associated with more favorable indices of arterial stiffness and endothelial function [1-3]. The early recovery period has particular diagnostic value because cardiac output, vascular resistance, and auto-

nomnic regulation of heart rate continue to readjust after muscular activity has ceased. Studies of central hemodynamics following standardized exercise have shown that recovery trajectories depend on the exercise mode and may differ substantially even with a comparable volume of active muscle mass [4, 5]. The rate of heart rate decline after exercise is also associated with age and training status and reflects the restoration of parasympathetic influence [6]. Thus, the simultaneous assessment of central hemodynamics and heart rate variability (HRV) at fixed recovery time points makes it possible to distinguish between the effector and regulatory components of the response.

The type of physical exercise determines the predominant mechanism of the hemodynamic response. During dynamic exercise, increased CO is accompanied by reduced resistance in the active muscles; static exercise produces a more pronounced pressor component, the magnitude of which depends on contraction intensity and the muscle mass involved [4, 5, 7]. Static-dynamic exercise combines features of both modes and has specific early recovery dynamics [8, 9]. High-intensity interval exercise (HIIE) involves repeated transitions between exercise and short recovery intervals; in a randomized study, its effects were assessed simultaneously using he-

modynamic parameters and heart rate variability [10]. This supports the inclusion of dynamic, static, static-dynamic, and high-intensity interval exercise in a single protocol.

The nature of the acute response and the rate of recovery are modified by systematic training. Differences between trained and untrained individuals are evident in the blood pressure response and the condition of the vascular wall [1-3]. At the same time, similar HRV values in athletes trained in explosive and aerobic disciplines indicate that training orientation alone does not always explain differences in autonomic profiles [11]. In resistance fitness, static-dynamic exercise has been shown to alter cardiovascular parameters [9]. However, resistance training programs and functional training using TRX-type suspension systems differ in movement structure, stabilization demands, and the contribution of static work; therefore, their adaptive effects should not be regarded as equivalent without direct comparison.

Study [12] systematized data on reactive and adaptive changes in the circulatory system of men according to age and exercise orientation. However, practical verification of these patterns requires a unified design combining baseline morphofunctional characterization, standardized exercise tests, recording of central hemodynamics and HRV at fixed intervals during early recovery, and repeat assessment of adaptation. Such an integrated scheme makes it possible to compare acute reactivity with the development of stable adaptive changes in untrained individuals and representatives of different training modalities.

The aim of the study.

To substantiate a conceptual approach and develop a methodological framework for investigating reactive and adaptive changes in the circulatory system depending on the type of physical exercise and the nature of the training stimulus, based on an integrated assessment of central hemodynamics and autonomic regulation.

Object and research methods.

The study is planned to be conducted at the National University of Ukraine on Physical Education and Sport. The work is methodological in nature and is aimed at developing and theoretically substantiating a comprehensive approach to studying reactive and adaptive changes in the circulatory system under different types of physical exercise. The study methodology involves the development of an integrated model for investigating the functional state of the circulatory system, which includes:

1. development of an assessment protocol integrating indices of central hemodynamics and autonomic regulation of cardiac activity;
2. classification of physical exercise according to the nature of its physiological effects;
3. substantiation of the study design, taking into account both acute reactive changes and long-term adaptive remodeling.

At the time of manuscript preparation, the study was at the implementation stage; therefore, quantitative results are not presented. The main focus of the work is the development and substantiation of the methodological framework. Men in early adulthood are planned to be enrolled in the study. Following baseline assessment and verification of the inclusion and exclusion criteria, they will be divided into three groups according to the

nature of their physical activity - a control group (untrained individuals); a group of individuals who regularly perform conventional resistance exercise; a group of individuals engaged in functional training using TRX-type suspension systems.

This approach allows the training modality to be considered a key factor determining the specific development of adaptive responses in the circulatory system. The inclusion criteria are male sex; early adulthood; absence of clinically significant cardiovascular, endocrine, and musculoskeletal disorders; a stable level of physical activity during the preceding months; and provision of written informed consent to participate in the study. The exclusion criteria are acute diseases or decompensated chronic diseases; conditions that limit the safe performance of physical exercise; use of medications that may affect cardiovascular parameters; and an irregular physical activity pattern or an abrupt change in that pattern before the study begins.

The study design comprises two stages. The first stage is an initial assessment and includes evaluation of baseline morphofunctional parameters and analysis of reactive changes in the circulatory system in response to different types of exercise. The second stage is comparative and involves repeat assessment after a specified period (1 year) to evaluate adaptive changes that develop under the influence of systematic physical activity.

The functional state of the circulatory system will be assessed through an integrated analysis of central hemodynamic indices and HRV parameters, thereby allowing simultaneous characterization of the effector and regulatory mechanisms of the cardiovascular response. The developed study protocol has a modular structure and comprises several interrelated blocks, each designed for the stepwise assessment of the functional state of the circulatory system during physical exercise and recovery. This structure enables an integrated analysis of reactive and adaptive changes that considers both effector and regulatory mechanisms.

Block 1 (baseline morphofunctional assessment) involves determining the baseline levels of morphological and functional parameters that characterize participants and provide a basis for interpreting subsequent exercise-induced changes. This block includes anthropometric assessment of the main indices of physical development and recording of central hemodynamic parameters under resting physiological conditions. Functional assessment includes central hemodynamic parameters, particularly SV, CO, cardiac index (CI), and total peripheral vascular resistance (TPVR), which characterize the efficiency of the cardiac pumping function and the condition of the vascular bed. This block also includes analysis of heart rate variability as an indicator of autonomic regulation of cardiac activity, enabling assessment of the balance between the sympathetic and parasympathetic divisions of the autonomic nervous system at baseline.

Block 2 (physical exercise protocol) is designed to standardize the performance of exercise modalities that differ in their mechanisms of action on the circulatory system. The protocol includes four types of exercise: dynamic, static, static-dynamic, and HIIE. This selection covers the principal modes of muscular activity and makes it possible to investigate the specific hemodynamic response according to the structure of the exercise stimulus.

Dynamic exercise predominantly activates the central component of the circulation [4, 5], whereas static exercise is characterized by increased TPVR [5, 7, 13]. Static-dynamic exercise combines these mechanisms [8, 9], while HIIE creates conditions for maximal mobilization of the body's regulatory systems [10].

Block 3 (assessment of reactive changes during exercise) involves recording circulatory parameters immediately before exercise and at several time points immediately after its completion. During this period, changes in central hemodynamic parameters reflecting the mobilization of the functional reserves of the heart and blood vessels will be assessed. It should be noted that changes in HR during and immediately after exercise affect the duration of cardiac intervals. Therefore, HRV will be studied by recording a rhythmocardiogram only immediately before exercise and immediately after hemodynamic parameters have normalized. Thus, analysis of reactive changes makes it possible to identify the type of hemodynamic response and the characteristics of autonomic regulation of the circulatory system during different types of exercise in individuals with different training orientations.

Block 4 (assessment of parameters during the rapid recovery period) is designed to investigate the recovery dynamics of the functional state of the circulatory system after exercise cessation. Parameters will be recorded at fixed time intervals after exercise, enabling assessment of the rate at which hemodynamic indices normalize and autonomic balance is restored. This recovery period is a highly informative phase that reflects the effectiveness of regulatory mechanisms and the level of the body's functional reserves, which is of fundamental importance for assessing adaptive capacity.

Block 5 (control of study conditions) includes standardization of assessment conditions to minimize the influence of extraneous factors on study outcomes. The timing of assessments, dietary regimen, level of prior physical activity, and rest periods between individual protocol stages will be standardized. This approach improves the reproducibility and reliability of the data.

Block 6 (assessment of adaptive changes: longitudinal stage) will be implemented during the second stage of the study and involves repeat assessment after 1 year to evaluate changes over time in the functional state of the circulatory system and in the efficiency of autonomic regulation of cardiac activity. Comparative analysis of baseline and follow-up parameters will determine the nature of adaptive remodeling that develops under different types of physical activity and reveal between-group differences according to the training modality.

Methodological features of the study. The proposed approach to investigating the functional state of the circulatory system is based on the principles of standardization, differentiated exercise loading, and integrated assessment of the effector and regulatory mechanisms of the cardiovascular response. One of its key methodological features is the use of a multilevel analytical model that simultaneously assesses central hemodynamic indices and HRV parameters. This approach enables not only the recording of changes in the cardiac pumping function and the condition of the vascular bed but also their interpretation in terms of autonomic regu-

lation, thereby providing a deeper understanding of the mechanisms of adaptation.

Another important element of the methodological framework is the differentiation of exercise according to its structural and functional characteristics. The inclusion of dynamic, static, static-dynamic, and high-intensity interval exercise in the protocol is driven by the need to reproduce different patterns of hemodynamic response arising from the predominant recruitment of central or peripheral regulatory mechanisms. This protocol allows the circulatory response to be considered a function not only of intensity but also of the type of muscular activity. Particular attention is paid to standardizing exercise intensity. Exercise dosage is determined according to the participants' individual functional capacities, ensuring valid between-group comparisons and increasing the validity of the results. The need to avoid excessive functional strain, which may affect the nature of regulatory responses, is also taken into account.

A fundamentally important methodological feature is the analysis of parameters during the rapid recovery period. Unlike the traditional approach, which is limited to evaluating the resting state or the response during exercise, analysis of recovery dynamics makes it possible to assess the rate of normalization of hemodynamic parameters and restoration of autonomic balance. This period is regarded as a sensitive indicator of functional reserves and the efficiency of regulatory mechanisms. Another essential feature of our work is the implementation of a longitudinal approach involving repeat assessment to evaluate adaptive changes over time. This makes it possible to move from the analysis of isolated responses to the study of stable changes in the functional state of the circulatory system under the influence of systematic physical activity. Another important methodological consideration is the training modality as a factor in the development of adaptive responses. Comparing individuals who do not engage in regular physical activity with those who perform resistance or functional training allows identification of specific features of cardiovascular regulation associated with different types of muscular activity.

To improve the reliability of the results, assessment conditions will be standardized, including the time of day, dietary regimen, level of prior physical activity, and rest intervals between individual stages of the protocol. This approach minimizes the influence of extraneous factors and ensures data reproducibility. Thus, these methodological provisions constitute an integrated research system that enables comprehensive assessment of reactive and adaptive changes in the circulatory system while accounting for the multifactorial nature of its regulation. The study will be conducted in accordance with the ethical principles of the Declaration of Helsinki [14], Ukrainian legislation governing human participation in biomedical research [15, 16], and the internal regulations of the National University of Ukraine on Physical Education and Sport.

Research results and their discussion.

The process of developing the study protocol resulted in an integrated model for assessing the functional state of the circulatory system, combining analysis of reactive changes in response to physical exercise with evaluation of adaptive remodeling over time. This approach involves the integrated assessment of central

hemodynamic indices and HRV, enabling simultaneous characterization of the effector and regulatory mechanisms of the hemodynamic response.

One of the key outcomes of protocol development is its modular structure, which enables stepwise investigation of the functional state of the circulatory system during physical exercise and recovery. This structure allows the cardiovascular response to be viewed not as an isolated measure but as a dynamic process comprising an activation phase, a phase of maximal functional strain, and a recovery phase. The justified inclusion of different types of physical exercise in the protocol makes it possible to reproduce the principal patterns of hemodynamic response associated with different modes of muscular activity. Dynamic exercise is expected to produce a predominant increase in CO through enhanced cardiac pumping, whereas static exercise is expected to increase TPVR and the involvement of the vascular component of regulation. Static-dynamic exercise is expected to combine these mechanisms, while HIIE will create conditions for maximal mobilization of both central and peripheral regulatory components.

Including HRV parameters in the analysis enables the interpretation of hemodynamic changes from the perspective of autonomic regulation. Different types of exercise are expected to be accompanied by specific shifts in sympathovagal balance that reflect the characteristics of regulatory responses. This approach makes it possible to move from describing the external manifestations of a functional response to analyzing its underlying mechanisms.

In the proposed protocol, particular importance is assigned to assessing parameters during the rapid recovery period. This stage makes it possible to identify differences in the rate of normalization of hemodynamic parameters and restoration of autonomic balance, which is regarded as an indicator of the body's functional reserves. Recovery parameters are expected to differ substantially among individuals with different training statuses and patterns of physical activity, reflecting the specific nature of adaptive remodeling.

The longitudinal stage will enable assessment of long-term changes in the functional state of the circulatory system that develop under systematic training loads. The nature of adaptive changes is expected to de-

pend on the type of physical activity: changes associated with increased involvement of the vascular component of regulation may be more typical of individuals performing resistance exercise, whereas functional training may promote a more economical and balanced cardiovascular response.

Thus, the developed protocol provides a basis for the comprehensive analysis of reactive and adaptive changes in the circulatory system while accounting for the multifactorial nature of its regulation. Its application will generate new data on the mechanisms underlying adaptation to different types of physical exercise and clarify the role of individual components of the cardiovascular system in ensuring an effective functional response.

Conclusions.

1. A comprehensive model for investigating the functional state of the circulatory system was developed and theoretically substantiated. The model combines assessment of reactive changes in response to physical exercise with evaluation of long-term adaptive remodeling over time.

2. The proposed protocol is based on the integrated analysis of central hemodynamic indices and HRV, providing simultaneous assessment of the effector and regulatory mechanisms of the cardiovascular response.

3. The rationale for using different types of physical exercise and including parameters from the rapid recovery period as informative markers of functional reserves and the efficiency of regulatory processes was substantiated.

4. Implementation of the longitudinal approach provides opportunities to assess the specific adaptive changes in the circulatory system according to the nature of the training stimulus and the level of physical activity.

Prospects for further research.

They are associated with the practical implementation of the proposed protocol and the acquisition of quantitative data on reactive and adaptive changes in the circulatory system in response to different types of physical exercise. Further research will clarify relationships between central hemodynamic indices and autonomic parameters and determine how adaptive responses vary by training modality.

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РОЗРОБКА КОНЦЕПТУАЛЬНОЇ МОДЕЛІ ДОСЛІДЖЕННЯ РЕАКТИВНОСТІ ТА АДАПТАЦІЇ СИСТЕМИ КРОВООБІГУ ПРИ РІЗНИХ ТИПАХ ФІЗИЧНОГО НАВАНТАЖЕННЯ

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Резюме. Функціональний стан системи кровообігу є провідною складовою адаптації організму до фізичних вправ. Оцінювання лише показників спокою або безпосередньої реакції на м'язову роботу не відображає повного циклу гемодинамічної відповіді, особливо перебігу швидкого відновлення. Водночас різні типи вправ і тренувальних впливів зумовлюють неоднакове залучення центральних, периферичних та вегетативних механізмів регуляції.

Мета – обґрунтувати концептуальний підхід і розробити методологічне забезпечення вивчення реактивних і адаптивних змін системи кровообігу залежно від типу фізичних вправ й характеру тренувального впливу на основі інтегрованої оцінки центральної гемодинаміки.

Робота має методологічний характер. Запропоновано залучити чоловіків першого зрілого віку, розподілених на групи нетренованих осіб, прихильників класичних силових вправ і функціонального тренінгу TRX. Модель передбачає визначення ударного та хвилинного об'ємів крові, серцевого індексу, загального периферичного опору судин і показників варіабельності серцевого ритму до та після динамічних, статичних, статодинамічних і високоінтенсивних інтервальних навантажень, а також повторне обстеження через один рік.

Розроблено шестиблоковий протокол, який охоплює первинне морфофункціональне обстеження, стандартизовані вправи, оцінювання реактивних змін, показників швидкого відновлення, контроль умов і лонгітюдну оцінку адаптації. Обґрунтовано аналіз ефекторних параметрів кровообігу і механізмів вегетативного забезпечення. Кількісні результати не представлені - дослідження перебуває на етапі реалізації.

Розроблена модель формує методологічну основу комплексного вивчення реактивності і довготривалої адаптації системи кровообігу до фізичних вправ різного типу. Її реалізація дозволить визначити специфіку гемодинамічних і вегетативних перебудов та оцінити швидке відновлення як інформативний маркер функціональних резервів.

Ключові слова: система кровообігу, центральна гемодинаміка, фізичні вправи, функціональне тренування TRX, швидке відновлення, реактивність, адаптація.

DEVELOPMENT OF A CONCEPTUAL MODEL FOR STUDYING THE REACTIVITY AND ADAPTATION OF THE CIRCULATORY SYSTEM TO DIFFERENT TYPES OF PHYSICAL EXERCISE

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Abstract. The functional state of the circulatory system is central to adaptation to physical exercise. Assessment limited to resting parameters or the immediate muscular response does not reflect the complete hemodynamic response, particularly rapid recovery. Different types of exercise and training stimuli involve central, peripheral, and autonomic regulatory mechanisms to varying degrees.

Aim – to substantiate a conceptual approach and develop a methodological framework for studying reactive and adaptive circulatory changes according to exercise type and training stimulus, based on the assessment of central hemodynamics and autonomic regulation.

This methodological study will involve young adult men divided into groups of untrained individuals, individuals engaged in conventional resistance training, and those engaged in functional TRX training. The model includes assessment of stroke volume, cardiac output, cardiac index, total peripheral vascular resistance, and heart rate variability before and after dynamic, static, static-dynamic, and high-intensity interval exercise, with repeat assessment after one year.

A six-block protocol was developed, comprising baseline morphofunctional assessment, standardized exercise tests, evaluation of reactive changes and rapid recovery, control of experimental conditions, and longitudinal assessment of adaptation. Simultaneous analysis of circulatory effector parameters and autonomic regulatory mechanisms was substantiated. Quantitative results are not presented because the study is at the implementation stage.

The developed model provides a methodological basis for comprehensive investigation of circulatory reactivity and long-term adaptation to different types of physical exercise. Its implementation will help identify specific hemodynamic and autonomic adaptations and assess rapid recovery as an informative marker of functional reserves.

Key words: circulatory system, central hemodynamics, physical exercise, functional TRX training, rapid recovery, reactivity, adaptation.

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Conflict of interest:

The authors declare no conflict of interest.

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Received 23.05.2026
Accepted 14.08.2026
Published 29.09.2026