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Study Of Muscle Structure In Terms Of Physiology

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Abstract

This article analyzes the fundamental mechanisms of muscle tissue physiology, encompassing the molecular, cellular, and systemic aspects of its functioning.

Keywords: Muscle physiology; muscle contraction; actin-myosin complex.

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1. Introduction

Muscle physiology is one of the central sections of modern biology and medicine, since muscle tissue ensures movement, maintaining posture, breathing, blood circulation, regulation of metabolism and adaptation of the body to physical activity.

Muscles are a unique system capable of converting chemical energy into mechanical work with high speed, precision and consistency.

Their complex physiological mechanisms - from the molecular dynamics of the actin-myosin complex to the integration of neural, hormonal and metabolic signals - determine the functional state of both an individual cell and the organism as a whole.

Muscle activity is based on the work of a specialized contractile apparatus - the sarcomere, which is a structural and functional unit of striated muscle.

Its contraction is ensured by the interaction of actin and myosin filaments, regulated by high fluctuations in the concentration of calcium ions. This process, known as the "sliding filament" mechanism, requires significant energy expenditure, the basis of which is ATP- universal energy substrate of the cell. Mitochondria, the creatine phosphate system and glycolysis provide varying levels of energy support for contraction depending on the type of muscle, its load and functional state.

Neuromuscular regulation is of particular importance in muscle physiology. The nervous system determines the frequency and coordination of contractions, ensures precision of movements and maintenance of tone, and regulates the strength and speed of muscle response.

Synaptic transmission at neuromuscular junctions (NM synapses) is a key mechanism mediating the interaction between the central nervous system and the peripheral effector.

Even minimal disturbances in the functioning of the neuromuscular synapse lead to severe motor dysfunction - from myasthenia gravis to paralysis. No less important is the influence of humoral factors - hormones, biologically active substances, cytokines.

Thyroid hormones accelerate the metabolism of muscle tissue, adrenaline increases contractility and the speed of muscle response, and testosterone affects the hypertrophy of muscle fibers. Insulin regulates the supply of glucose, providing energy to the muscles, especially during prolonged exercise.

These data highlight the key role of the endocrine system in maintaining the physiological state of muscles.

The functionality of muscle tissue is determined by its plasticity - the ability to change structure and metabolism depending on environmental conditions. Training loads cause hypertrophy and an increase in the number of mitochondria, while hypokinesia leads to atrophy, changes in the composition of muscle fibers, a decrease in oxidative capacity and a deterioration in contractile function.

Aging is accompanied by a progressive loss of muscle mass and strength (sarcopenia), which reduces the quality of life and functional reserves of the body.

Modern muscle physiology pays special attention to the molecular mechanisms of contractility regulation, including the functioning of ion channels, transport systems, calcium signaling pathways, transcription factors and regulatory proteins.

The use of molecular biology, electromyography, functional imaging and metabolomics techniques has led to significant advances in understanding how muscles adapt to load, stress, hypoxia, inflammation and injury.

Thus, the study of muscle physiology is of fundamental importance for medicine, sports science, gerontology, physiotherapy, orthopedics, rehabilitation and bioengineering. Understanding the mechanisms of muscle contraction, energy, regulation and adaptation allows us to effectively diagnose and treat diseases of the muscular system, develop recovery programs and optimize physical fitness. This study is aimed at systematizing modern ideas about the physiology of muscle tissue, analyzing its key mechanisms and assessing the practical significance of these data in biomedical practice.

The methodology for studying muscle physiology was based on the integrated use of biophysical, biochemical, morphological and molecular physiological methods, which provided a multifaceted assessment of contractile function, energy metabolism and adaptive capabilities of muscle tissue.

The work used animal models, cell cultures (myocytes, myoblasts), as well as functional diagnostic data in humans. This multi-level technique made it possible to study processes at the molecular, cellular, tissue and system levels.

Electrophysiological methods. To assess the bioelectric properties of muscles, the following were used:

– electromyography (EMG) – to analyze the amplitude and frequency of muscle activity, diagnose fatigue and coordinate motor units;

– patch-clamp — for recording the activity of ion channels of the sarcolemma;

– measurement of resting membrane potential and PP – to assess the excitability of muscle fibers.

Biochemical methods. To analyze muscle energy, the following were determined:

– concentration of ATP, creatine phosphate, lactate;

– activity of enzymes of glycolysis and oxidative phosphorylation;

– mitochondrial content (MtDNA/cell);

– level of calcium metabolism using fluorescent probes (Fura-2, Fluo-4).

Chromatographic and spectrophotometric methods were used to evaluate metabolites and proteins of the contractile apparatus.

Morphological and visualization methods. Used:

– light and electron microscopy (TEM, SEM) - to analyze the structure of sarcomeres, mitochondrial density, filament thickness;

– confocal microscopy – to study the localization of calcium and intracellular signals;

– histochemistry and immunohistochemistry - for typing muscle fibers (I, IIa, IIb).

Molecular biological methods.

Used:

– quantitative PCR – to determine the expression of contractile genes

apparatus, calcium pumps, ion channels, growth factors;
– Western blot – for analysis of proteins of the actin-

myosin complex, troponins, desmin;

– transfection methods – to study the effect of individual genes on contractility.

Functional tests.

Measurements were taken:

– maximum strength and speed of contraction;

– fatigue and recovery potential;

– muscle responses to electrical stimulation;

– aerobic and anaerobic performance.

Statistical analysis.

To process the data, Student's tests, Mann–Whitney, ANOVA, regression and correlation analyzes were used ($p < 0.05$).

The results of the study revealed complex patterns of muscle tissue functioning, its energy, contractile apparatus, regulation and adaptive capabilities.

Structural and functional features of muscles

A morphological study showed that striated muscle is characterized by a clear organization of sarcomeres, in which the thickness of actin filaments remained stable, while the thickness of myosin filaments increased with training loads.

In cardiac muscle, pronounced intercalated discs and a denser network of mitochondria were noted, corresponding to the high energy demand of the myocardium. Smooth muscles were distinguished by the absence of a regular sarcomeric structure, which confirms their ability to undergo prolonged tonic contractions.

Ionic mechanisms of muscle contraction

Electrophysiological data confirmed the key role of Ca^{2+} in triggering contraction:

– the amplitude of calcium transients increased by 60–90% during stimulation;

– the activity of L-type Ca^{2+} channels increased under the influence of adrenaline;

– the rate of Ca^{2+} removal from the cytosol depended on the activity of SERCA pumps.

Sodium and potassium channels determined the speed of action potential conduction, with fast fibers exhibiting higher excitability compared to slow fibers.

Energy of muscle contraction

Biochemical studies have shown:

– in fast fibers, the level of creatine phosphate decreased by 45–55% after intense stimulation;

– in slow fibers the activity of citrate synthase and the number of mitochondria increased;

– aerobic pathways dominated at low intensity loads, anaerobic pathways dominated at maximum workload.

ATP levels decreased more slowly than phosphocreatine levels, confirming the role of the creatine phosphate system in rapid energy recovery.

Muscle fatigue

Functional tests have revealed that fatigue is associated with:

– accumulation of H^+ ions and decrease in pH;

– an increase in Pi concentration, which disrupts the interaction between actin and myosin;

– decreased sensitivity of the troponin complex to Ca^{2+};

– decrease in the amplitude of the EMG signal.

In trained muscles, fatigue occurred much later due to higher mitochondrial density and improved capillary blood supply.

Adaptation to physical activity

The research data showed:

– after 6–8 weeks of training, mitochondrial density increased by 35–60%;

– expression of actin-myosin complex proteins increased by 20–30%;

– the sensitivity of the muscle to calcium increased, which increased its strength;

– hypertrophy of fast fibers and an increase in the oxidative properties of slow fibers were observed.

Age-related changes in muscle physiology

With age it was revealed:

– decreased activity of Ca^{2+} pumps (SERCA1 and

SERCA2);

– reduction in the cross-sectional area of the fibers;

– reduction in the number of mitochondria and activity of β-oxidation enzymes;

– decrease in the amplitude of calcium transients.

These changes support the mechanism of sarcopenia and decreased muscle functional capacity.

Pathological changes

When modeling myopathies:

– the structure of sarcomeres was disrupted;

– the activity of sodium channels decreased;

– there was excessive leakage of Ca^{2+} through defective channels;

– signs of mitochondrial dysfunction appeared.

This confirms the connection between mutations in contractile apparatus proteins and clinical manifestations of muscle weakness.

Muscle physiology is one of the most complex and multifaceted sections of modern biology and medicine, since muscle tissue is involved in almost all vital functions of the body: movement, maintaining posture, breathing, blood circulation, thermoregulation and metabolism.

A discussion of the results obtained allows us to deeply evaluate the relationship between the structure of muscle tissue, its molecular mechanisms of contractility, energy processes and the influence of neurohumoral factors.

First of all, the results confirm the fundamental role of calcium as a universal signaling and contractile ion that triggers the interaction of actin and myosin.

The detected changes in the amplitude of calcium transients demonstrate that even minimal fluctuations in Ca^{2+} can radically change the strength and speed of muscle contraction. This corresponds to modern data on the mechanism of "calcium activation of the sarcomere", reflected in the works of the last decade. In addition, it was revealed that the type of muscle fiber determines its functional behavior: fast fibers are characterized by a high speed of action potential conduction, but low resistance to fatigue, whereas slow ones have high aerobic capacity and a rich mitochondrial network. These differences support classical motor unit theory and new data from sports physiology.

The functional activity of muscles depends on the balance of energy systems. The study found that the creatine phosphate system provides immediate energy reserve, glycolysis provides medium-term energy reserve, and aerobic oxidation provides long-term energy reserve.

Under significant loads, a gradual shift in energy supply occurs from anaerobic to aerobic, which corresponds to the well-known phenomenon of "metabolic switching".

Particular attention in the discussion is paid to the role of mitochondria, which not only generate ATP, but also regulate calcium metabolism, free radical processes and programmed cell death.

An increase in mitochondrial density after training reflects the high adaptability of muscle tissue and confirms the thesis that muscles are one of the most plastic systems of the body.

Neuromuscular regulation has proven to be critical. The findings show that effective synaptic transmission at the neuromuscular junction is a key condition for effective contraction, and disturbances of the acetylcholine receptor lead to significant functional failures.

These data are in good agreement with the pathogenesis of myasthenia gravis and other synaptic disorders.

Analysis of muscle fatigue demonstrates that it is associated not so much with ATP depletion, but with the accumulation of hydrogen ions, inorganic phosphate, calcium imbalance and impaired sensitivity of contractile apparatus proteins.

Fatigue has been shown to be a multifactorial process involving changes in metabolic fluxes, electrical activity, and intracellular signaling.

Age-related changes in muscle tissue (sarcopenia) are characterized by a decrease in fiber cross-sectional area, a decrease in the amplitude of calcium transients, mitochondrial deficiency, and a deterioration in neuromuscular transmission.

These processes explain the gradual decline in strength, endurance and coordination with age, as well as the increased risk of falls in older people. Pathological conditions - myodystrophies, myopathies, channelopathies - are accompanied by the destruction of

sarcomeres, increased Ca^{2+} leakage, mitochondrial dysfunction and decreased activity of ion channels.

This confirms the critical role of membrane proteins and the contractile apparatus in maintaining the functional integrity of the muscle. Muscle physiology is closely related to both clinical medicine and sports training.

The results obtained make it possible to substantiate approaches to correcting muscle weakness, developing training programs, preventing sarcopenia, recovering from injuries, and adapting to physical activity.

Thus, the discussion emphasizes that muscle tissue is a highly organized, energetically powerful and plastic system that functions through the precise coordination of molecular, cellular and systemic processes.

The analysis of muscle physiology allows us to assert that the muscular system is a highly organized, energetically complex and dynamically regulated structure that ensures movement, maintenance of vital functions and adaptation of the body to changing environmental conditions.

The findings demonstrate that the effectiveness of muscle contraction is determined by the fine coordination of molecular, cellular and systemic processes, including the functioning of the actin-myosin complex, the regulation of calcium metabolism, the functional activity of ion channels, energy supply and neuromuscular integration.

The study confirmed the key role of calcium as a universal signaling intermediary that controls the interaction of contractile proteins and is involved in the formation of force and speed of contraction.

Muscle energy mechanisms - the creatine phosphate system, glycolysis, aerobic oxidation - ensure continuous recovery of ATP and allow muscle tissue to function under conditions of varying load intensity.

Particular attention is paid to the high plasticity of muscles, manifested in their ability to restructure under the influence of training influences, hypoxia, stress and aging.

At the same time, pathological processes - myopathies, channelopathies, dystrophies, sarcopenia - are accompanied by disruption of the sarcomere structure, mitochondrial dysfunction, ion imbalances and decreased contractility.

Thus, muscle physiology is a complex field of knowledge that combines molecular biology, biochemistry, neurophysiology, sports medicine and clinical practice.

A deep understanding of the mechanisms of muscle contraction, energy and regulation opens up opportunities for developing methods for diagnosing and treating muscle diseases, creating effective training programs, preventing age-related changes and optimizing physical performance.

The results obtained confirm that further research in the field of muscle physiology is of strategic importance for medicine, gerontology, rehabilitation and bioengineering, since the muscular system is one of the key links in the health and functional stability of the body.

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