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MYOFIBRILLOGENESIS: FORMATION OF THE CONTRACTILE APPARATUS OF MUSCLE CELLS (LITERATURE REVIEW. ISSUES OF INTEGRATION BETWEEN RESEARCH DISCIPLINES)

Kobeza P.A. ✉ **Myofibrillogenesis: formation of the contractile apparatus of muscle cells (Literature review. Issues of integration between research disciplines).**
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ABSTRACT. Background. Myofibrillogenesis is a critical process for the normal functioning of muscle cells, as the ability of muscles to contract and perform basic physiological functions depends on its efficiency. Understanding the molecular and cellular mechanisms that regulate myofibril formation is important for fundamental biology and biomedicine. Disorders in myofibrillogenesis can lead to various myopathies and other diseases associated with muscle dysfunction. **Objective:** The objective of this review is to study and form a comprehensive understanding of the latest concepts in the interaction of myofibrillogenesis mechanisms at the molecular and cellular levels, including the study of genetic regulation, synthesis and organization of contractile proteins, cytoskeletal organization, and intercellular interactions ensuring myofibril stability and functional integration. **Methods:** Systematic search of scientific publications in international databases such as PubMed, Scopus, and Google Scholar. Utilization of atlases and methodological materials from leading universities specializing in morphology. Analysis of virtual preparations using key methods such as fluorescence microscopy, electron microscopy, and genetic modification techniques. **Results:** Myofibrillogenesis involves genetic regulation, synthesis and organization of contractile proteins, cytoskeletal framework formation, sarcomere organization, intercellular interactions, and mechanotransduction. Myofibrils mature through intercellular interactions and interactions with the sarcoplasmic reticulum and T-tubules. **Conclusion:** Myofibrillogenesis is a complex process involving genetic regulation, protein synthesis and organization, biomechanical influences, and intercellular interactions. Its understanding is crucial for fundamental biology, medicine, and the development of methods for restoring muscle tissue in pathological conditions.
Key words: myofibrillogenesis, sarcomere, actin, myosin.

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Introduction

Myofibrillogenesis is the process of formation of the contractile apparatus of muscle cells, which ensures their functional activity [1, 2]. It is complex and multi-stage [3], includes the synthesis and organization of contractile proteins [4, 5], the formation of sarcomeric organization and integration into the general system of muscle fiber. Myofibrillogenesis is a critical process for the normal functioning of muscle cells, since the ability of muscles to contract and perform their basic physiological functions depends on its efficiency. In this regard, understanding the molecular and cellular mechanisms that regulate myofibril formation is important for fundamental biology and biomedicine [6-8]. Disorders in the processes of myofibrillogenesis can lead to the development of various myopathies and other diseases associated with muscle dysfunction, such as muscular dystrophy [9, 10], myositis and other degenerative diseases [11-14].

Objective

The purpose of this review includes the need to study and form a general idea of the latest concepts in the process of mutual work of the mechanisms of myofibrillogenesis at the molecular and cellular levels,

in particular, the study of genetic regulation, the processes of synthesis and organization of contractile proteins, as well as cytoskeletal organization and intercellular interactions that ensure the stability and functional integration of myofibrils [16]. This study aims to uncover the basic molecular mechanisms that determine the structure and function of muscle cells [17], as well as to study the role of mechanical and biochemical factors in the processes of myofibril formation and stabilization. The relevance of studying the mechanisms of myofibrillogenesis is due to the need for a deeper understanding not only of the molecular aspects of the formation of the contractile apparatus of muscle cells, but also of the interaction between various cellular structures, mechanical and biochemical factors that ensure the effective organization and stability of myofibrils [18]. This allows us to predict the possible consequences of disorders in these processes and opens up new opportunities for the development of therapeutic strategies for the treatment of muscle diseases.

Of particular importance is the study of the genetic regulation of myofibrillogenesis, since it is through the activity of transcription factors, such as MYOD and MYF5, that the initiation of muscle fiber formation is determined [19, 20]. Disturbances in these mechanisms can have serious consequences for the normal development and functioning of muscle tissue [21].

In addition, the relevance of studying the mechanisms of myofibrillogenesis is enhanced by new advances in cell biology, molecular biology, and biomechanics, which allow for a detailed study of the complex interactions between cellular structures and external factors [22], such as physical activity and hormonal changes. This contributes to the development of new approaches to the treatment of muscle diseases and the search for effective methods for restoring muscle tissue functions after injuries or pathological damage [23].

Methods

In addition to a systematic search of scientific publications in international scientific databases such as PubMed, Scopus and Google Scholar, other effective approaches can be used to obtain a deeper understanding and support scientific research. One such approach is the use of atlases and methodological materials from leading universities in the world specializing in morphology [24].

Morphology atlases and methodological materials from universities such as Harvard University, University of Cambridge, Stanford University and others are an important source for studying structural aspects, functional characteristics and development of muscle cells and myofibrils [25, 26]. Atlases provide visualization of complex biological processes such as myofibrillogenesis with accurate images and detailed descriptions of morphological changes occurring at different stages of cell development.

Obtain visual materials that illustrate the stages of myofibrillogenesis, structural features of sarcomeres and myofibrils, which facilitates the understanding of complex morphological processes [27]. Analyze microscopic images that demonstrate tissue and cellular structures, helping to gain a deeper understanding of the mechanisms of cytoskeletal organization and myofibril stability [28-30]. Use interactive teaching and modeling methods that allow you to simulate various aspects of myofibrillogenesis in real time using specialized software [31, 32]. Such materials often include explanations of experimental methods used in university laboratories to study cellular processes [33-35]. A preliminary review includes the analysis of virtual preparations by key methods. Fluorescence microscopy to study the localization of proteins in cells [36-38]. Electron microscopy for detailed analysis of subcellular structures. Genetic modification methods to study the functional roles of specific genes in myofibrillogenesis.

Methodological guides prepared by scientists from leading universities and research institutions are also used for data collection and analysis [39]. These materials usually contain detailed protocols for conducting studies in the field of molecular biology and morphology, which allows standardizing experimental procedures and ensuring comparability of results between different laboratories [40]. The use of atlases and methodological materials from leading universities in the world is an important component of a comprehensive approach to the study of myofibrillogenesis. They allow not only to clarify the known mechanisms, but also contribute to the discovery of new aspects of muscle cell functioning at the molecular level, which may be useful for further fundamental interdisciplinary research and clinical applications [41-44].

Results and discussion

The synthesis of contractile proteins occurs under the control of genetic mechanisms that determine when and in what quantities actin, myosin, troponin and tropomyosin will be produced. Genetic regulation begins with transcription, when DNA in the cell nucleus serves as a template for the synthesis of messenger RNA (mRNA). This process is controlled by special transcription factors that activate or suppress the work of the corresponding genes [45]. The factors MyoD and MRF4 play a key role in stimulating the expression of muscle proteins during the development of muscle cells [46-48].

After the formation of mRNA, it leaves the cytoplasm, where it becomes the basis for protein synthesis. Translation occurs in ribosomes - the process during which amino acids are combined in a certain sequence according to the genetic code. Initially, individual protein chains of actin, myosin and regulatory proteins are formed, which are subsequently subjected to post-translational modifications [49, 50, 51]. These modifications, such as phosphorylation or acetylation, affect their ability to interact and subsequently organize into contractile structures. The syn-

thesis of contractile proteins is a very energy-intensive process, therefore it requires the active work of mitochondria, which provide the cell with energy in the form of ATP. In addition, this process is influenced by extracellular signals, such as growth factors, hormones (in particular, insulin-like growth factor IGF-1) and mechanical stimuli, which can change the activity of the corresponding genes [52].

After protein synthesis in ribosomes, they enter the endoplasmic reticulum system, where their folding and primary modification occur. The correct folding of myosin is particularly important, since this protein consists of heavy and light chains, which must associate correctly to form functional myosin filaments [53]. Chaperone proteins, such as HSP90, play a critical role in this process, helping protein molecules to acquire the correct spatial structure. Subsequently, the synthesized proteins are transported to the Golgi apparatus, where they may undergo additional modifications, such as glycosylation or phosphorylation [54]. They then travel to the sites of myofibril assembly in the sarcoplasm. Actin and myosin interact with accessory proteins such as α-actinin, which anchors actin filaments in Z-disks, and titin, which stabilizes the sarcomere structure.The regulation of contractile protein synthesis is extremely sensitive to changes in the internal and external environment of the cell. Hormonal factors such as testosterone and growth hormone can stimulate this process, while catabolic states (e.g., nutrient deficiency or stress) inhibit the formation of new proteins and can cause the degradation of existing myofibrils [55]. In addition, physical activity affects the expression of the corresponding genes: regular training activates signaling pathways that stimulate protein biosynthesis, while hypodynamia or immobilization, on the contrary, lead to their degradation [56].

Thus, the synthesis of contractile proteins is a multilevel process that includes genetic regulation, transcription, translation, post-translational modifications, and myofibril assembly. The interaction between various structural and regulatory proteins ensures the correct formation of sarcomeres and maintenance of the functional activity of muscle cells [57, 58]. The formation of the cytoskeletal framework includes two key processes:

1. Aggregation of actin filaments and connection with the desmin network.
2. The role of integrins in mechanotransduction of signals to organize the structure of myofibrils.

The formation of the cytoskeletal framework of myofibrils begins with the aggregation of actin filaments, which form a framework for future contractile structures [59]. Actin filaments polymerize from G-actin monomers with the participation of regulatory proteins, such as profilin and thymosin-β4, which control the balance between the monomeric and filamentous forms of actin. A key step is their ordered organization and anchoring in Z-discs, where actin interacts with α-actinin to form stable complexes necessary for sarcomere function [60].

The desmin network, consisting of desmin intermediate filaments, provides a link between neighboring myofibrils and stabilizes them in the sarcoplasm. Desmin forms a network that anchors the Z-discs of myofibrils to the sarcolemma, maintaining the spatial organization of the muscle fiber [61]. It also interacts with the proteins plectin and synemin, which further strengthen the cytoskeleton and promote its connection to membrane structures [62]. Disruption of the desmin scaffold can lead to myofibril instability and the development of myopathies.

Integrins, which are transmembrane receptors, play a critical role in the mechanotransduction of signals necessary for the correct organization of myofibrils. They connect the intracellular actin cytoskeleton with the extracellular matrix, ensuring the stability of the muscle fiber and the transmission of mechanical signals that affect muscle differentiation and adaptation [63]. Integrins activate a number of signaling pathways, including FAK (focal adhesion kinase) and MAPK, which regulate the expression of proteins necessary for the formation and remodeling of myofibrils. In response to mechanical stress, these signals contribute to the enhancement of the synthesis of structural proteins and the stabilization of the cytoskeletal network, which is important for maintaining muscle function and adaptation to physical exertion. The organization of sarcomeres is a critical stage in the formation of the contractile apparatus of muscle cells, which ensures their functional activity [64-66]. The sarcomere, as the basic structural unit of the muscle, consists of thin actin filaments and thick myosin filaments, which interact during the contraction process. Myosin filaments are integrated into the actin filament system through a mechanism of cross-bridge formation regulated by proteins such as troponin and tropomyosin, which control the availability of the connection between myosin heads and actin filaments [67]. The contraction process begins after the myosin heads form cross-bridges with the actin filaments, which leads to the displacement of the actin filaments relative to each other and, as a result, to the shortening of the sarcomere. Such shortening occurs within the sarcomere, where Z-discs serve as points of attachment for the actin filaments [68]. Z-discs contain proteins, in particular α-actinin, which stabilize the actin filaments and ensure their correct ordering. The interaction of actin filaments with α-actinin in the Z-discs contributes to the organization of the sarcomeres and the stability of the muscle structure during function. The connection between the Z-discs and the plasmalemma is mediated by costamer proteins, in particular integrins, which act as transmembrane receptors connecting the intracellular actin cytoskeleton to the extracellular matrix [69]. This mechanism of mechanical load transmission ensures the stability of muscle fibers, as it affects the organization of sarcomeres and their integration with membrane structures. Costamer proteins, such as talin, wicklin, and dystrophin, are involved in maintaining the integrity of the cell mem-

brane and ensuring its connection with the cytoskeleton. Disruption of the function of these proteins can lead to the development of muscle diseases, such as muscular dystrophy, which is accompanied by weakening of muscle fibers and their destabilization. The process of myofibril maturation is a complex and multi-step process in the development of a muscle cell, where intercellular interactions and the integration of various components of the cellular structure play an important role. The coordination of myofibrils within the myocyte is necessary for the formation of an effective contractile apparatus that ensures normal muscle function [70]. This coordination involves the stable arrangement of myofibrils, their interaction with each other, as well as with other components of the cellular structure, such as the sarcoplasmic reticulum and transverse tubules. Myofibrils, which are the basic structural units of the muscle cell, must be correctly oriented and interact with each other to ensure synchronized muscle contraction [71,72]. This interaction includes the organization of myofibrils into bundles, their stability, and appropriate anchoring by cytoskeletal proteins. Myofibril alignment involves interactions between actin filaments, myosin filaments, and other structural proteins that provide mechanical stability and elasticity to the muscle fiber [73]. One important aspect of myofibril maturation is their interaction with the sarcoplasmic reticulum and transverse tubules. The sarcoplasmic reticulum, a network of membrane structures surrounding myofibrils, plays an important role in storing and regulating calcium levels in the cell. Calcium is a key element in initiating muscle contraction because it activates troponin, which allows myosin heads to interact with actin filaments. Transverse tubules (T-tubules) are part of the membrane system that provides electrical impulse transmission into the cell, which stimulates the release of calcium from the sarcoplasmic reticulum. This interaction between membrane structures and myofibrils allows for the synchronization of muscle contractions and the normal functioning of muscle tissue. In general, myofibril maturation is a process that requires precise coordination between intercellular interactions, the structural organization of sarcomeres, and the effective regulation of calcium ions, which ensures the normal functioning of the muscle fiber [74]. Myogenesis, the process of formation and development of muscle cells, is regulated by a number of genetic factors that determine both the differentiation of myocytes and the maturation of muscle fibers [75,76]. A key role in myogenesis is played by the genes MYOD and MYF5, which are part of a family of transcription factors that activate the expression of genes responsible for the formation of muscle tissue. The genes MYOD and MYF5 encode transcription factors that are critical for the initiation of myogenesis. MYOD activates the myocyte differentiation program, promoting the transition from a promitotic state to a myogenic cell population. The interaction of MYOD with other regulatory proteins, such as MYOG (myogenin), determines the subsequent differentiation of cells into mature muscle fibers. MYF5, although having a similar function to MYOD, is active at early stages of development, ensuring the initiation of muscle cell formation at the stage of mesodermal development. Both genes are key for the correct formation of muscle cells, and defects in them can lead to impaired myogenesis and the development of muscle diseases. Myostatin, also known as the gene-protein inhibitor of myogenesis, is an important regulator of muscle cell maturation. It functions through a negative feedback mechanism, restraining excessive muscle mass gain by inhibiting myoblast differentiation and proliferation. Myostatin negatively affects myocyte differentiation, limiting their transition from myoblasts to mature muscle fibers. Reduced levels of myostatin or mutations that cause its insensitivity can lead to muscle hypertrophy, as demonstrated in some animals and humans with excessive muscle development [77]. This mechanism is important for controlling normal myocyte maturation and maintaining muscle tissue homeostasis. MYOD and MYF5 genes are important for the initiation and regulation of myogenesis, while myostatin regulates myocyte maturation, limiting their excessive proliferation and helping to maintain a normal balance between muscle growth and maturation. The processes of myofibril organization and muscle fiber contraction depend largely on a variety of signaling pathways that regulate cellular activity. One of the key mechanisms controlling myofibrillogenesis and muscle function is calcium-dependent signaling pathways, as well as the involvement of serine-threonine kinases in these processes [78]. Calcium is an important molecule that is actively involved in the regulation of muscle contraction and myofibril organization [79, 80]. Changes in the concentration of calcium in the cytosol of cells activate a number of signaling pathways that directly affect the organization of myofibrils. One of the main effectors of calcium signals is calmodulin, a protein that binds calcium and changes its conformation, activating a variety of enzymes and proteins involved in the regulation of cellular functions.

Calmodulin interacts with various kinases and phosphatases that regulate processes such as muscle contraction, cytoskeletal stabilization, and myofibril remodeling. For example, calmodulin activates calcium/calmodulin-dependent protein kinase (CaMK), which regulates the activity of proteins responsible for maintaining the structural organization of myofibrils [81]. Changes in intracellular calcium levels are also important for the interaction between actin and myosin, which is essential for muscle contraction.

Serine-threonine kinases are important molecules in the regulation of many cellular processes, including myofibril organization. These kinases phosphorylate their substrates, which alters their activity and functionality. Some of the key serine-threonine kinases involved in myofibrillogenesis are AMPK (AMP-activated protein kinase), Rho kinases, and

p38 MAP kinase. AMPK is important for the regulation of cellular energy balance and can activate a number of processes that stimulate myocyte differentiation in response to low energy levels. Rho kinase is involved in the regulation of the cytoskeleton and ensures the stability of actin filaments in myofibrils. In addition, it contributes to the organization of focal adhesions, which is necessary for normal adhesion between the cell and the extracellular matrix. P38 MAP kinase is actively involved in the stress response processes, regulating myogenesis through its influence on the expression of genes encoding the structural components of myofibrils. All these serine-threonine kinases play a key role in the synchronization of the different stages of myofibrilogenesis, ensuring stable organization of myofibrils and proper functioning of the muscle fiber [82]. Calcium-dependent mechanisms through calmodulin and serine-threonine kinases are critically important for the regulation of myofibril organization [83], which includes the stability of actin filaments, interaction with myosin, and adaptation of muscle cells to mechanical and metabolic loads. Biomechanical factors play a crucial role in the processes of development and function of muscle cells. Mechanical load is a powerful stimulus for the regulation of both myocyte differentiation and their adaptation to changes in the external environment [84]. Mechanical forces arising during physical activity interact with cellular structures and signal cells about the need to activate certain genetic and molecular mechanisms that affect the functionality and development of muscle fibers.

Mechanical load directly affects myocyte differentiation through mechanotransduction, the process by which cells perceive mechanical stimuli and convert them into biochemical signals. This is accomplished by integrins, which link the myocyte cytoskeleton to the extracellular matrix. Mechanical stress activates signaling pathways such as Rho kinase, MAP kinase, and calcium-dependent mechanisms that regulate the expression of genes involved in myogenesis [85]. Mechanical forces also stimulate the proliferation and differentiation of myoblasts, which develop into mature myocytes. In particular, stretching or compression of muscle fibers leads to the activation of genes that control the formation of structural components of myofibrils, such as actin, myosin, and desmin. This process allows myocytes to respond to mechanical stress, which is necessary for normal muscle function. Adaptive changes in muscle are a response to changes in functional load, such as physical training, intense physical exertion, or recovery from injury. In response to increased load, myocytes can undergo hypertrophy - an increase in their size and number of myofibrils. This process provides greater strength and endurance of the muscle fiber, which is an adaptation to increased loads [86]. The basis of this mechanism is the synthesis of new proteins that are part of myofibrils, as well as the reorganization of the myocyte cytoskeleton.

On the other hand, a decrease in load, for example, in the case of prolonged immobilization or insufficient physical activity, leads to muscle atrophy. In this case, the number of myofibrils and their organization decreases, which reduces the functional capabilities of the muscle. Adaptation of muscle cells to changes in load is carried out through the activation of mechanotransduction mechanisms [87], which include proteins that regulate the mechanical stability of cells, as well as enzymes that stimulate the synthesis of structural proteins. Therefore, mechanical load is an important factor that regulates both the development and adaptation of muscle cells to changes in the environment [88]. Changing the functional load contributes to both the activation of muscle hypertrophy and atrophy mechanisms, which are important processes for maintaining optimal functional activity of muscle tissue [90, 91].

Prospects for further development

The study of myofibrillogenesis is one of the most promising and relevant areas in modern morphology and cell biology. This is due to the possibility of applying the knowledge gained not only for fundamental research, but also for the development of new therapeutic strategies for the treatment of muscle diseases. The prospects for further development in this area open up numerous directions for research and innovative solutions.

One of the most promising directions in the study of myofibrillogenesis is the improvement of genetic and molecular methods. Thanks to the development of CRISPR-Cas9 and other genome editing technologies, it is possible to more accurately and effectively modify genes involved in the processes of myofibrillogenesis. This will allow to study in detail the functional roles of specific genes in the formation of muscle fibers. To identify the mechanisms of gene expression regulation at different stages of muscle cell development. Develop new therapeutic strategies to correct genetic defects that cause myopathies and other muscle diseases. Of particular importance is the study of transcription factors, such as MYOD and MYF5, which are critical for the initiation of myogenesis. Molecular studies of these factors may allow the creation of models for the correction of disorders in the genetic processes of muscle cell formation.

Current research is increasingly focused on the study of biomechanical factors that influence the processes of myofibrillogenesis. This includes the study of mechanical loads that regulate the organization of myofibrils and the stability of sarcomeres. An important aspect is also the interaction of cells with their microenvironment, in particular with the extracellular matrix, which can affect the development and stability of muscle fibers.

Developing new methods for analyzing the biomechanical aspects of myofibrillogenesis may allow to determine how mechanical loads or physical activity change the structure and function of muscle cells. To understand how muscles adapt to different biome-

chanical conditions, which may be important for rehabilitation programs after injuries or surgical interventions. To develop innovative materials and methods for the treatment of muscle injuries or degenerative diseases, such as muscular dystrophy.

Using the latest technologies for visualization and analysis. Imaging technologies are becoming an integral part of research in morphology. Fluorescence microscopy, electron microscopy and other advanced methods allow obtaining high-resolution images of the microstructures of muscle cells and myofibrils. The development of new high-resolution visualization technologies opens up opportunities for to study in more detail the processes of sarcomere formation and their organization at the molecular level. Analysis of interactions between different cellular structures, such as the cytoskeleton, sarcoplasmic reticulum and membrane components. Study of molecular mechanisms of stability and dynamics of myofibrils in response to changes in external conditions.

These methods allow obtaining data on morphogenesis that could not be achieved by traditional microscopic methods, and allow a more accurate assessment of the mechanisms of functioning of myofibrils at different stages of their development. Regeneration and therapeutic applications. Another important direction is the development of therapeutic methods for the restoration of muscle tissues in injuries or diseases. The use of stem cells for the regeneration of muscle tissue has already shown some success, but requires further research. Modern technologies allow the use of stem cells to regenerate damaged myofibrils and restore their functions. In addition, the development of gene therapy methods and treatment using microRNAs may provide new opportunities for the correction of genetic defects that cause muscle cell degeneration.

The prospect of using nanotechnology to create biocompatible materials that can be used to repair damaged muscle tissue opens up new possibilities for clinical applications. This approach could significantly improve the outcomes of patients with muscle injuries and degenerative diseases, allowing for accelerated recovery of muscle function. Future research into myofibrillogenesis is likely to be characterized by interdisciplinary approaches that combine biological, chemical, physical, and engineering sciences. Collaboration between molecular biologists, engineers, physiologists, and clinicians will allow the development of new methods for studying and treating muscle diseases. Progress in this area may also lead to the creation of personalized treatments that take into account individual genetic and biochemical characteristics of patients, which could significantly increase the effectiveness of therapy.

Conclusions

1. Myofibrillogenesis is a complex process involving genetic regulation, protein synthesis and organization, biomechanical influences, and intercellular interactions. Its understanding is important for fundamental biology, medicine, and for the development of methods for restoring muscle tissue in pathological conditions.

2. Genetic regulation of myofibrillogenesis is the basis for the formation of functional muscle cells. Myofibrillogenesis begins with genetic regulation that determines the synthesis of contractile proteins (actin, myosin, troponin, tropomyosin). Genetic factors, such as the transcription factors MYOD and MYF5, play a critical role in the initiation of myogenesis, ensuring the correct development of muscle cells. Defects in these genes can lead to disorders in the formation of muscle fibers, which has serious consequences for the functioning of muscle tissue.

3. The mechanisms of synthesis and organization of contractile proteins determine the efficiency of myofibril functioning. The process of synthesis of contractile proteins is very energy-intensive and requires the integration of various cellular mechanisms, including post-translational modifications and protein folding. Actin and myosin, as the main components of sarcomeres, must correctly interact and organize into structural units to ensure muscle contractile function. The influence of external and internal factors, such as physical exertion or hormonal changes, can regulate this process, stimulating or inhibiting protein biosynthesis.

4. Cytoskeletal organization and intercellular interactions are key to myofibril stability. The formation and stabilization of the cytoskeleton of muscle cells occurs through the aggregation of actin filaments, interaction with the desmin network and integrins, which provide mechanical stability of cells. The proper functioning of these mechanisms is critical for maintaining myofibril integrity and muscle fiber stability, which in turn affects the ability of muscles to perform their contractile functions.

5. Sarcomere organization and interaction with the plasmolemma determine the efficiency of muscle contraction. The structural organization of sarcomeres, which includes correctly ordered actin and myosin filaments, is the basis for muscle contraction. The connection of Z-discs with the plasmolemma through costamere proteins (e.g., integrins) is important for transmitting mechanical signals and ensuring synchronized work of myofibrils, which is crucial for the normal functioning of muscle tissue. Disruption of this process can lead to serious muscle diseases.

6. Intercellular interactions and mechanotransduction contribute to the maturation and stabilization of myofibrils. The alignment of myofibrils within the myocyte and their interaction with the sarcoplasmic reticulum and transverse tubules are important steps in myofibril maturation. The interaction between myofibrils and membrane structures such as the sarcoplasmic reticulum regulates calcium metabolism, which is essential for muscle contraction. These intercellular interactions also contribute to the stability and efficiency of muscle contraction, which is essential for normal muscle function.

7. The prospects for further developments in the study of myofibrillogenesis indicate the need for an integrated approach that integrates molecular biology, biomechanics, engineering, and clinical sciences. Further improvements in genetic and molecular methods, the development of imaging technologies, and the use of stem cells and nanotechnology promise significant progress in the treatment of muscle diseases and the development of new therapeutic strategies.

Information on conflict of interest

There are no potential or apparent conflicts of interest related to this manuscript at the time of publication and are not anticipated.

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Кобеза П.А. Міофібрилогенез: формування скоротливого апарату м'язових клітин (Огляд літератури. Питання інтеграції між науковими дисциплінами).

РЕФЕРАТ. Актуальність: Міофібрилогенез є критичним процесом для нормального функціонування м’язових клітин, оскільки від його ефективності залежить здатність м’язів скорочуватися та виконувати основні фізіологічні функції. Розуміння молекулярних та клітинних механізмів, що регулюють формування міофібрил, є важливим для фундаментальної біології та біомедицини. Порушення процесів міофібрилогенезу можуть призвести до розвитку різноманітних міопатій та інших захворювань, пов’язаних з м’язовою дисфункцією. **Мета.** Метою цього огляду є вивчення та формування загального уявлення про новітні концепції процесу взаємодії механізмів міофібрилогенезу на молекулярному та клітинному рівнях, зокрема, дослідження генетичної регуляції, процесів синтезу та організації скоротливих білків, а також цитоскелетної організації та міжклітинних взаємодій, що забезпечують стабільність та функціональну інтеграцію міофібрил. **Методи.** Систематичний пошук наукових публікацій у міжнародних наукових базах

даних, таких як PubMed, Scopus та Google Scholar. Використання атласів та методичних матеріалів провідних університетів світу, що спеціалізуються на морфології. Аналіз віртуальних препаратів за ключовими методами, такими як флуоресцентна мікроскопія, електронна мікроскопія та методи генетичної модифікації. **Результати.** Міофібрилогенез включає генетичну регуляцію, синтез та організацію скоротливих білків, формування цитоскелетного каркасу, організацію саркомерів, міжклітинні взаємодії та механотрансдукцію. Цитоскелетна організація включає агрегацію актинових філаментів та зв'язок з десміновою мережею. Міофібрили дозрівають через міжклітинні взаємодії та взаємодію з саркоплазматичним ретикулумом та Т-трубочками. Механічні фактори впливають на диференціацію та адаптацію міоцитів. **Підсумок.** Міофібрилогенез є складним процесом, що включає генетичну регуляцію, синтез та організацію білків, біомеханічні впливи та міжклітинні взаємодії. Його розуміння є важливим для фундаментальної біології, медицини та для розробки методів відновлення м'язової тканини при патологічних станах.

Ключові слова: міофібрилогенез, саркомер, актин, міозин.