УДК 616.72:[616.8-009.12:615.823]](048.3)

DOI: http://dx.doi.org/10.15674/0030-598720231100-107

Conceptual model of the influence of low-frequency vibration on the process of restoration of joint mobility after immobilization

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Disruption of joint mobility (contracture) is a frequent consequence of the treatment of injuries or orthopedic diseases, when the method of immobilization is used in the treatment process. One of the physiotherapeutic methods of preventing contractures and restoring joint mobility after long-term immobilization is vibration therapy. Objective. Create a concept of the effect of low-frequency vibration on joints and peri-articular tissues after immobilization. Methods. The work was performed using a meta-analysis of literature sources from scientific databases. The publications were analyzed, which considered the impact of vibration on joints or had data on its biological impact on body tissues. Results. The physiological impact of vibration on the body is based on mechanical, physico-chemical and thermal effects. The expression of the physiological response depends on the frequency and amplitude of oscillations, conditions of conducting and localization. The concept is based on the features of the impact of vibration on the structural elements of limbs and joints. The vibration applied to the limb irritates mechanoreceptors, which send a signal to the central nervous system, and thanks to motoneurons, muscle contraction occurs, which affects peripheral blood flow and blood oxygenation. Accordingly, redox processes in tissues are launched. Micromovements caused by vibration contribute to the nutrition of cartilage and metabolism in the synovial fluid, improving the nutrition of periarticular tissues. This contributes to the recovery of both joint and adjacent tissues. Contraction of muscles through motoneurons gives impetus to a gradual increase in their motor activity and strength, restoration of nutrition and cartilage surface - to restoration of mobility. Conclusions. The created conceptual model of the effect of low-frequency vibration on joints with limited mobility due to immobilization takes into account tissue changes under its influence. The concept involves restoration of nutrition of tissues and muscles adjacent to the joint. It is vibration, due to the possibility of transmitting vibrational energy between tissues, that enables the processes of muscle contraction, which increase the blood supply and metabolism of the joint.

Порушення рухомості суглобів (контрактури) є частим наслідком лікування травм або ортопедичних захворювань, коли у процесі лікування застосовують метод іммобілізації. Одним із фізіотерапевтичних методів профілактики контрактур і відновлення рухомості суглобів після тривалої іммобілізації є вібротерапія. Мета. Створити концепцію впливу низькочастотної вібрації на суглоби та періартикулярні тканини після іммобілізації. Методи. Роботу виконано за допомогою метааналізу джерел літератури з наукових баз даних. Проаналізовано публікації, де розглянуто вплив вібрації на суглоби або є дані щодо її біологічного впливу на тканини організму. Результати. В основі фізіологічного впливу вібрації на організм лежать механічні, фізико-хімічні та теплові ефекти. Вираженість фізіологічної відповіді залежить від частоти й амплітуди коливань, умов проведення та локалізації. Концепція базується на особливостях впливу вібрації на структурні елементи кінцівок і суглобів. Застосовувана до кінцівки вібрація подразнює механорецептори, які подають сигнал у ЦНС і завдяки мотонейронам відбувається скорочення м'язів, котре впливає на периферичний кровоток і оксигенацію крові. Відповідно, запускаються окислювально-відновні процеси в тканинах. Мікропереміщення, спричинені вібрацією, сприяють живленню хряща й обміну речовин у синовіальній рідині, покращенню живлення періартикулярних тканин. Це сприяє відновленню як тканин суглоба, так і прилеглих до нього. Скорочення м'язів через мотонейрони дає поштовх до поступового збільшення їхньої рухової активності та сили, відновлення живлення та поверхні хряща — до відновлення рухомості. Висновки. Створена концептуальна модель впливу низькочастотної вібрації на суглоби з обмеженням рухомості внаслідок іммобілізації враховує зміни тканин під її дією. Концепція передбачає відновлення живлення прилеглих до суглоба тканин і м'язів. Саме вібрація завдяки можливості передавання енергії коливання між тканинами дає змогу ввімкнути процеси скорочення м'язів, які посилюють кровопостачання й обмін речовин суглоба. Ключові слова. Суглоб, імобілізація, концептуальне моделювання, низькочастотна вібрація.

Key words. Joint, immobilization, conceptual modeling, low-frequency vibration

Introduction

Contractures are a loss of joint mobility caused by structural changes not in bone tissue, but in muscles, ligaments, and tendons. Today, it is the most common clinical problem, as this abnormal condition negatively affects the daily life of patients, reducing its quality [1]. Impaired joint mobility is a frequent consequence of the treatment of various injuries or orthopedic diseases when the immobilization method is used. Patients with limb immobilization, especially long-term, have a high risk of developing joint contractures, which affect the final results of treatment of injuries and orthopedic diseases [2].

One of the physiotherapeutic methods of preventing contractures and restoring the mobility of joints after long-term immobilization is vibrotherapy (from Latin *vibrare* — to shake, oscillate and from Greek *therapeia* — treatment) [3, 4]. The technique involves the influence of low-frequency mechanical waves, which is carried out in direct contact with the patient's tissues or body and leads to selective excitation by vibration of various mechanoreceptors, causing a number of physiological changes and sanogenic effects. The most important ones include analgesic, trophic, anti-inflammatory, lymphatic drainage, vasoactive and tonic. Apparatus for vibrotherapy is divided into devices for local (vibromassage) and general action (for the whole body). Previously, we developed a conceptual model of the formation of contracture (permanent restriction of movement) in joints after long-term immobilization or restriction of mobility [5].

Purpose: to create a concept of the effect of low-frequency vibration on joints and peri-articular tissues after immobilization.

Material and methods

The study was performed using a meta-analysis of literature sources from scientific bases Cochrane Library, Scopus, National Library of Medicine — National Institutes of Health, ReLAB-HS Rehabilitation Resources Repository, Mendeley Reference Manager, the Physiological Society library, and literature on physiology and biochemistry of domestic and foreign authors.

The study involved an assessment of the data on the impact of vibration on joint tissues, the circulatory system, and muscles. 80 sources were analyzed, of which 32 were selected, where the impact of vibration on joints or body tissues was considered directly.

Results and their discussion

The physiological impact of vibration on the body is based on mechanical, physico-chemical and thermal (manifested to a lesser extent) effects. The expression of physiological mechanisms depends on intensity and parameters (frequency, amplitude) of impact, conditions of implementation and localization [3, 4, 6, 7]. Frequencies in the range of 10–200 Hz have the most noticeable effect on body tissues.

The primary reaction of the body to the local effect of mechanical vibrations occurs due to direct interaction with cells and the environment. The amount of energy transmitted from the source of vibration to a person directly depends on the frequency and amplitude of oscillations. Sensory perception of vibration is carried out by nerve receptors of the skin, Meissner's glomerular corpuscles and Pacinian corpuscles. The frequency range of vibrational sensitivity of Meissner corpuscles is 2–40 Hz, and the limit amplitude is 35–100 μm. Mechanoreceptors enhance the processes that take place in the tissues and convert them into energy that is much higher than that of the active vibration factor. Impulses from vibroreceptors are transmitted to the central nervous system (CNS) through the posterior columns of the spinal cord. Afferent flows arising after stimulation of mechanoreceptors form local, segmental, generalized body reactions [8, 9].

Mechanical vibrations with a frequency of more than 50 Hz are responsible for the selective irritation of mechanoreceptors, blood vessels, vegetative nerve conductors, which leads to the expansion of muscle-type blood vessels, increased local blood flow and lymph drainage, contributes to a decrease in muscle tone and activation of trophic processes in other tissues.

One of the main impacts of the therapeutic effect of vibrations is pain relief. Its mechanism is conditioned by the adaptation of the body due to the development of inhibition signs in the central nervous system. Weak vibrational irritations results in narrowing of blood vessels, strong ones in expansion. Low frequencies of mechanical vibrations trigger vascular atony; high frequencies (100–200 Hz) cause spasm.

Mechanical fluctuations in frequencies are transmitted to the central nervous system and are realized on the periphery in the form of short-term muscle contractions. The vibration acts on their entire volume, there is a significant increase in the contraction capacity of the muscles, the metabolism increases without the accumulation of lactic acid, which allows you to quickly restore the muscles after physical exertion and injuries.

Vibration promotes relaxation and strengthening of muscle stretching, increases the elasticity of ligaments and tendons, increases mobility in the articular-ligamentous apparatus, normalizes trophic processes, contributing to the full production of synovial fluid [2, 10].

Contractures formed as a result of immobilization respond to low-frequency vibration that is applied directly to the affected joint. Researchers have noted the positive effect of low-frequency oscillations on increasing the amplitude of movements in the joints, but without a comprehensive study [2, 10]. Studies on the effect of low-frequency local vibration on joints were carried out by the Soviet researcher V. T. Nazarov. He created a series of devices for local low-frequency vibration to increase the range of motion of athletes and dancers, and subsequently substantiated the therapeutic effect of vibration on damaged joints and peri-articular tissues [11, 12]. Unfortunately, the proven effectiveness of local vibration has not been widely used in medical rehabilitation.

Changes in the tissues adjacent to the joint begin with the blocking of motor nerve impulses that gradually reduce and over time turn off the function of muscle contraction. According to M. I. Arinchin [13], muscles perform not only the function of support and movement, but also play a significant role in blood circulation, providing the so-called «peripheral heart» function. A decrease in the supply of nutrients to the tissues of the joint and the loss of nutrition of the muscles due to the slowing down of blood circulation leads to their reconstruction, i. e. atrophy, fibrotization, deformation and degeneration of the cartilage.

The task of rehabilitation involves restarting the processes of restoring joint mobility. Its implementation begins precisely with the restoration of nutrition, that is, blood circulation in the muscles of the limb, and the involvement of the joint tissue in the process. Of course, this is a long-term work, because recovery does not happen quickly.

So, if the changes in the joints of the limbs begin with the slowing down of blood circulation, it should be assumed that the recovery depends on a full blood supply. Muscle contraction plays an important role in the work of blood vessels of the limbs. Impulses transmitted from the CNS to muscles by motor nerves are known to cause muscle contraction. Proprioceptors are responsible for the feedback signal from the muscle to the central nervous system. Receptors that respond to a mechanical stimulus are called mechanoreceptors. They are present in tendons, muscle fascia, joint bursae and in all organs. In the case of deformation of these nerve endings, nerve irritation occurs and the biopotential from them is sent to the central nervous system. The sensitivity of the receptors is very high, they respond to mechanical tissue displacements of 10–11 m (the size of a hydrogen atom), for a displacement of 10–6 m, a generator potential arises in them [8, 9].

According to the Dubois-Raymond law of irritation (accommodation), the irritating action depends not only on the absolute magnitude of the direct current or its density, but more on the speed of its increase over time. Under the slowly increasing effect of the stimulus, excitation does not occur due to the adaptive reaction of the tissue. This phenomenon was called accommodation [14, 15]. And although the Dubois-Raymond law applies to the irritation of tissues by electric current, let us try to attribute it to mechanical vibrations, namely to the vibration effect. With some assumptions, for mechanoreceptors vibration can be considered to be a very strong stimulus, since the direction of mechanical deformation changes rapidly. But there is also a limit to the rate of change of the excitation factor — it should not be too high for the receptors to respond to such stimuli. For mechanoreceptors, the sensitivity frequency is within 10–104 Hz (Fig. 1).

It should be noted that the frequencies and amplitudes that are optimal for stimulating mechanoreceptors are higher than for performing the blood-pumping function of muscles. To determine the optimal vibration effect for its launch, it is necessary to consider some positions of the muscles.

Skeletal (striated) muscles are bundles of muscle fibers consisting of myosymplasts and myosatellitocytes. The cytoplasm of myosymplasts contains myofibrils, which consist of actin and myosin myofilaments (contractile proteins actin and myosin). In the fibril, these proteins partially mutually penetrate each other's space, and during muscle contraction, actin threads slide between myosin threads, during relaxation, the reverse occurs.

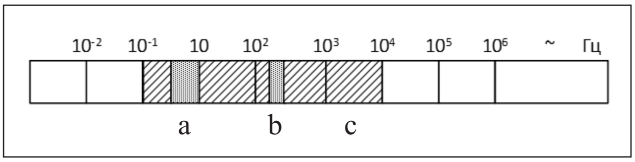

Fig. 1. Section of the spectrum of sensitivity of mechanoreceptors to mechanical vibrations: a–c — limits of sensitivity, a — the most effective frequencies resonant for organs and the human body; b — resonance frequencies for proteins and cells; c – approximate frequency spectrum to which the mechanoreceptor responds

The energy for such a relative movement of protein strands comes mainly from the splitting into component parts of adenosine triphosphoric acid (ATP). Then, thanks to a series of chemical transformations, ATP is restored again and the actin-myosin protein complex is ready to contract again. Enzymatic activity changes under the influence of external factors, in particular, vibration. Actomyosin is sensitive to vibrations mainly in the range of 10–500 Hz. Its enzymatic activity significantly decreases at frequencies of 25, 100, 200 and 300 Hz. Maximum oppression of the actin-myosin complex activity is observed as a result of vibration for 30 minutes, when up to 90 % of enzymatic activity disappears. But these changes are easily reversible within 5–30 minutes. Therefore, vibration stimulation will be useful if its duration does not exceed the specified time.

Thus, the vibration effect acting along the muscle fiber irritates the mechanoreceptors, which causes the muscle fibers to contract. This, in turn, infuses the vessels located in the muscles and starts the process of blood pumping. With the restoration of blood circulation, tissue nutrition is gradually restored. The more vessels, including small ones, are involved in the blood circulation process, the faster recovery will occur.

One of the evidences of the expediency of using local low-frequency vibration for development of immobilization limitation of joint mobility is a hypothesis put forward and developed by M. I. Arinchin [13].

A study of the function of the water-lipid-protein complex of blood cells showed that the activity of oxygen-dependent reactions under the influence of low-frequency vibration increases. That is, at the cellular level, it has been determined that low-frequency vibration has a positive effect on the activation of energy exchange between the cytoplasm and the external environment of the cell [16–18]. Therefore, it can be predicted that the activation of oxygen-dependent processes in cells and, accordingly, in tissues, accelerates healing processes. Moreover, the additional supply of oxygen accelerates the start of redox reactions of metabolism, energy and nervous activity.

K. E. Games et al. [2] in a meta-analysis found an increase in peripheral blood flow as a result of low-frequency vibration of the whole body, but without noticeable signs of muscle oxygenation. It can be stipulated that the restoration of full blood circulation ensures the full involvement of oxygen, which enters the tissues during vibration therapy, in biochemical processes.

The schematically described process is shown in Fig. 2.

Long-term immobilization or restriction of limb mobility is known to result in a decrease in muscle strength, and later to atrophy, gradual resorption of its tissues, up to the complete death of the limbs. And this occurs against the background of preserving the integrity of blood vessels and the normal functioning of the heart. This probably explains the very painful reorganization of the body after limb amputation. After all, it was believed that limbs are only organs of support and movement. Therefore, after healing the stump and eliminating the mental trauma, one would expect relief in the heart activity and better blood supply to other organs. In fact, it turns out to be the opposite. The body painfully rebuilds its functions for several more years [19]. Therefore, each muscle is not only an organ of movement, but also takes an active part in ensuring blood supply to a certain part of the system and vital activity of the body in general.

If the effect of low-frequency vibration on muscles and the circulatory system has been studied and its effectiveness has been proven in experimental studies, then the healing effect of vibration on bone, connective and cartilage tissues has hardly been investigated. This is explained by the fact that changes in these tissues occur more slowly than in muscles and blood vessels, so studying the process requires long-term observations.

In recent years, whole-body vibration (WBV) has become a popular therapeutic and preventive method

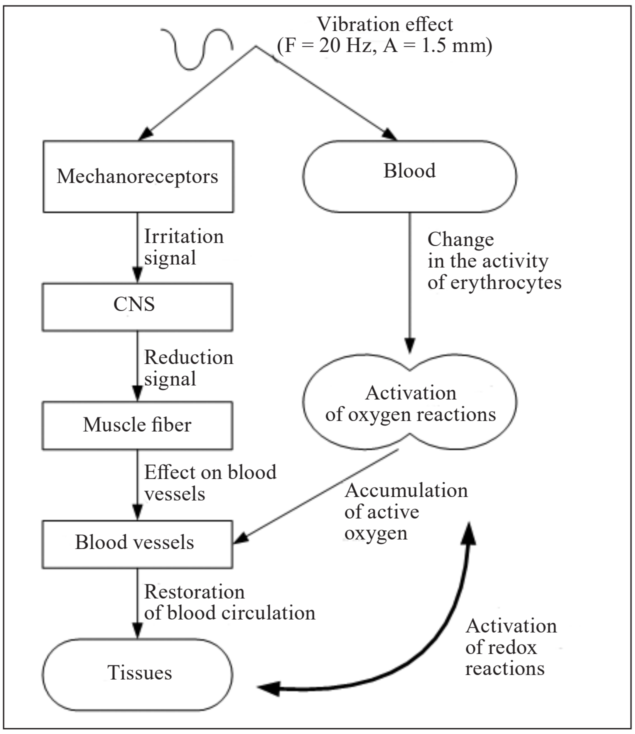

Fig. 2. Impact of vibration on muscles and circulatory system

of stimulating muscle tone, energy and nervous processes in the body [20]. Quite a lot of studies, including meta-analyses of specialized literature, have been devoted to the assessment of the effectiveness of this method. Let us try to use this information to evaluate the effect of local low-frequency vibration on the joints without involving the whole body.

Studies have shown that WBV has positive effects on age-related and inactivity-induced bone loss [21, 22], can inhibit bone resorption, promote bone formation, increase bone alkaline phosphatase, and enhance muscle strength [23, 24].

Another positive effect of low-frequency vibration is the prevention of osteoporosis [25, 26]. It should be noted that osteoporotic changes are a risk factor for bone fractures in the elderly. Therefore, the vibration effect can be not only a way to rehabilitate a joint immobilized as a result of an injury, but also to prevent the cause of a fracture, i.e. osteoporosis. K. Pichler et al. [27] hypothesized that by changing the activity of bone modeling/remodeling receptors, mechanical stimulation can inhibit bone destruction, that is, mechanical stimulation can increase bone formation and prevent osteoporotic bone fractures. But these studies still have experimental value, which must be confirmed in clinical settings.

Regarding the effect of low-frequency vibration on the cartilage, there is little material. Usually, specialists study the condition of the peripheral tissues of the joint, the destruction of articular cartilage, and not its repair. Let us try to find out the processes that occur in the articular cartilage under the influence of local low-frequency oscillations. If the direction of the vibration flow is applied along the limb, for example, to the heel during the development of the knee joint, or to the radiocarpal zone in a state of full extension during the development of the elbow, it can be assumed that oscillations will occur in the joint cavity, while observing micro-movement of the articular ends of bones. Thus, movement processes in the joint will begin, but, unlike normal movements with a significant amplitude, micromovements will not destroy the surface of the cartilage, but will only start recovery processes in it.

Irritation of mechanoreceptors and, accordingly, the longitudinal passage of mechanical vibrations will cause contraction of muscles, compression of blood vessels by them and, accordingly, an increase in blood flow. This will ensure the removal of the products of cartilage metabolism and the supply of nutrients, and in portions with a frequency high enough for the joint. Blood flow to the joint will cause an increase in tissue temperature, which, in turn, will increase muscle contraction and, accordingly, blood supply due to the work of thermoreceptors.

The mechanical wave, passing along the bone and bumping into various structures, is refracted and changes speed (Fig. 3). Some particle returns and is repeatedly reflected within the medium. Given that the wave band is wide, a significant zone of microvibrations is formed in the joint, which act in different directions, stimulating the joint cavity and the entire depth of the cartilage. The period of oscillation of the wave at a frequency of 20 Hz is 0.05 s, so a new pulse is sent every 0.05 s, and because the speed of propagation of the vibration wave in different structures of the limb is very different (bone ~ 3300 m/s, skin ~ 1610 m/s, cartilage ~ 1510 m/s, synovial fluid ~ 1510 m/s, blood ~ 1600 m/s [28]), separate areas of vibration oscillations with different coating densities are formed in different tissues. Cartilage repair is enhanced under the conditions of periodic loads [29, 30], micro-oscillations do not lead to its destruction, but on the contrary, periodic soft impact can contribute to its restoration. However, full recovery can occur only in the case of short periods of immobilization, until irreversible changes have taken place.

Thus, we determined the main positive mechanisms of local low-frequency vibration for the recovery of joints after immobilization. An interesting experiment was conducted on rats by C. Zhang et al. [31]. The purpose of the study was to assess the influence of vibration on the stretch reflex and the quantitative relationship between dynamic muscle responses and low-frequency vibrations, namely 2–16 Hz. It was determined that the muscle strength in the state «with the stretch reflex» was significantly greater than without it, and the difference increased with the frequency of vibration exposure.

We did not find similar sources, but on the basis of this study, it can be predicted that the introduction of elements of physical exercises, namely, extension

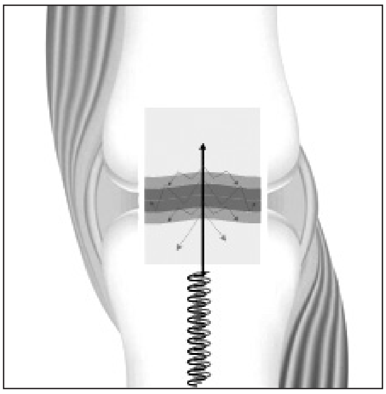

Fig. 3. Propagation of a mechanical wave through a joint

and bending during vibration therapy, can improve the condition of the joint. Postisometric relaxation (PIR) is a well-known method of low-traumatic joint development. In this case, not only mechanical PIR exercises will be effective, but also a change in the direction of the vibration effect, involving an increasing volume of tissues in the excitation process. Moreover, it has been observed that low-frequency vibration reduces pain syndrome [32], so during PIR a greater range of flexion/extension movements can be performed than without vibration.

We have considered the effects of low-frequency vibration on muscles, circulatory system and joints. Let us try to combine the above conclusions into one whole (Fig. 4).

Without repeating the entire mechanism of the influence of vibration on the structural elements of limbs and joints, as it is described above, let us focus on the main aspects.

Therefore, the vibration applied to the limb irritates the mechanoreceptors, which send a signal to the central nervous system, and owning to the motoneurons, muscle contraction occurs. It affects peripheral blood flow. At the same time, the oscillations affect the accumulation of oxygen in the blood, which, together with increased blood circulation, trigger redox processes in the tissues. That is, tissues are saturated with oxygen; metabolic products are removed, etc.

The effect of vibration on joint tissues involves restoration of micromovements, which contributes to the nutrition of cartilage, as well as the exchange of substances of synovial fluid of the joint with blood plasma through the synovial membrane. The synovial membrane is saturated with blood vessels and nerve endings, therefore, through mechanoreceptors, it responds to vibration stimulation by contraction and activation of blood circulation. In this way, the cartilage is saturated with moisture, its surface is restored, and the ability of synovial fluid to provide nutrition is normalized.

Restoration of nutrition of the periarticular tissues of the joint leads to their regeneration, contraction of muscles through motoneurons gives impetus to a gradual increase in their motor activity and strength, restoration of nutrition and surface of the cartilage triggers activation of mobility. The combination of these changes contributes to the restoration of joint mobility.

Certainly, with long-term immobilization of the limbs, when tissue transformations in the-form of cartilage ossification, muscle atrophy, and vascular remodeling have occurred, there is little hope for full recovery of mobility. Moreover, this process, both with the help of vibration and with the use of other physiotherapeutic methods, takes more time than the duration of immobilization, and this difference enhances with the increase in the time of immobilization.

In this case, it is logical to assume that in order to speed up recovery, it is necessary to slow down the reconstruction of joint tissues during the period of immobilization. If it is not possible to impose excessive loads on the limb and perform physical exercises of flexion/extension, then it is possible to at least preserve the nutrition of the joint cartilage, blood circulation of muscles and adjacent tissues. Today, for this purpose, contrast baths or bandages are used to ensure blood flow, finger movements are recommended.

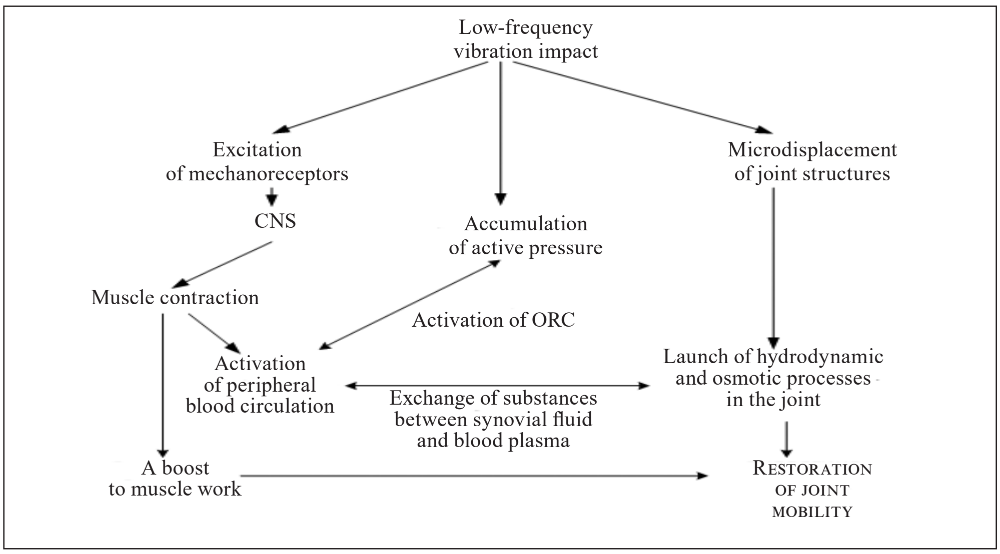

Fig. 4. Conceptual model of the impact of vibration on blood, articular and periarticular tissues

It can be assumed that local low-frequency exposure to the immobilized limb can also lead to preservation, albeit limited, of blood circulation and nutrition of the cartilage. Of course, the impact should be short-lived, not cause pain, vibrations should not be applied to metal structures. It must be performed under the close supervision of a doctor.

Conclusions

The elaborated conceptual model of the effect of low-frequency vibration on joints with limited mobility due to immobilization takes into account the changes in joint tissues under its influence. The concept involves the restoration of nutrition of the tissues and muscles adjacent to it. It is vibration, due to the ability to transfer vibrational energy between tissues, that enables the processes of muscle contraction, increasing the blood supply and metabolism of the joint.

The use of the model will allow healthcare practitioners to develop a system of therapeutic measures to prevent the development of contractures.

Conflict of interest. The authors declare no conflict of interest.

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The article has been sent to the editors 19.01.2023

CONCEPTUAL MODEL OF THE INFLUENCE OF LOW-FREQUENCY VIBRATION ON THE PROCESS OF RESTORATION OF JOINT MOBILITY AFTER IMMOBILIZATION

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