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BIOPHYSICAL FOUNDATIONS OF THE ACTION OF MODERN HARDWARE MASSAGE TECHNOLOGIES

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Abstract. *The article is devoted to the biophysical analysis of the principles of action of modern hardware massage technologies with an emphasis on comparing their effectiveness and feasibility of use depending on the physiological state of the patient and therapeutic tasks. The aim of the article is to perform a comparative analysis of different hardware-based massage technologies, with particular attention to the rationale for their application depending on specific therapeutic objectives and underlying conditions. During the scientific research, general scientific methods of cognition were used: analysis, synthesis, systematization, comparison, modeling and generalization. The results of the study show that each of the considered hardware massage technologies has its own unique dominant biophysical mechanism of influence on tissues. In particular, vacuum massage is characterized by direct mechanical deformation and tissue displacement, which leads to macro- and microdeformations, stretching, decompression, with subsequent improvement of lymphatic and venous drainage, structural restructuring of tissues and stimulation of microvessels. Ultrasonic massage works by radiation force, acoustic streaming and microdeformations, causing microscopic tissue vibrations, enhancing interstitial fluid transport and changes in intercellular connections in the extracellular matrix, combining mechanical and thermal effects. Electromyostimulation, in turn, causes depolarization of motor nerves, inducing cyclic contractions and relaxation of muscle fibers, stimulating neuromuscular activity, local blood circulation and NO-dependent vasodilation with a slight metabolic load. A differentiated assessment of the feasibility of using each of the technologies was carried out: vacuum massage is recommended for stagnant phenomena and drainage disorders; ultrasonic - for affecting deep and dense tissues, including areas of fibrosis; electromyostimulation - for muscle weakness, circulatory disorders and hypodynamia. The practical significance of the study is to create a scientifically sound basis for choosing an adequate technology of apparatus massage in clinical and rehabilitation practice.*

Keywords: *apparatus massage, biophysical mechanisms, vacuum, ultrasound, electromyostimulation*

Introduction.

The apparatus massage procedure is actively used all over the world. The demand for it is steadily growing, and at the same time, technologies of apparatus effects on adipose and skin tissue are rapidly developing. According to the American Society of Plastic Surgeons (ASPS), in 2024 [14] tens of millions of minimally invasive aesthetic procedures were performed in the USA, among which a significant share are apparatus and energy-oriented interventions. In particular, in 2024, 447,581 procedures of non-invasive fat reduction and 439,032 procedures of non-invasive skin tightening were recorded, which confirms the mass and routine nature of these methods in clinical practice in the USA [14]. The presented statistical data are used not as economic or marketing indicators, but as an indicator of clinical significance and widespread implementation of hardware methods in routine medical practice, which indirectly reflects the level of their acceptability, safety, and demand among patients.

The non-invasive body contouring segment is one of the most dynamic in global aesthetic medicine. According to Grand View Research [9], the global non-invasive fat reduction market was valued at approximately US$2 billion in 2025 and is projected to grow to US$4.3 billion by 2030, at a CAGR of 16.2%. North America, including the United States, dominates this market, accounting for approximately 38.6% of global revenue, reflecting the high concentration of technology, clinics, and affordable demand in the region [9]. Among services, the United States is dominated by technologies that combine effectiveness with minimal intervention in the patient's daily life. According to ASPS [14], the absolute leaders of the minimally invasive segment remain injection techniques and hardware procedures for the skin: neuromodulators (over 9.8 million procedures in 2024), hyaluronic fillers (5.3 million), laser and light methods of skin treatment and remodeling (over 3 million procedures) [14].

Literature Review.

The issue of the biophysical foundations of the action of modern technologies of apparatus massage is sufficiently covered in the scientific literature, which is confirmed by a wide range of current publications in international publications. In order to carry out a comparative study based on the grouping and synthesis of scientific sources of information, literature covering several key areas was used. In particular, the issues of vacuum technologies of apparatus massage were considered in the works of such researchers as J. Meirte et al. [8], Marafioti et al. [6]. Ultrasonic techniques were considered in detail in the works of K.B. Bader [1], M.A. O'Reilly [11] and J.B. Fowlkes [2]. The topic of electromyostimulation is devoted to the studies of T.W. Janssen [5] and H. Oda [12], who analyze vascular and muscle responses to electrical stimulation.

In addition, the work uses specialized literature that highlights the physiological foundations of the impact on the muscular and cardiovascular systems, in particular, the position of the American College of Sports Medicine [4], as well as expert literature and analytical sources that provide statistics on the growth of the market for non-invasive massage and hardware cosmetology [9], [14]. This makes it possible to combine the scientific and practical perspective of the analyzed techniques.

Despite the presence of a significant number of scientific publications devoted to individual technologies of hardware massage, there is a lack of comparative analysis of their biophysical mechanisms of action. That is why this work acquires scientific significance.

The author's new contribution is a systematic comparative analysis of vacuum, ultrasound, and electromyostimulation technologies of apparatus massage from the standpoint of their basic biophysical mechanisms of action, which allows us to justify a differentiated choice of technique depending on the clinical task and functional state of tissues.

The purpose of the article is to conduct a comparative analysis of various technologies of hardware massage with an emphasis on the feasibility of their use depending on different tasks and prerequisites.

Research Results.

Modern technologies of apparatus massage, in particular vacuum, ultrasound and electromyostimulation, realize their therapeutic effect through different, but complementary biophysical mechanisms of influence on tissues. If we describe each massage technology in general, then vacuum technologies mainly provide superficial and deep mechanical restructuring of tissues, ultrasound – combined mechanical-thermal effect with high controllability of the depth of action, and electromyostimulation – neuromuscular and vascular activation with minimal metabolic load, which justifies their differentiated or combined use depending on therapeutic and aesthetic goals. Let us consider each technology in more detail.

Vacuum massage (from a biophysical point of view) is a method of mechanical influence on biological tissues, which is implemented through the local negative pressure. The main biophysical feature of vacuum massage is the induction of mechanical deformation of the skin, subcutaneous fat and deeper layers. Under the influence of negative pressure, tissues undergo stretching and shearing, which directly activates mechanosensitive cellular structures and the intercellular matrix. This effect, as noted in clinical studies, in particular in the work of Furhad S., Sina R.E., Bokhari A.A., enhances microcirculation, improves venous and lymphatic outflow and promotes faster removal of cellular metabolic products [3].

Vacuum creates a mechanical load that plays an important role in the construction and restoration of the intercellular basis of tissues. Under the influence of tissue deformation, connective tissue cells, in particular fibroblasts, are stimulated, as a result of which the synthesis of their components is activated. This process is a necessary condition for the restoration of elasticity and tissue architectonics [8]. As noted in the study by Meirte J., the use of such massage in conditions of fibrosis is especially significant, when the dermis and hypodermis lose their clear structure, forming a dense and immobile layer.

Vacuum massage also has a significant effect on adipose tissue. This happens as follows: negative pressure contributes to the mechanical loosening of fat depots, improving local blood circulation and activating metabolic processes in adipocytes. The combination of vacuum with other physical factors increases the efficiency of reduction (reduction in the amount) of adipose tissue, which confirms its importance in body correction and modeling procedures [6].

In general, vacuum massage is a tool that simultaneously affects the shape, density and functional state of tissues [13]. Let us consider its main characteristics and significance for apparatus massage in Table 1.

According to the author, the key advantage of vacuum massage is its ability to create controlled mechanical deformation of tissues without additional thermal load. From a biophysical standpoint, this allows to effectively activate mechanosensitive cellular structures and intercellular matrix, which is critically important for connective tissue remodeling. Clinically, this means that vacuum massage is especially appropriate in cases of tissue congestion, fibrosis and r educed elasticity of the dermis and

Table 1 – Technological features of vacuum apparatus massage

Factor	Description
Principle of action	It works by creating a vacuum that gently draws in the tissues without heating or risk of overheating
Effect on adipose tissue	Fat cells are loosened; metabolism is activated, and the efficiency of fat reduction increases (especially when combined with other methods)
Combination with other physical factors	Enhances the effects of electromagnetic fields and electrical stimulation without additional thermal load
Relevance for body contouring	Improved mechanical impact, make vacuum massage an important component of body contour correction and tissue condition improvement

Source: systematized by the author based on research [3, 6, 8, 13]

hypodermis. This distinction is critical for the choice of technique in patients for whom thermal or electrical effects are undesirable, but intense mechanical stimulation is necessary.

Thus, vacuum massage from a biophysical point of view is a method of controlled mechanical stimulation, which provides activation of microcirculation, remodeling of intercellular connections and influence on adipose tissue. In contrast, ultrasonic massage technologies act on cells through slight heating, which provides enhancement of microcirculation. This is a slightly different type of action. Let's consider it.

The technology is widely studied in the scientific literature. Of the new studies (over the past 2 years), the technology is described in the most detail by Bader K. B. [1]

Ultrasonic apparatus massage is based on the action of high-frequency mechanical waves that propagate in biological tissues and transfer energy to them without an ionizing effect (damage to tissues at the atomic level, changing their structure). Ultrasound is a non-ionizing type of energy, however, with sufficient exposure parameters, it is capable of inducing these biological effects [2]. The main biophysical mechanisms of ultrasound action are thermal and mechanical interactions with tissues [10]. The thermal effect occurs due to the absorption of ultrasound energy by tissues, which leads to an increase in local temperature [11].

The mechanical effect of ultrasound is realized through the transmission of a wave pulse to tissues and biological fluids, which causes microdisplacement of cellular structures and fluid flows (acoustic streaming) [16]. These processes form a mechanical load on cells and the intercellular basis of tissues.

An important biophysical property of ultrasonic massage is the radiation force of ultrasound. It causes directed mechanical pressure on tissues. This effect depends on the intensity (ISPTA), wave frequency and physical properties of tissues, in particular viscosity and acoustic impedance (i.e. resistance) [16]. Therefore, the radiation force contributes to the mechanical "massage" of tissues at the microlevel.

Under certain parameters, ultrasound can induce cavitation phenomena, i.e. the interaction of the wave with gas nuclei or microbubbles. When ultrasound passes through tissues, it creates alternating compression and rarefaction. In the rarefaction phase, microbubbles form around the gas nuclei presents in the tissue fluid. They begin to pulsate, increase and decrease in time with the wave. Cavitation can be stable or inertial. Ultrasonic apparatus massage and physiotherapeutic applications are characterized by modes in which stable or minimal cavitation activity dominates, providing mechanical stimulation without destructive tissue damage [7]. Low-intensity pulsed ultrasound (LIPUS), which is often the basis of apparatus massage, is characterized by a slight thermal effect and predominantly mechanical action. It causes tissue microdeformations and fluid streaming without significant heating and without the need for external salting agents [7]. Let's consider the technological characteristics of this massage in Table 2.

Table 2 – Technological features of ultrasonic apparatus massage

Biophysical factor	**Characteristics and mechanism of action**
Nature of ultrasound	A mechanical, non-ionizing wave. Under certain exposure parameters, it is capable of inducing measurable biological effects in tissues
Thermal effect	Absorption of ultrasound energy causes a local rise in tissue temperature. The degree of heating depends on frequency, acoustic power, intensity, and tissue attenuation properties
Mechanical action of the wave	Causes micro-movements of cells and tissue structures; basis of the mechanical massage effect
Radiation force of ultrasound	Directed mechanical pressure generated by the ultrasound field leads to localized tissue deformation, with the effect determined mainly by intensity and frequency

Source: systematized by the author based on research [7,10, 11, 16]

Thus, ultrasonic apparatus massage from a biophysical point of view is a method of controlled mechanical and moderate thermal action, which is implemented through radiation force, streaming, tissue microdeformations and limited cavitation phenomena. Unlike ultrasonic apparatus massage, which acts directly on living and fatty cells, electromyostimulation massage works by stimulating muscle contractions. This is a fundamentally different approach to solving the problem of body shaping. Let us consider the main features of this type of apparatus massage.

Electromyostimulation massage (EMS) is based on the action of an external low-frequency electric current, which causes controlled contractions of skeletal muscles through the activation of motor nerve fibers. At a low stimulation intensity, approximately at the level of 4 Hz, these contractions are rhythmic in nature, do not turn into tetanic spasms and do not lead to rapid muscle fatigue. This is what fundamentally distinguishes this mode from high-frequency electrical stimulation, which is much more taxing [12].

An important feature of electromyostimulation massage is that the muscles work passively, without the active participation of the central nervous system. In fact, the body receives the effect of muscle work without the need to perform physical exercises, which allows this method to be used with minimal overall load [4].

Rhythmic muscle contractions during EMS enhance local blood circulation. Muscles act as a kind of “pump” that improves blood flow through the vessels. This increases the mechanical effect on the vascular wall and stimulates the formation of nitric oxide, a substance that dilates the vessels and reduces their tone. As a result, the vessels become more elastic, and blood flow in the affected area is better [5]. That is why after a course of procedures, a decrease in vascular stiffness is noted, especially in areas that were directly subjected to electrical stimulation [15].

Another advantage of electromyostimulation massage is its low metabolic load. During the procedure, there is no significant accumulation of lactic acid, which usually causes pain and discomfort in the muscles. Due to this, EMS is well tolerated, does not cause pronounced pain and can be safely used in courses [12]. Let us consider in more detail the technological features of this type of massage in Table 3.

Table 3 – Technological features of electromyostimulation massage

Biophysical feature	Description of mechanism
Low-frequency electric field	Based on the use of low-frequency current (about 4 Hz) that rhythmically activates motor nerve fibers without causing sustained contractions or muscle fatigue
Passive muscle contractions	Muscle contractions occur without voluntary control, resembling the effect of light aerobic activity
Low metabolic intensity	Energy demand remains low, roughly equivalent to 2 METs, similar to standing or slow walking
Minimal lactate stress	Only a slight increase in lactate levels is observed, which stays below the anaerobic threshold
Activation of the muscle pump	Rhythmic contractions support venous return and improve local circulation
Increased shear stress	Enhanced blood flow raises shear stress on the vascular endothelium, serving as an important mechanical stimulus
Stimulation of nitric oxide production	Increased shear stress activates endothelial mechanisms that promote nitric oxide release and vessel dilation
Therapeutic appropriateness	Due to its biophysical characteristics, EMS is suitable for individuals with limited mobility or lower limb disorders as an adjunct or alternative to conventional aerobic exercise

Source: systematized by the author based on research [4, 12, 15]

Therefore, electromyostimulation massage from a biophysical point of view is a method of controlled electrical activation of muscles, which implements mechanical effects through passive contractions, induces a local increase in blood flow, increases endothelium-dependent vasodilation and reduces peripheral vascular stiffness. The combination of these mechanisms determines its use as a low-intensity, locally directed physical factor, especially promising for people with limited motor activity or lower limb pathology [12].

The features of the application of these types of apparatus massage, as well as their effectiveness, are presented in the comparative Table 4.

The expected results of the use of hardware massage methods are usually assessed by a combination of objective and subjective indicators. The most common quantitative criteria include changes in the volume and circumference of the treated areas, the thickness of the dermis and subcutaneous fat (according to ultrasound imaging), elastography indicators, as well as local hemodynamic parameters assessed by Doppler.

Table 4 – Comparative characteristics of the biophysical foundations of modern apparatus massage technologies

Biophysical parameter	Vacuum massage	Ultrasound massage	Electromyostimulating massage
Dominant biophysical mechanism	direct mechanical deformation and tissue shearing	radiation force, acoustic streaming, micro-deformations	depolarization of motor nerves and passive muscle contractions
Nature of tissue deformation	macro- and micro-deformations, stretching, decompression	microscopic vibrations and local shear	cyclic contractions and relaxations of muscle fibers
Depth of biophysical impact	superficial and subcutaneous, depending on vacuum intensity	adjustable, depending on frequency and intensity	limited to the innervation zone of the stimulated muscles
Effect on interstitial fluids	enhanced lymphatic and venous drainage	acoustic streaming, improved fluid transport	indirect, via muscle pump
Interaction with extracellular matrix	mechanical remodeling of ECM	micromechanical stimulation and alteration of intercellular connections	secondary effect through changes in blood supply
Effect on muscle tissue	indirect	minimal or indirect	direct, through induced contractions
Vascular mechanism	mechanical stimulation of microvessels	combination of mechanical and thermal effects	NO-dependent vasodilation
Metabolic load	absent	minimal	low, equivalent to light aerobic exercise
Biophysical orientation	structural tissue remodeling	micromechanical and energy stimulation	neuromuscular and vascular activation
Appropriateness of use	tissue congestion, densification, impaired drainage, reduced elasticity, local fat deposits	designed to provide regulated deep mechanical stimulation of tissues	used in conditions associated with limited motor activity
Combination potential	enhances the effects of other physical factors	compatible with mechanical and electrical modalities	effective when combined with mechanical stimulation

Source: systematized by the author

Functional and clinical indicators include tissue elasticity indices, the degree of cellulite severity (cellulite grading scales), as well as the subjective assessment of pain and patient comfort using pain score scales.

At the same time, the evidence base for the effectiveness of hardware massage has a number of limitations. These include the heterogeneous quality of clinical studies, significant heterogeneity of exposure protocols, different device parameters and duration of treatment courses, as well as the relatively rare use of placebo-controlled and randomized designs. This makes direct comparison of results difficult and requires careful interpretation of the data obtained.

The use of hardware massage techniques is not always advisable, in particular in cases where mechanical, energy or electrical effects can damage tissues or negatively affect the general condition of the body, which necessitates the abandonment of these methods. In the presence of acute inflammatory processes, infections, active skin lesions, bleeding, thrombosis and vascular weakness, it is especially important to find alternative methods of correcting cellulite and other fatty disorders. The use of hardware massage techniques is also not recommended in patients with cardiovascular, neurological or systemic diseases. In such cases, the use of hardware massage is possible only after a thorough medical assessment and with the permission of the attending physician.

Conclusions

Thus, the article presents for the first time in a generalized form a comparative biophysical model of the action of the main hardware massage technologies, which allows for a reasonable comparison of their clinical capabilities and application limits. Modern hardware massage technologies realize their therapeutic effect not through one universal mechanism, but through various, complementary ways of influencing tissues. Each of these approaches has its own "point of application" and forms a specific tissue response, which determines the clinical outcome.

Thus, vacuum technologies provide a greater degree of mechanical tissue restructuring at the surface level, ultrasound technologies are able to regulate the depth of impact, while electromyostimulation approaches have a fundamentally different approach, based on physical muscle tension. This is what justifies both their separate and combined use depending on specific therapeutic and aesthetic tasks.

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