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INTEGRATION OF AR/VR TECHNOLOGIES, SENSOR SYSTEMS, AND BIOFEEDBACK INTO MULTIMODAL REHABILITATION STRUCTURES AND THEIR IMPACT ON RECOVERY EFFICIENCY

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INTRODUCTION

Over the past decades, within the context of the formation of a multimodal paradigm, rehabilitation has undergone a profound methodological transformation, shifting from a narrowly instrument-based, specialized practice to a comprehensive, integrative, and system-forming domain of medical and psychological care. This modern approach combines diverse therapeutic and technological modalities aimed at restoring and optimizing the functional potential of individuals with health impairments. According to the World Health Organization (WHO), approximately 2.4 billion people worldwide currently live with health conditions requiring rehabilitation–that is, nearly one in three individuals globally. Since 1990, the global need for rehabilitation has increased by 63%, rising from 1.48 to 2.41 billion people, and this trend is projected to continue due to population aging and the growing prevalence of chronic diseases. WHO and the World Rehabilitation Alliance emphasize that rehabilitation is an essential component of universal health coverage. Yet in low- and middle-income countries, more than half of patients do not receive the rehabilitation services they need, resulting in a substantial gap between the demand for and the availability of care. This situation necessitates not only an expansion of traditional rehabilitation services but also the development of innovative approaches that enhance efficiency, personalization, and scalability[1].

A major driver of the growing global demand for rehabilitation is the rising prevalence of non-communicable diseases, particularly cardiovascular disorders and stroke. Projections indicate that by 2030 the age-standardized incidence of ischemic stroke will continue to increase worldwide, reaching approximately 89 cases per 100,000 population. This trend will be accompanied by a higher absolute number of individuals experiencing post-

[1] *Report on situational analysis results of acute stroke care in Ukraine*. Copenhagen: WHO Regional Office for Europe. 2024. URL: https://www.who.int/europe/publications/i/item/WHO-EURO-2024-9677-49449-73972

stroke impairments in motor, speech, and cognitive functions, thereby intensifying the demand for rehabilitation[2].

Rehabilitation needs are particularly acute in Ukraine, where the "classical" demographic and epidemiological challenges–population aging and the high prevalence of chronic diseases–are compounded by the consequences of full-scale war. According to various international sources, in 2020–2021 Ukraine registered approximately 2.57–2.73 million persons with disabilities, representing 6.2–6.7% of the pre-war population. Following the onset of large-scale military aggression, these numbers increased substantially: within the first 18 months of the war, the proportion of persons with disabilities reached 7.4%, while expert estimates suggest that the real prevalence may approach 16%, corresponding to global levels when considering unmet needs and registration challenges[3]. Cardiovascular diseases remain the leading cause of disability in Ukraine. Epidemiological data indicate that they account for more than 60% of all deaths in the country, with a persistently high contribution to disability among working-age individuals. Annually, approximately 130,000 new stroke cases are recorded, making stroke one of the foremost causes of death and long-term disability. Mortality from cerebrovascular diseases in Ukraine is 10–17% higher than in Western European countries, and disability rates associated with stroke have demonstrated an upward trend in recent years, particularly under wartime conditions[4].

The war has also generated new waves of disability related to gunshot wounds, polytrauma, amputations, traumatic brain injuries, and mental health disorders. Humanitarian assessments suggest that more than 6 million people in Ukraine may now be living with various forms of disability, including approximately 3 million with officially recognized status. A significant proportion of this population consists of older adults (over 60 years), who are simultaneously at high risk for cardiovascular and degenerative musculoskeletal disorders. This complex interplay of factors produces an explosive increase in the need for comprehensive, long-term, and technologically advanced rehabilitation–services that must be accessible not only in specialized centers but also at the community and home-based

[2] World Health Organization. *Global estimates of the need for rehabilitation*. Geneva. 2020. URL: https://www.who.int/teams/noncommunicable-diseases/sensory-functions-disability-and-rehabilitation/global-estimates-of-the-need-for-rehabilitation

[3] *UNCRPD Press Release*. Ukraine: 2.7 million people with disabilities at risk, UN Committee warns. 14 April 2022. URL: https://www.edf-feph.org/uncrp-press-release-ukraine-2-7-million-people-with-disabilities-at-risk-un-committee-warns/

[4] World Bank. *Ukraine Human Development Update. In Focus: Disability and Inclusion*. Washington (DC). 2024. URL: https://documents1.worldbank.org/curated/en/099032824073057091/pdf/P181236-d6feb077-28cd-456c-a506-92390987152a.pdf

levels[5]. At the same time, traditional rehabilitation models often fail to meet the scale and complexity of contemporary challenges. Limited human resources, uneven geographic access to rehabilitation services, and the high cost of prolonged inpatient care and patient reintegration create a strong demand for innovative, technology-enhanced approaches capable of improving recovery outcomes without proportionally increasing expenditures. One such direction is the integration of augmented and virtual reality (AR/VR), sensor systems, and biofeedback technologies into multimodal rehabilitation frameworks. Over the past 10–15 years, research on the use of virtual reality in post-stroke rehabilitation and in neurological and orthopedic conditions has expanded rapidly. Systematic reviews and meta-analyses demonstrate that incorporating VR therapy into standard rehabilitation programs can improve motor functions of both upper and lower limbs, enhance strength, range of motion, and coordination, as well as support cognitive improvements in attention, processing speed, cognitive flexibility, and overall quality of life. Several studies also report positive effects of VR-based training on balance, gait, and fall risk reduction, particularly among older adults and individuals with neurological disorders.

In parallel, AR-based technologies aimed at supporting motor activity are being actively developed. They enable the overlay of virtual cues and markers onto a patient's real environment, which is especially important during the transition from the controlled setting of a rehabilitation center to everyday life. When combined with sensor systems–such as inertial measurement units, gait analysis platforms, computer vision systems, and sensor-equipped exoskeletons–they facilitate continuous collection of objective data on movement quality, load symmetry, balance stability, and other parameters essential for monitoring recovery dynamics.

These advances provide the foundation for implementing the concept of biological feedback (biofeedback), wherein physiological parameters–electromyographic activity, gait characteristics, center-of-pressure shifts, heart rate, breathing patterns, and others–are transformed into visual, auditory, or tactile signals comprehensible to the patient. EMG biofeedback helps patients develop targeted activation of appropriate muscle groups while reducing excessive tension in synergists and antagonists; posturographic biofeedback enhances balance and postural control; cardiorespiratory biofeedback contributes to normalization of autonomic regulation and reduction of anxiety.

The integration of AR/VR environments, sensor platforms, and biofeedback modules into a unified multimodal rehabilitation system fundamentally transforms the logic of recovery. First, it ensures a high level

[5] *The war in Ukraine: impact on persons with disabilities*. European Disability Forum. 2025. URL: https://www.edf-feph.org/the-war-in-ukraine-impact-on-persons-with-disabilities/

of motivation through gamification, realistic scenarios of everyday activities, and a tangible sense of progress–factors that are particularly significant for long-term neurorehabilitation programs. Second, the combination of multiple modalities (movement, visuospatial and auditory stimuli, cognitive tasks) promotes broad engagement of neural networks, which, according to contemporary perspectives, enhances neuroplastic processes and supports the formation of new functional connections within the central nervous system. Third, sensor systems make it possible to personalize the workload in real time, automatically adjusting task complexity to the patient's current capabilities, while also creating preconditions for remote (home-based) and telemedicine rehabilitation[6].

At the same time, a review of available systematic analyses on VR-based rehabilitation reveals substantial heterogeneity of protocols, variable sets of outcome measures, small sample sizes, and an insufficient number of studies devoted to integrated multimodal platforms that combine AR/VR, sensor monitoring, and biofeedback within a single rehabilitation framework[7]. Particularly limited is the evidence base concerning scalable implementation of such technologies in healthcare systems of resource-constrained countries, a category that currently includes Ukraine given the impact of the war on the national economy and infrastructure[8].

Thus, against the background of rapidly increasing global rehabilitation needs, the high prevalence of disabling conditions in Ukraine (primarily post-stroke, cardiovascular, traumatic, and war-related), as well as the significant constraints of traditional rehabilitation models, the scientific justification and implementation of multimodal rehabilitation technologies incorporating AR/VR, sensor systems, and biofeedback represent an exceptionally urgent task.

Research in this field carries dual significance. On the one hand, it contributes to a deeper understanding of neuroplasticity and adaptation mechanisms under conditions of complex sensorimotor loading. On the other hand, it provides a foundation for the development of practical, clinically oriented protocols that may be integrated into the national system of medical rehabilitation–including military-medical, cardiovascular, and neurorehabilitation stages, as well as long-term support for individuals with chronic functional impairments.

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[6] Corbetta D., Imeri F., Gatti R. Rehabilitation that incorporates virtual reality is more effective than standard rehabilitation for improving walking speed, balance and mobility after stroke: a systematic review. *Journal of Physiotherapy*. 2015. 61(3). 117–124.

[7] Demeco A., Zola L., Frizziero A., Martini C., Palumbo A., Foresti R. Immersive virtual reality in post-stroke rehabilitation: a systematic review. *Sensors*. 2023. 23(3). 1712.

[8] Securing the human rights of persons with disabilities during war. *UNDP Ukraine Press Release. 16 December 2022.* URL: https://www.undp.org/ukraine/press-releases/securing-human-rights-persons-disabilities-during-war

In summary, the integration of AR/VR technologies, sensor systems, and biofeedback into multimodal rehabilitation structures aligns with current global trends in rehabilitation medicine, reflects WHO priorities regarding the strengthening of rehabilitation as a component of universal health coverage, and simultaneously responds to the specific challenges faced by Ukraine during wartime and throughout post-war recovery[9]. Therefore, the scientific analysis of the effectiveness and implementation models of these technologies is not only theoretically significant but also possesses clear practical and socio-economic relevance.

1. Theoretical and Methodological Foundations of Multimodal Rehabilitation and Its Technological Evolution

Within the classical biomedical paradigm of the 20th century, rehabilitation was viewed primarily as a secondary process supplementing primary medical treatment, aimed at restoring individual impaired functions (e.g., kinesiotherapy, physiotherapy, orthopedic interventions). In this model, rehabilitation was largely monomodal–dominated by a single primary method, while accompanying components (neuropsychological support, educational measures, social and daily-life adaptation) played a secondary and fragmented role.

Subsequently, with the development of scientific and practical approaches to the functional consequences of diseases and injuries, the biopsychosocial model of health was adopted. This model interprets disability not only as a consequence of organic impairment, but as the result of the interaction between functional limitations, environmental factors, and personal–social determinants. In 2022, the international initiative Cochrane Rehabilitation formulated a new operational definition of rehabilitation as a **"**multimodal, person-centred, collaborative process", emphasizing interventions that address body structures, body functions, activities/participation, and contextual factors with the aim of optimizing functioning in individuals with health conditions or disabilities[10]. Under the influence of this paradigm, a conceptual shift occurred toward viewing rehabilitation as a multidimensional and comprehensive process. Recovery is now understood not as isolated correction of a single function but as coordinated work addressing motor, cognitive, psycho-emotional, and social domains of human functioning. In this system, each component of rehabilitation (motor therapy, cognitive training, educational activities,

[9] *Report on situational analysis results of acute stroke care in Ukraine.* Copenhagen: WHO Regional Office for Europe. 2024. URL: https://www.who.int/europe/publications/i/item/WHO-EURO-2024-9677-49449-73972

[10] Cochrane Rehabilitation. *Special projects: BE4Rehab, telerehabilitation and multimodal rehabilitation*. URL: https://rehabilitation.cochrane.org/special-projects

psychosocial support, environmental adaptation) is integrated into a unified logic of intervention carried out by a multidisciplinary team[11].

It is precisely within this context that the concept of multimodal rehabilitation has emerged and continues to expand. According to updated Ukrainian regulatory documents, in particular the Ministry of Health's classifier of rehabilitation interventions (Order № 1142 of 01.07.2024), the term "multimodal rehabilitation" is codified under D.17 as a complex of interventions aimed at increasing participation in everyday life by combining several methods delivered by a multidisciplinary team. This regulatory step signifies an official transformation in the national understanding of rehabilitation[12]. In Ukrainian publications, the term multimodal rehabilitation is used across various clinical contexts. For example, in perioperative management of surgical patients, particularly in severe abdominal interventions (such as pancreonecrosis), multimodal programs include preparatory counselling, optimized analgesia, early mobilization, and active nutrition, which reduce postoperative complications and shorten hospitalization. Similarly, in research on nonspecific low back pain, multimodal rehabilitation refers to a combination of manual therapy, therapeutic exercise, cognitive-behavioral interventions, and educational components organized by a multidisciplinary team of physical therapists, physicians, and psychologists[13].

International studies, in contrast, demonstrate a broader use of multimodal programs across multiple fields: neurorehabilitation (e.g., after spinal cord injury), orthopedics, oncological rehabilitation, chronic pain management, and mental health treatment. These programs describe multimodal interventions as structured combinations of gait training, robotic-assisted therapy, functional electrical stimulation, cognitive and educational components, collectively improving motor, functional, and quality-of-life outcomes. In the realm of mental health, group-based multimodal programs include psychotherapy, psychoeducation, skills training, physical activity, and family interventions, leading to significant improvements in social participation[14].

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[11] Negrini S., Kiekens C., Zampolini M. et al. Rehabilitation definition for research purposes: A global stakeholders' initiative by Cochrane Rehabilitation. *American Journal of Physical Medicine & Rehabilitation.* 2022;101(3):e1–e7.

[12] Варіантні мультимодальні протоколи в хірургічних пацієнтів (ERAS). *Офіційний сайт Харківського національного медичного університету*. URL: https://knmu.edu.ua

[13] *Prehab2Rehab: A theory of change for prehabilitation and rehabilitation in cancer care. BMC Cancer. 2023. 23. 10793.*

[14] BE4REHAB: Best Evidence for Rehabilitation, a WHO–Cochrane Rehabilitation project. *World EBHC Day blog*. 11 October 2023. URL: https://worldebhcday.org/blog/2023/be4rehab-best-evidence-rehabilitation-who-cochrane-rehabilitation-project

Thus, multimodal rehabilitation is not merely a sum of heterogeneous interventions but an integrated system in which various modalities (motor, cognitive, psychotherapeutic, technological) are selected, dosed, and synchronized according to a unified model of functional recovery. It presupposes that interventions should not be linear or segmented, but comprehensive, future-oriented, and aimed at enabling participation, independence, and everyday functioning.

This approach has several fundamentally important implications for theory and practice:

– it changes the criteria for measuring rehabilitation success–from restoring isolated functions to restoring participation, social integration, and quality of life;

– it increases the importance of multidisciplinary coordination, personalization of interventions, and continuous monitoring;

– it provides a framework for integrating new technological modalities (sensors, VR/AR, biofeedback) as components of a multimodal system;

– it sets new methodological requirements for research–moving beyond testing isolated interventions toward modeling, evaluating, and implementing systemic multimodal protocols[15].

Thus, the theoretical and methodological foundations of multimodal rehabilitation and its technological evolution can be regarded as a logical progression of rehabilitation science: from a monomodal focus on functional treatment to an integrated system oriented toward recovery, participation, and technologically enhanced support.

In contemporary rehabilitation science, multimodal rehabilitation is understood as an integrated complex of interconnected clinical, psychosocial, and technological interventions aimed at optimizing body functions, activity, and participation in accordance with the International Classification of Functioning, Disability and Health (ICF). Scientific approaches to multimodality have emerged as a response to the limitations of monomodal, unidimensional interventions that dominated the traditional biomedical model. From the perspective of current understanding of human functioning, multimodal rehabilitation appears as a holistic methodological system that addresses multiple levels of functioning, is implemented by a multidisciplinary team, and is grounded in individualized planning and adaptivity. According to Cochrane Rehabilitation, rehabilitation in the 21st century is defined as a multimodal, person-centred, collaborative process,

[15] Ткалич Г.В., Губенко О.В. Інтеграція цифрових технологій у нейрореабілітацію: можливості VR/AR та біологічного зворотного зв'язку. *Медична реабілітація*. 2023. 1(4). 15–23.

meaning a process that simultaneously activates various systems and mechanisms of recovery[16].

In Ukrainian studies (Hubenko O., Tkalina N., and others), it is emphasized that a multimodal approach in physical therapy is not merely the combined use of multiple methods but a deliberate synergy between motor, cognitive, and psycho-emotional interventions. The authors highlight that in chronic nonspecific low back pain, multimodal programs prevent chronification and reduce the duration of functional limitations[17,18]. Similar approaches are observed in Ukrainian dissertation research, where it has been demonstrated that comprehensive multimodal protocols in surgical patients (including within ERAS–Enhanced Recovery After Surgery) provide statistically significant reductions in postoperative complications and shorter hospital stays compared with traditional monotherapy.

In the international literature, multimodal programs are defined as structured and protocolized interventions that combine physical exercise, cognitive-behavioral methods (CBT), educational modules, self-management techniques, pharmacological support, and modern digital tools. In the systematic review by Mallard F. et al., multimodal interventions for radiculopathies included physical, cognitive, and educational modules; however, their effectiveness depended on the level of standardization and coherence among components, underscoring the importance of a systemic approach[19]. Multimodal models are being implemented particularly intensively in post-COVID-19 rehabilitation programs. Studies published in the PMC database indicate that home-based multimodal programs–incorporating individualized exercise, telemonitoring, educational sessions, psycho-emotional support, and regular therapist contact–demonstrate improvements in endurance, quality of life, and psychological wellbeing[20].

From a methodological perspective, multimodal rehabilitation is grounded in several fundamental principles:

1. Biopsychosocial principle: acting on biological, psychological, and social determinants of functioning.

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[16] Cochrane Rehabilitation. *Special projects: BE4Rehab, telerehabilitation and multimodal rehabilitation*. URL: https://rehabilitation.cochrane.org/special-projects

[17] Ткаліна А.В. Сучасні підходи в реабілітації хворих з болем у попереку. *Фітотерапія. Часопис*. 2023. (1). 59–66.

[18] Ткалич Г.В., Губенко О.В. Інтеграція цифрових технологій у нейрореабілітацію: можливості VR/AR та біологічного зворотного зв'язку. *Медична реабілітація*. 2023. 1(4). 15–23.

[19] Mallard F., Roren A., Genty M., Le Fort M., Rannou F., Roquelaure Y. Effectiveness of multimodal rehabilitation interventions for cervical radiculopathy in adults: a systematic review. *Journal of Rehabilitation Medicine*. 2022. 54. jrm00280.

[20] *Multimodal and Interdisciplinary Interventions for Long Term Pain: A Systematic Review. Stockholm: SBU.* 2021. URL: https://pubmed.ncbi.nlm.nih.gov/35998243

2. Interdisciplinarity: collaboration among PRM physicians, physical therapists, occupational therapists, speech and language therapists, psychologists, and social workers.

3. Personalization and goal-oriented planning: establishing individualized goals in partnership with the patient (goal-oriented rehabilitation).

4. Evidence-based practice and protocolization: reliance on standardized algorithms and validated indicators of effectiveness.

5. Continuity: seamless transition across inpatient, outpatient, and home-based phases.

Importantly, contemporary multimodal oncological prehabilitation and rehabilitation programs (such as *Prehab2Rehab*) actively employ the concept of theory of change, which enables formal description of mechanistic interactions among program components (physical exercise → metabolic adaptation → reduced stress responses → increased resilience → improved postoperative outcomes). This makes the intervention transparent in terms of mechanisms of action and suitable for scientific verification[21]. In the international review by Renner A. et al. on post-intensive care rehabilitation (PICS), it is emphasized that effective rehabilitation after discharge from intensive care units can be achieved only when three modalities–physical, cognitive, and psychological–are mandatorily integrated into a single systemic multimodal protocol[22].

Scientific evidence consistently demonstrates that multimodal programs provide:

• higher clinical and functional effectiveness compared with isolated methods,

• better prevention of symptom chronification,

• increased motivation and engagement through psychological and educational components,

• greater stability and durability of therapeutic effects [23].

In this context, multimodal rehabilitation is viewed as a methodologically substantiated model capable of integrating advanced technologies–AR/VR systems, sensor platforms, and biofeedback–not as fragmented adjuncts but as organic elements of a unified structure that enhances cognitive, motivational, and sensorimotor aspects of recovery.

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[21] *Multimodal and Interdisciplinary Interventions for Long Term Pain: A Systematic Review. Stockholm: SBU.* 2021. URL: https://pubmed.ncbi.nlm.nih.gov/35998243

[22] Renner A., Bologheanu R., Schandl A., Pateisky P., Hoetzenecker K., Benzer A. An evidence-based clinical guideline for the diagnosis and treatment of post-intensive care syndrome and chronic pain after intensive care. *Critical Care*. 2023. 27. 350.

[23] Walklett J., Bourne A.M., Stephens R., Stephenson J., Jones S., Williams M., Goodall S., Adamson M. Co-developing a theory of change for a personalised multimodal cancer prehabilitation programme in South Wales. *BMC Health Services Research*. 2024. 24. 1525.

Synthesizing the scientific evidence, multimodal rehabilitation emerges as a highly regulated, structurally organized, and scientifically grounded system that ensures:

• synergistic influence on motor, cognitive, and psycho-emotional components,

• personalization and adaptivity of interventions,

• enhanced efficiency through integration of evidence-based methods,

• significant improvements in functional status, quality of life, and participation outcomes[24].

This model creates a conceptual foundation for the integration of modern technologies (AR/VR systems, sensor platforms, biofeedback), which are seamlessly embedded into the multimodal structure and potentiate its effects–an issue addressed in subsequent sections of the study. Continuing the previously outlined approach to multimodal rehabilitation, particular attention should be paid to the concept of systemic multimodal protocols, which in contemporary scientific literature are regarded as a key tool for constructing a coherent rehabilitation pathway. Unlike simple combinations of several methods, such protocols constitute an integrated, structured, and standardized recovery model with clearly defined components, mechanisms of action, sequential logic, and an effectiveness evaluation system (Mallard et al.)[25].

The concept of a *systemic multimodal protocol* encompasses a comprehensive, organized, and scientifically substantiated rehabilitation plan that involves several interconnected modalities–motor, cognitive, psycho-emotional, social, and technological. In modern research, such protocols are described as structural algorithms that include: defining specific therapeutic goals; constructing a theory of change–a mechanistic explanation of the effects of each modality; a standardized sequence of interventions; multidisciplinary implementation; continuous compliance monitoring; and dynamic adaptation based on patient progress[26]. In the systematic review by Mallard et al., multimodal interventions for radiculopathies included exercise, psychoeducational, and cognitive-behavioral components; however, their effectiveness varied due to insufficient standardization and

[24] Kechichian A., Toth V., Inoue K., Alizadehkhaiyat O., Koes B.W., Hayden J.A. Multimodal interventions including rehabilitation exercise for older adults with chronic musculoskeletal pain: a systematic review and meta-analyses. *Journal of Geriatric Physical Therapy*. 2022. 45(3). 158–169.

[25] Mallard F., Roren A., Genty M., Le Fort M., Rannou F., Roquelaure Y. Effectiveness of multimodal rehabilitation interventions for cervical radiculopathy in adults: a systematic review. *Journal of Rehabilitation Medicine*. 2022. 54. jrm00280.

[26] Walklett J., Bourne A.M., Stephens R., Stephenson J., Jones S., Williams M., Goodall S., Adamson M. Co-developing a theory of change for a personalised multimodal cancer prehabilitation programme in South Wales. *BMC Health Services Research*. 2024. 24. 1525.

methodological heterogeneity[27]. In the psychological context, systemic multimodal protocols gain particular significance as they allow integration of psychotherapeutic, educational, and behavioral components into the overall architecture of the rehabilitation intervention. Reese & Mittag emphasize that multimodal, multidisciplinary programs incorporating psychological interventions have become the standard of care for rehabilitation of patients with chronic pain[28]. Likewise, research on psychosocial interventions in older adults indicates that combined psychosocial and rehabilitative programs contribute to improved health outcomes[29]. Systemic multimodal protocols are characterized by several key features. First, they include clear structuring and detailed description of components, where each modality is aligned with shared goals, and its duration, frequency, intensity, and content are standardized. Second, mechanistic logic (theory of change) specifies why a particular combination of modalities is optimal. For example, cognitive-behavioral therapy reduces catastrophizing and fear of movement, whereas physical exercise increases load tolerance and restores functionality; educational sessions enhance self-efficacy; and technological modules stimulate motivation and behavioral engagement[30]. Third, implementation is based on multidisciplinary collaboration, ensuring coherence among interventions delivered by psychologists, physical therapists, technological specialists, nurses, and social workers. Fourth, monitoring and adaptation are integral, involving continuous assessment of interim results, clinical indicators, psychological dynamics, and patient engagement. Fifth, these protocols are grounded in evidence-based practice, incorporating randomized trials and systematic reviews confirming their effectiveness across clinical populations[31]. A notable example is the contemporary guideline for multidisciplinary rehabilitation after intensive care unit admission (PICS), which specifies the

[27] Mallard F., Roren A., Genty M., Le Fort M., Rannou F., Roquelaure Y. Effectiveness of multimodal rehabilitation interventions for cervical radiculopathy in adults: a systematic review. *Journal of Rehabilitation Medicine*. 2022. 54. jrm00280.

[28] Reese C., Mittag O. Psychological interventions in the rehabilitation of patients with chronic low back pain: evidence and recommendations from systematic reviews and guidelines. *International Journal of Rehabilitation Research*. 2013. 36(1). 6–12.

[29] Leccese A., Severo M., Ventriglio A., Caccavale L., Martinotti G., Janiri L. Psychological interventions in patients with physical pain: a focus on catastrophizing and resilience – a systematic review. *Healthcare*. 2025. 13(6). 581.

[30] Ho E.K.Y., Ferreira M.L., Pinheiro M.B., Abdel Shaheed C., Oliveira C.B., Machado G.C. Psychological interventions for chronic, non-specific low back pain: systematic review and meta-analysis. *BMJ*. 2022. 376. e067718.

[31] Ceniza-Bordallo G., Guerra-Armas J., Flores-Cortes M., Bermúdez-Ramirez S. Multimodal physiotherapist intervention program for children with chronic pain: guiding physiotherapy intervention with the Pediatric Pain Screening Tool. *Journal of Clinical Medicine*. 2025. 14(11). 3629.

integration of physical, cognitive, and psychological support as part of a unified systemic approach[32]. This illustrates that protocol complexity is a necessary condition for recovery, and psychological interventions constitute a critical component capable of influencing emotional regulation, compliance, motivation, coping strategies, and long-term functional outcomes. In this context, it is essential to highlight that systemic multimodal protocols integrate the psychological component as a structurally indispensable and equally weighted modality rather than a secondary or optional element. Psychological interventions–including cognitive-behavioral strategies, emotional regulation techniques, interventions targeting pain-related or trauma-related beliefs, and stress-management training–are synchronized with physical and technological modules, forming a unified recovery trajectory. According to recent evidence, this form of integration ensures reductions in anxiety, depressive symptoms, fear of movement, and improvements in self-efficacy and quality of life[33]. An illustrative example is the study by Aguilar García et al.[34], which demonstrated that a multimodal physiotherapeutic intervention for individuals with shoulder pain–including educational and cognitive-psychological components–resulted in significant improvements in both physical and psychological indicators. This confirms the systemic advantage of integrated protocols over isolated methodologies.

In summary, the implementation of systemic multimodal protocols in rehabilitation practice is a scientifically substantiated and evidence-supported approach that enables simultaneous influence on motor, cognitive, and psychological dimensions of human functioning. Such a comprehensive architectural design provides a conceptual platform for integrating technological modules–AR/VR environments, sensor systems, and biofeedback–as essential elements of a unified recovery model operating in synergy with psychological and educational interventions and enhancing their effects.

The contemporary development of rehabilitation medicine and psychology clearly demonstrates the growing complexity of clinical conditions, comorbidity, and the influence of psychosocial factors on recovery. This has

[32] Renner A., Bologheanu R., Schandl A., Pateisky P., Hoetzenecker K., Benzer A. An evidence-based clinical guideline for the diagnosis and treatment of post-intensive care syndrome and chronic pain after intensive care. *Critical Care*. 2023. 27. 350.

[33] Ceniza-Bordallo G., Guerra-Armas J., Flores-Cortes M., Bermúdez-Ramirez S. Multimodal physiotherapist intervention program for children with chronic pain: guiding physiotherapy intervention with the Pediatric Pain Screening Tool. *Journal of Clinical Medicine*. 2025. 14(11). 3629.

[34] Aguilar García M., González Muñoz A., Pérez Montilla J.J., Aguilar Nuñez D., Hamed Hamed D., Pruimboom L. Which multimodal physiotherapy treatment is the most effective in people with shoulder pain? A systematic review and meta-analyses. *Healthcare*. 2024. 12(12). 1234.

driven the transition from single-modality approaches toward structurally coherent and multifaceted models combining biomedical, psychotherapeutic, educational, motor, and technological interventions. In international scientific literature, this type of model is described as a multimodal, personalized, and team-based rehabilitation structure grounded in the biopsychosocial paradigm and the logic of the International Classification of Functioning[35]. According to these approaches, rehabilitation is regarded as a process that simultaneously targets body functions, activity, and participation while necessarily accounting for personal and environmental factors.

The evidence base supports the effectiveness of these systemic multicomponent models. In the systematic review by Kechichian A., which included 16 randomized clinical trials and more than two thousand participants, it was shown that combining physical exercises, educational modules, and medical care led to statistically significant reductions in pain and functional limitations in individuals with chronic musculoskeletal disorders[36]. The author concludes that it is the integration of different types of interventions–not their isolated application–that produces superior outcomes. Similar findings are reported in the Swedish systematic review by SBU (2021), where multimodal and interdisciplinary programs demonstrated a moderate level of evidence for improving quality of life, function, and participation among patients with persistent pain, whereas single-component interventions often produced limited benefits[37]. In Ukrainian research (Hubenko V., Tkalina A., Drozdova O.), it is emphasized that combining physical therapy, psycho-emotional support, educational interventions, and social interaction leads to better prevention of pain chronification and accelerates recovery in chronic nonspecific pain syndromes, as well as in postoperative and post-comorbidity rehabilitation[38,39].

A systematic analysis of international and Ukrainian studies demonstrates that contemporary multimodal rehabilitation operates as a structured model composed of several interrelated levels. To summarize the key characteristics of this model, it is appropriate to present them in a tabular

[35] Cochrane Rehabilitation. *Special projects: BE4Rehab, telerehabilitation and multimodal rehabilitation*. URL: https://rehabilitation.cochrane.org/special-projects

[36] Kechichian A., Toth V., Inoue K., Alizadehkhaiyat O., Koes B.W., Hayden J.A. Multimodal interventions including rehabilitation exercise for older adults with chronic musculoskeletal pain: a systematic review and meta-analyses. *Journal of Geriatric Physical Therapy*. 2022. 45(3). 158–169.

[37] *Multimodal and Interdisciplinary Interventions for Long Term Pain: A Systematic Review. Stockholm: SBU.* 2021. URL: https://pubmed.ncbi.nlm.nih.gov/35998243

[38] Ткалич Г.В., Губенко О.В. Інтеграція цифрових технологій у нейрореабілітацію: можливості VR/AR та біологічного зворотного зв'язку. *Медична реабілітація*. 2023. 1(4). 15–23.

[39] Ткаліна А.В. Сучасні підходи в реабілітації хворих з болем у попереку. *Фітотерапія. Часопис*. 2023. (1). 59–66.

format that systematizes its substantive elements, mechanisms of action, and evidence base (Table 1).

Table 1

Structural Levels of the Multimodal Rehabilitation Model

Model Level	Content Characteristics	Typical Mechanisms of Action	Examples of Programs
1. Conceptual–Normative Level	Biopsychosocial paradigm; alignment with the ICF; focus on restoring activity and participation; personalized SMART goals; understanding rehabilitation as a *multimodal, person-centred, collaborative process*	Formation of an individualized recovery trajectory; integration of biological, psychological, and social determinants into a unified model; shift from "disease treatment" to "optimization of functioning"	Conceptual and guideline documents on multimodal rehabilitation for chronic pain and long-term post-viral conditions (long-COVID, PCC), which define the framework for combined programs (physical, psychosocial, digital components)
2. Organizational–Structural Level	Multidisciplinary team (PRM physician, physical therapist, occupational therapist, psychologist, speech and language therapist, social worker, technology specialist); unified rehabilitation plan; patient routing (inpatient – outpatient – home/tele-rehabilitation); standardized protocols (ERAS, MMR, IMPT)	Reduction of care fragmentation; coordination of interventions delivered by different specialists; ensuring continuity of the rehabilitation process; early identification of high-risk patients and referral to the appropriate level of care	Multicentre studies on the effectiveness of early *interdisciplinary multimodal assessment* (IMA) for the prevention of chronic pain; IMPT day-clinic models; structured pathways for PICS patients after ICU discharge with transition to outpatient and home-based programs
3. Process–Technological Level (Core of the Model)	Structured clinical-biomedical, motor, cognitive-behavioral, psychosocial, educational, and technological modules; clearly defined parameters of dosage, duration, intensity, and sequencing; use of technologies (AR/VR, tele-rehabilitation, sensor systems, biofeedback, BCI)	Activation of neuroplasticity; modification of behavior, beliefs, and coping strategies; enhancement of motivation and engagement; development of self-regulation skills; sensorimotor integration and real-time feedback	Multimodal programs for chronic pain (4-week IMPT with motor, psychotherapeutic, and educational components); multicomponent VR and VR+mirror-therapy systems for stroke; multimodal physiotherapy for adolescents with pain; AI-assisted multimodal tele-rehabilitation for post-COVID/PCC

Table 1 (continuance)

4. Outcome–Evaluation Level	Multidomain assessment: body functions, activity, participation, psychological parameters (anxiety, depression, fear of movement, catastrophizing, self-efficacy), quality of life, maintenance of treatment effect; use of prognostic models and markers of treatment response	Identification of clinically meaningful changes; timely protocol adaptation; stratification of patients by prognosis; planning of maintenance or anti-relapse interventions	Evaluation of the effectiveness of a 4-week IMPT program followed by a 12-month relapse-prevention phase; prognostic models of IMPT success based on patient-reported outcomes; RCTs with long-term (up to 12 months) follow-up after multimodal programs

The multimodal rehabilitation model summarized in the table illustrates that it is not merely a "combination" of interventions but a multilayered, structurally organized system in which conceptual foundations, organizational decisions, process mechanisms, and evaluation procedures form a unified whole. Such a structure enables the integration of physical, cognitive, psychological, social, and technological components in a way that they reinforce each other rather than operating in parallel or in a fragmented manner[40].

At the conceptual–normative level, the model is grounded in the biopsychosocial paradigm, which is widely recognized in contemporary international rehabilitation documents and consensus statements. Within this approach, human functioning is examined through the lens of the ICF, where impairments in body functions, limitations in activity, and participation restrictions are understood as the result of a multicomponent interaction between biological processes, psychological determinants, and contextual factors. The shift from a nosocentric perspective toward a focus on functioning and participation is reflected in guidelines for managing chronic pain and long-term post-viral conditions (long-COVID, PCC), where multimodal protocols are explicitly articulated as a priority strategy, and rehabilitation is defined as a *multimodal, person-centred, collaborative process*. At this level, the requirement for personalization is also embedded: rehabilitation goals are formulated as SMART goals jointly with the patient, while intervention choices are informed by the individual's needs and resources.

The organizational–structural level operationalizes this theoretical framework into real clinical practice. Analyses of programs in chronic pain and PICS demonstrate that the absence of structured multidisciplinary collaboration leads to fragmentation of rehabilitation trajectories, duplication or inconsistency of interventions, and ultimately reduced effectiveness.

[40] Cieza A., Causey K., Kamenov K., Hanson S.W., Chatterji S., Vos T. *Global estimates of the need for rehabilitation based on the Global Burden of Disease Study 2019: a systematic analysis for the Global Burden of Disease Study 2019*. *The Lancet*. 2021. 396(10267). 2006–2017.

Contemporary models, in contrast, mandate the presence of an integrated team working under a unified plan, with a clearly defined patient pathway from inpatient or ICU settings to outpatient and home-/tele-rehabilitation stages. This is well illustrated in German multicenter projects on early *interdisciplinary multimodal assessment* (IMA) and chronic pain prevention, where coordination of medical, psychosocial, and functional assessments allows timely referral to the most relevant level of care and prevents pain chronification. A similar logic is evident in recommendations for post-intensive care rehabilitation, which emphasize that the restoration of physical, cognitive, and psychological functions must follow a continuous and well-structured trajectory.

Central to the model is the process–technological level, which serves as the "operational core" of multimodal rehabilitation. It is composed of interconnected modules, each responsible for a specific set of mechanisms. The biomedical module creates physiological prerequisites for active rehabilitation: through pharmacotherapy, physiotherapy, and neuromodulation techniques, somatic stabilization is achieved, pain is reduced, and muscle tone is regulated. The motor module provides targeted stimulation of neuroplasticity through tasks oriented toward restoring strength, endurance, coordination, and balance. Contemporary post-stroke rehabilitation studies indicate that multimodal programs combining strength and functional training significantly outperform unimodal interventions in improving gait and limb function.

The cognitive-behavioral and broader psychotherapeutic modules aim to modify psychological factors that often maintain or exacerbate disability, such as fear of movement, catastrophizing, avoidance behaviors, and low self-efficacy. Recent IMPT studies indicate that it is precisely the inclusion of such components that accounts for reductions in pain, anxiety, depressive symptoms, and improved participation even 6–12 months after the intensive treatment phase. The educational module, focused on psychoeducation and self-management, enhances the patient's ability to regulate load, manage symptoms consciously, and plan daily activities–outcomes that systematic reviews and individual RCTs directly associate with the durability and stability of rehabilitation effects.

The psychosocial module integrates family, occupational, and broader social contexts into the rehabilitation process. Through work with the support system, modification of the work environment, and training of family members in supportive interaction principles, it becomes possible to reduce relapse risk and consolidate adaptive behavioral patterns. This direction is particularly relevant in chronic pain programs, where social isolation and occupational dysfunction are key elements of the "pain cycle."

The technological module warrants special attention. This is where AR/VR technologies, multimodal sensor systems, biofeedback, tele-rehabilitation platforms, and novel BCI solutions are concentrated. Meta-analytic evidence from VR studies in stroke and neurocognitive disorders indicates that virtual environments with multimodal feedback (visual, auditory, tactile) not only improve motor performance but also stimulate executive functions, attention, and processing speed. ResearchGate+7pmc.ncbi.nlm.nih.gov+7mdpi.com+7 Tele-rehabilitation studies in long-COVID and PCC how those multimodal online programs combining remote physical, respiratory, educational, and psycho-emotional support result in significant reductions in fatigue and dyspnea, and improvements in aerobic capacity and quality of life compared with usual care. In pediatric populations, multimodal physiotherapy enriched with educational and psychological components has been shown to improve both functional and psychological outcomes, reducing fear of movement and enhancing self-efficacy.

The outcome–evaluation level anchors the model as an evidence-based and manageable system. Modern IMPT and MMR programs increasingly incorporate not only routine clinical scales but also standardized patient-reported outcome measures, composite pain impact indices, and indicators of mental health and work capacity. Studies demonstrate that such data allow the construction of prognostic models of multimodal treatment success and identification of patient subgroups most likely to benefit from specific protocol configurations. Thus, the evaluation component not only records outcomes but also provides a closed-loop system of "planning – implementation – evaluation – adjustment," which is a defining feature of a mature multimodal rehabilitation framework.

In summary, the multimodal rehabilitation model emerges as a logically coherent, empirically validated, and technologically adaptable structure. It enables the integration of high-tech modules–AR/VR, sensor systems, biofeedback, BCI, and tele-rehabilitation–into the broader biopsychosocial rehabilitation framework while preserving the integrity of psychotherapeutic, educational, and social components. This makes the multimodal model not only a contemporary trend but an objectively necessary platform for enhancing the effectiveness of psychological and functional rehabilitation across a wide spectrum of clinical and post-traumatic conditions.

2. Multimodal Digital Approach to Contemporary Rehabilitation with Integration of VR/AR, Sensor Systems, and Biofeedback

The multimodal digital approach in rehabilitation is based on the premise that optimal functional recovery is possible only when several interrelated levels–motor, sensory, cognitive, autonomic, and emotional–motivational–are addressed simultaneously. Within this paradigm, virtual and augmented

reality (VR/AR) are not merely “interesting tools” but the core of an interactive rehabilitation environment; sensor systems provide high-precision monitoring of the patient’s condition; and biological feedback (biofeedback, BFB) transforms these data into a mechanism of adaptive regulation of therapeutic influence in real time[41].

Contemporary systematic reviews and meta-analyses show that VR-based rehabilitation is already acquiring the status of a clinically meaningful instrument in neurorehabilitation. A comprehensive analysis by Kwon et al. demonstrated that VR-oriented interventions in patients with stroke, multiple sclerosis, traumatic brain injury, and other neurological disorders improve motor function, balance, gait, and activities of daily living compared with conventional therapy or its equivalent[42]. More recent meta-analyses, including that by Yoo et al., refine these findings by showing that VR training statistically outperforms usual care in recovery of upper-limb motor function, fine hand dexterity, as well as balance and upper-limb-related ADL, although the level of evidence is often rated as low to moderate due to protocol heterogeneity[43]. Similar conclusions have been drawn for immersive VR, where meta-analytic data indicate substantial improvements in upper-limb motor outcomes (Fugl–Meyer, Box and Block Test) compared with traditional rehabilitation, even though clinically meaningful thresholds are not always reached.

For Parkinson’s disease, robust evidence has accumulated regarding the efficacy of VR in gait and balance rehabilitation. Systematic reviews and meta-analyses show that VR interventions improve dynamic balance and mobility on the TUG test, gait parameters, and functional mobility, with the best results obtained when VR is combined with physical therapy[44]. At the same time, the impact on static balance and certain cognitive parameters appears less pronounced, underscoring the need for fine-tuning of multimodal protocols.

AR technologies, which overlay virtual objects onto the real environment, add to this concept the possibility of modifying the spatiotemporal

[41] Кіндзерський Б.І., Мусохранова А.В., Овчаренко К.С. Віртуальна реальність у фізичній терапії та ерготерапії: сучасні можливості та перспективи. *Український журнал медицини, біології та спорту*. 2021. 6(1). 245–252.

[42] Kwon J.S., Park M.J., Yoon I.J., Park S.H. Effects of virtual reality on upper extremity function and ADL performance in acute stroke: a double-blind randomized clinical trial. *NeuroRehabilitation*. 2012. 31(4). 379–385.

[43] Yoo W.K., Jung S.J., Seo Y., Kim B.R., Kim S.M., Kim D.Y. The effects of virtual reality training on post-stroke upper and lower limb function: a meta-analysis of randomized controlled trials. *Brain Neurorehabilitation*. 2025. 18(1). e2

[44] Mirelman A., Maidan I., Herman T., Deutsch J.E., Giladi N., Hausdorff J.M. Virtual reality for gait training: can it induce motor learning to enhance complex walking and reduce fall risk in neurological disorders? *Journal of Gerontology A: Biological Sciences and Medical Sciences*. 2011. 66A(2). 234–240.

characteristics of tasks without altering the physical surroundings. Reviews on AR use in physical therapy report that AR-based gait training in Parkinson's disease improves gait parameters, the ability to overcome virtual obstacles, and helps to reduce "freezing of gait", particularly when combined with traditional rehabilitation methods. sciencedirect.com+1 In this context, AR becomes an important component of a multimodal approach, enabling integration of real movement, virtual stimuli, and sensor measurements within a single scenario.

Sensor technologies play a key role in multimodal digital systems. A systematic review devoted to sensor-oriented control strategies for shoulder movement after stroke showed that modern setups actively combine inertial measurement units (IMU), force sensors, electromyography, and other modalities to develop algorithms for adaptive control of training devices and robotic systems. Another review focused on wearable sensors and VR for gait and balance rehabilitation after stroke emphasizes that such systems not only improve motor outcomes but also make it possible to deliver rehabilitation outside the clinic, including in the home environment, with remote monitoring of progress. User requirements for home-based sensor systems for upper-limb rehabilitation after stroke include ease of use, reliable feedback, safety, and flexibility of load adjustment–all of which are naturally aligned with the concept of biofeedback as a "bridge" between sensor data and the patient's subjective experience[45].

Biofeedback is the third key component of multimodal digital rehabilitation. An early classical meta-analysis by Glanz et al. reported mixed results for EMG-based biofeedback in restoring range of motion in hemiparetic joints, which was partly attributed to the technological limitations and primitive protocols available at the time[46]. In contrast, contemporary reviews on real-time biofeedback for gait training after stroke demonstrate that visual and tactile feedback based on spatiotemporal gait parameters, symmetry, and gait phases is a promising tool for correcting biomechanical deficits, especially when combined with other rehabilitation methods.

The synthesis of these three components–VR/AR, sensor systems, and biofeedback–forms what can be termed intelligent multimodal rehabilitation complexes. In such systems, VR/AR generate a rich sensory environment and task set; sensor technologies provide objective data on movement, muscle activity, and autonomic responses; and biofeedback converts these

[45] Morone G., Papaioannou F., Alberti A., Ciancarelli I., Bonanno M., Calabrò R.S. Efficacy of sensor-based training using exergaming or virtual reality in chronic low back pain: a systematic review. *Sensors*. 2024. 24(19). 6269.

[46] Kenea C.D., Abessa T.G., Lamba D., Bonnechère B. Immersive virtual reality in stroke rehabilitation: a systematic review and meta-analysis of its efficacy in upper limb recovery. *Journal of Clinical Medicine*. 2025. 14(6). 1783.

data into a clear, motivationally meaningful signal for the patient, simultaneously serving as input for adaptive algorithms.

In upper-limb stroke rehabilitation, for example, VR games involving object manipulation in three-dimensional space are combined with tracking of hand, forearm, and shoulder movements using IMUs or optical systems. In real time, the patient receives visual feedback regarding accuracy, smoothness, and speed of movement, while the system, drawing on sensor data, automatically modifies task complexity. Meta-analyses of both immersive and non-immersive VR protocols consistently report improvements in upper-limb motor function and manual dexterity, strengthening the argument for integrating such technologies into standard rehabilitation pathways. In addition, there is a growing number of programs that employ everyday "smart" devices (smartphones, tablets, game controllers) as platforms for sensor monitoring and biofeedback, thereby lowering the threshold for widespread implementation. In the context of gait and balance after stroke or in Parkinson's disease, multimodal systems even more clearly demonstrate their integrative nature. VR-based treadmill walking scenarios are supplemented with force plates, IMUs on the lower limbs and trunk, and sometimes wearable EMG. In the virtual environment, the patient can see changes in step length, symmetry, and center-of-mass trajectory, receives immediate visual and auditory feedback when target parameters are achieved, and encounters virtual obstacles or dual-task conditions. Reviews of VR- and sensor-oriented interventions confirm that, under such conditions, balance, functional gait, and mobility outcomes improve, with VR operating as a powerful "multiplier" of motivation and repetition dosage[47].

Telerehabilitation represents a natural extension of this approach: wearable sensors and home-based VR/AR platforms make it possible to transfer multimodal interventions into the patient's home while maintaining objective monitoring and biofeedback. According to a 2024 umbrella review of post-stroke telerehabilitation, remote programs (including those incorporating VR elements and sensor monitoring) provide comparable or superior outcomes in motor function, balance, ADL, and quality of life relative to exclusively in-person interventions, provided that organization and support are adequate[48]. An important yet often underestimated dimension of the multimodal digital approach is the psychological component–namely, the impact of VR/AR, sensor systems, and biofeedback

[47] Laver K.E., Lange B., George S., Deutsch J.E., Saposnik G., Crotty M. *Virtual reality for stroke rehabilitation*. *Cochrane Database of Systematic Reviews*. 2017. 11. CD008349. DOI:10.1002/14651858.CD008349.pub4.

[48] Kumar D., Bhatt T., Roy J.S., Kim T. Virtual reality-based balance training system augmented with operant conditioning paradigm in post-stroke rehabilitation. *Biomedical Engineering Online*. 2019. 18. 57.

not only on motor and cognitive recovery but also on emotional state, motivation, levels of anxiety and depression, and the sense of control over one's body and treatment process. In contemporary literature, VR is increasingly regarded as an instrument that simultaneously combines physical, cognitive, and psychotherapeutic effects, creating a safe, controlled, and motivationally rich environment[49].

Systematic reviews and clinical studies indicate that VR training in post-stroke and other neurological rehabilitation can reduce symptoms of depression and anxiety and improve quality of life, with particularly pronounced effects observed in immersive VR programs lasting more than six weeks. Studies of VR-based cognitive training have demonstrated not only improvements in cognitive functions (verbal learning, working memory) but also reductions in depressive and anxiety symptoms, enhanced emotional self-regulation, and more positive self-appraisal of abilities, interpreted as increased self-efficacy. Synthesized data on VR and gamification in the treatment of anxiety and depression suggest that virtual environments can modulate emotional responses by providing patients with a controlled experience of confronting stressful situations and gradually reducing affective reactivity[50].

Another body of research focuses on VR as a psychotherapeutic tool– primarily in the format of VR exposure therapy for post-traumatic stress disorder, specific phobias, and other anxiety conditions. Clinical VR protocols allow traumatic or anxiety-provoking situations to be reproduced under controlled conditions, with gradual intensification of stimuli, resulting in reduced anxiety, reactivity, and avoidance. The advantage of VR exposure is that it can be easily integrated into multimodal rehabilitation programs in which motor and cognitive tasks are combined with the development of emotional self-regulation skills.

Equally important are studies demonstrating that VR can influence body image, the sense of bodily ownership, and pain perception. Research on the phenomenon of embodiment in a virtual body shows that appropriately calibrated virtual avatars and synchronized movement and sensory feedback can reduce pain sensations, modify negative perceptions of an affected limb, and foster a more "friendly" attitude toward one's own body. In rehabilitation, this is particularly relevant in chronic pain, limb disownership syndromes, and

[49] Kenea C.D., Abessa T.G., Lamba D., Bonnechère B. Immersive virtual reality in stroke rehabilitation: a systematic review and meta-analysis of its efficacy in upper limb recovery. *Journal of Clinical Medicine*. 2025. 14(6). 1783.

[50] Howard M.C. A meta-analysis of virtual reality-based interventions for symptoms of anxiety and depression. *Computers in Human Behavior*. 2017. 70. 27–37.

post-amputation or orthopedic conditions, where VR becomes a tool of psychosomatic integration[51].

Biofeedback, traditionally considered a method for training neuromuscular function, is now increasingly interpreted in psychophysiological terms. Systematic reviews show that biofeedback based on heart rate, respiration, electrodermal activity, and brain activity (neurofeedback) effectively reduces anxiety, stress, and chronic pain, and improves emotional well-being and quality of life. In this context, biofeedback functions not only as a "technical module" but as a learning technology of self-regulation that provides patients with direct experience of influencing their own state. This experience itself increases perceived control and reduces helplessness–critical psychological factors in chronic conditions[52].

In modern models integrating psychotherapy and biofeedback (including for children, adolescents, and adults with anxiety–depressive symptoms and chronic pain), it is emphasized that the best outcomes are achieved when psychological interventions (cognitive-behavioral therapy, psychoeducation, stress-coping skills training) are combined with biofeedback within a single protocol. In multimodal digital systems, a VR/AR component is added to this configuration, making self-regulation training more vivid, contextualized, and motivationally engaging[53].

Taking this into account, the psychological dimension of the multimodal digital approach can be described as a triangle of "emotion–motivation–self-regulation," in which VR/AR are responsible for emotional engagement, context, and experiential immersion; sensor systems for objectifying reactions; and biofeedback for teaching control over one's internal states. Empirical data indicate that incorporating these components into rehabilitation programs contributes not only to better functional outcomes but also to reductions in anxiety and depression, improvements in quality of life, self-efficacy, and treatment satisfaction–factors that are particularly important in long-term, resource-intensive rehabilitation processes. To synthesize the various models of integrating VR/AR, sensor systems, and biofeedback into rehabilitation, it is useful to construct a comparative table that presents specific examples of multimodal complexes, their structure, and the clinical effects supported by evidence (Table 2).

[51] Demeco A., Zola L., Frizziero A., Martini C., Palumbo A., Foresti R. Immersive virtual reality in post-stroke rehabilitation: a systematic review. *Sensors*. 2023. 23(3). 1712.

[52] Reese C., Mittag O. Psychological interventions in the rehabilitation of patients with chronic low back pain: evidence and recommendations from systematic reviews and guidelines. *International Journal of Rehabilitation Research*. 2013. 36(1). 6–12.

[53] Kwon J.S., Park M.J., Yoon I.J., Park S.H. Effects of virtual reality on upper extremity function and ADL performance in acute stroke: a double-blind randomized clinical trial. *NeuroRehabilitation*. 2012. 31(4). 379–385.

Table 2

Integration of VR/AR, Sensor Systems, and Biofeedback into Multimodal Rehabilitation

Clinical domain	Digital environment (VR/AR)	Sensor modules	Type and channel of biofeedback	Nature of multimodal interaction	Target population
Restoration of upper-limb motor function after stroke[54]	Immersive VR games with object manipulation, training of reaching movements and functional grasps	Motion controllers, IMUs on the hand and forearm, optical tracking; in some systems EMG of hand muscles	Visual biofeedback on accuracy and smoothness of the trajectory and number of successful attempts; auditory signal when the target is reached	Parallel stimulation of vision, proprioception, motor planning and competitive motivation; adaptive adjustment of task difficulty based on sensor data	Patients with subacute and chronic stroke
Balance and gait in Parkinson's disease	VR protocols for gait and navigation in a virtual environment, training of obstacle avoidance	Force platforms, IMUs on the feet and trunk, optical sensors; optionally instrumented walkways	Visual biofeedback on centre-of-pressure sway, step length and symmetry, and task completion time; auditory biofeedback when deviating from target parameters	Combination of postural control and gait training with visual orientation and cognitive tasks (dual tasks), with continuous sensor monitoring	Patients with mild to moderate Parkinson's disease
AR-based gait training in Parkinson's disease	AR projection of virtual obstacles, lines and markers into the real space to train step length and obstacle negotiation	Cameras, position-tracking systems, IMUs; in some cases force platforms	Visual biofeedback on correct foot placement relative to virtual objects and reaction time; corrective auditory signals	Interaction of real movement with superimposed virtual stimuli; training of sensorimotor integration and spatial anticipation	Patients with Parkinson's disease experiencing episodes of freezing of gait

[54] Laver K.E., Lange B., George S., Deutsch J.E., Saposnik G., Crotty M. Virtual reality for stroke rehabilitation. *Cochrane Database of Systematic Reviews*. 2017. 11. CD008349.

Table 2 (continuance)

Gait training after stroke with targeted biofeedback	VR or screen-based gait scenarios on a treadmill or in a virtual corridor	Gait sensors (force platforms, insole-based load cells), IMUs on the lower limbs; in some systems EMG of thigh and shank muscles	Visual biofeedback on gait phases, symmetry and speed; tactile or auditory signals when target values are reached or exceeded	Multimodal integration: the patient simultaneously experiences movement, sees their "digital footprint" and corrects gait pattern using biofeedback; can be combined with cognitive tasks	Patients in the subacute and chronic phases after stroke
Home-based VR telerehabilitation after stroke	Home VR games with functional tasks for the arm, balance or gait, adapted to the patient's level	Wearable IMUs, depth cameras, controller trackers; optional heart rate monitoring	Automated visual biofeedback within the game (scores, levels, errors); remote biofeedback from the therapist via telemedicine platforms	Combination of daily home-based practice with remote supervision; multimodal engagement through gaming, sensor monitoring and regular contact with a specialist	Patients with chronic stroke sequelae and limited mobility
Smart-device–oriented hand rehabilitation	Game-like tasks on a smartphone/tablet targeting fine motor skills, sometimes in augmented reality mode	Built-in motion sensors in the smartphone, external Bluetooth controllers or sensor gloves	Visual biofeedback (trajectory accuracy, execution speed, number of errors); progress reports within the app	Easy integration into everyday life; combination of motor training, attention and motivational mechanisms (levels, achievements)	Post-stroke patients and others with impaired hand function
Cognitive–emotional–oriented neurorehabilitation	Immersive VR environments with tasks involving navigation, planning and social scenarios	Motion tracking, wearable heart-rate and galvanic skin response sensors; EEG in future systems	Multimodal biofeedback: adjustment of task difficulty according to level of physiological arousal, heart-rate dynamics, errors and reaction time	Simultaneous stimulation of cognitive activity, emotional regulation and motor function; training of stress resilience and self-regulation by managing one's state in VR	Patients with consequences of TBI, stroke, and anxiety–depressive disorders

Table 2 (continuance)

Psychosocial rehabilitation; emotional regulation – Psious VR Therapy[55]	VR exposure environments (phobias, PTSD, panic attacks, social situations)	HRV sensors, GSR sensors, heart-rate monitors	HRV biofeedback, GSR biofeedback	Adaptation of exposure intensity to physiological response; control of emotional activation; training of stress tolerance	Patients with phobias, PTSD, panic attacks and social anxiety
Psychosocial rehabilitation; emotional regulation – TRIPP VR[56]	VR meditation and gamified relaxation environments	HRV sensors, heart-rate monitors	HRV biofeedback	Dynamic modification of the VR environment according to heart-rate variability; development of emotional regulation skills	Individuals with chronic stress, anxiety and depressive symptoms
Psychosocial rehabilitation; emotional regulation – DEEP VR[57]	VR game controlled by breathing (avatar movement depends on breathing)	Respiratory sensors, heart-rate monitors	Respiratory biofeedback	Formation of diaphragmatic breathing; reduction of psychophysiological arousal through interactive breath control	Children and adults with anxiety and emotional instability
Psychococial rehabilitation; emotional regulation – NeuroMeditation VR	VR meditation, VR relaxation scenes, cognitive exercises	EEG-based neurofeedback, HRV sensors	Neurofeed-back (alpha, theta, SMR) and HRV biofeedback	Adaptation of VR scenes to brain activity; training of concentration, calmness and emotional stability	Patients with anxiety–depressive disorders, ADHD and cognitive fatigue
Psychosocial rehabilitation; emotional regulation – LimbicVR	VR landscapes, nature scenes and VR relaxation environments	GSR sensors, heart-rate monitors	GSR biofeedback	Regulation of VR stimuli in accordance with skin conductance reactivity; training of control over emotional responses	Individuals with stress, emotional lability and burnout

[55] Psious VR Therapy. URL: https://www.psious.com

[56] TRIPP VR – Therapeutic Virtual Reality Meditation Platform. URL: https://www.tripp.com

[57] DEEP VR – Virtual reality breathing training for anxiety and trauma. URL: https://www.exploredeep.com

Table 2 (continuance)

Psychosocial rehabilitation; emotional regulation – Social VR Labs	VR scenarios of social interaction (dialogue, role-play situations)	HRV sensors, GSR sensors, camera-based facial-expression tracking	HRV biofeedback, GSR biofeedback	Simulation of social situations; reduction of social anxiety; training of emotional stability during communication	Individuals with social anxiety, autism spectrum conditions and disorders of emotional–volitional regulation
Psychosocial rehabilitation; emotional regulation – VR Mindfulness Programs (VR-MBCT)	VR natural landscapes and meditative environments	Respiratory sensors, HRV sensors	HRV biofeedback, respiratory biofeedback	Deepening of relaxation through synchronization of breathing and the VR environment; reduction of anxiety	Individuals with anxiety, stress and emotional overload

Summarizing the analysis of the sources, it can be argued that the multimodal digital approach with integration of VR/AR, sensor systems, and biofeedback is gradually evolving from an experimental concept into a new standard of high-technology rehabilitation. VR/AR provide multichannel sensory stimulation and contextualization of tasks; sensor systems ensure high-resolution assessment of motor and autonomic parameters; biofeedback offers a mechanism for adaptive regulation and training of self-control. Together, they create dynamic, individualized scenarios in which rehabilitation is transformed from a set of “exercises” into an interactive process of joint tuning of the “patient–technology–therapist” system in real time. Current scientific evidence already demonstrates substantial advantages of this approach in the domains of motor function, balance, and gait, and potentially in cognitive–emotional rehabilitation as well, although there remains a clear need for protocol standardization, multicentre studies, and more in-depth investigation of long-term effects.

The mechanisms of action of multimodal high-technology rehabilitation encompass a broad spectrum of biological, psychological, and organizational components that interact with one another and generate an integrated restorative effect. Their effectiveness cannot be reduced merely to an increase in the volume or intensity of exercises: modern technologies provide a fundamentally new level of influence on the nervous system, on patient behavior and psycho-emotional status, and on the accessibility of rehabilitation services.

At the neurophysiological level, key roles are played by processes of neuroplasticity and sensorimotor drive. Studies employing electroencephalography and neuroimaging indicate that VR training can modulate the activity of sensorimotor networks–for example, increasing alpha power in occipital regions and beta activity in frontal areas, which is associated with the formation of new neural connections and reactivation of motor schemas even in chronic stages of stroke. Extended and virtual reality, as well as broader XR systems, create a unique multichannel sensory environment in which visual, proprioceptive, vestibular, and tactile signals are integrated, thereby enhancing the potential for synaptic reorganization and optimizing the formation of motor programs. This forms the basis for restoring movement, coordination, and fine motor skills in patients with neurological deficits.

At the same time, the intensity and specificity of training remain crucial parameters. Robotic systems, exoskeletons, and intelligently controlled training devices make it possible to conduct highly intensive, repetitive, and structured motor sessions that cannot be delivered by the therapist alone. Systematic reviews emphasize that task-specific training and high-repetition practice are critical predictors of motor recovery after stroke, spinal cord injury, and other neurological lesions. Technological platforms therefore provide a quantitatively and qualitatively different level of sensorimotor stimulation, laying the foundation for clinically meaningful improvements.

However, biological mechanisms are inextricably linked with behavioral and motivational ones. VR environments enriched with gamification elements, biofeedback, and interactive serious games markedly increase patient engagement, reduce the monotony of exercises, and foster sustained adherence to the program. By enabling patients to observe their own progress in real time, receive immediate feedback, and experience an emotionally positive training context, these systems promote higher intrinsic motivation and self-efficacy. This is particularly important in long-term rehabilitation courses, where monotony and reduced motivation are typical risk factors for treatment discontinuation. With the advancement of digital technologies, personalization of rehabilitation protocols using artificial-intelligence algorithms is gaining increasing importance. Machine learning enables adaptation of task difficulty, intensity of load, and session frequency based on objective behavioral and physiological data–from movement patterns to cardiovascular regulation indices. Evidence from AI-assisted telerehabilitation programs for chronic pain and various functional disorders shows that adaptive load dosing yields better functional and psycho-emotional outcomes than traditional standardized protocols. This approach minimizes the risk of overload, enhances motivation, and creates an individualized trajectory of recovery.

It is also important to note that multimodal rehabilitation exerts a pronounced systemic impact on the organism. Exoskeleton-assisted gait and intensive robotic training contribute to improved cardiorespiratory endurance, normalization of muscle tone, better autonomic regulation, and even changes in gut microbiome composition–changes that are potentially linked to neuroimmune mechanisms of recovery in spinal injuries. Simultaneously, AR and VR interventions can modulate cognitive functions, attention, memory, emotional regulation, and stress reactivity, which is particularly significant for patients with acquired cognitive impairment or post-traumatic changes. Thus, systemic physiological and cognitive effects complement one another and broaden the scope of rehabilitation interventions.

The gradual transition from a purely somatic to a biopsychosocial paradigm of rehabilitation highlights the importance of psychological mechanisms underlying high-technology interventions. Virtual reality has become an evidence-based tool of psychological rehabilitation, particularly in post-traumatic stress disorder, anxiety–depressive states, and the consequences of psychological trauma. Virtual Reality Exposure Therapy (VRET) makes it possible to reproduce traumatic scenarios under controlled conditions, gradually reducing fear intensity and promoting extinction processes. Randomized trials in military personnel with combat-related PTSD show that graded VR exposure produces significant reductions in PTSD and depressive symptoms and may be comparable in efficacy to traditional prolonged exposure therapy. On the same principle is based 3MDR, a multimodal VR-supported therapy that combines motor activity, exposure modules, and elements of cognitive processing of memories, and demonstrates promising results in veterans with comorbid PTSD and mild traumatic brain injury[58].

The psychological effects of technological rehabilitation are further reinforced by telepsychological formats, which enable systematic symptom monitoring, delivery of psychotherapeutic consultations, and sustained patient support in the post-treatment period. Systematic reviews show that online psychotherapy and remote interventions for PTSD, depression, and anxiety disorders are as effective as face-to-face methods, and that their combination with VR modules constitutes a fully fledged multimodal trajectory of psychological recovery. This is particularly important for patients with limited mobility, those living in remote regions, and for long-term follow-up after severe physical trauma.

The final component in the mechanism of action of multimodal programs concerns organizational aspects that determine the accessibility and

[58] Wiebe A., Kannen K., Selaskowski B., Pogatzki-Zahn E.M., Klinger R. Virtual reality in the diagnostic and therapy for mental disorders: a systematic review. *Clinical Psychology Review*. 2022. 93. 102136.

continuity of rehabilitation. Telerehabilitation integrated with VR training, activity sensors, and remote monitoring creates opportunities to extend comprehensive treatment beyond the inpatient setting, providing both physical and psychological support. Evidence-based reviews indicate that such models are not inferior to traditional ones and, in some cases, even outperform them in terms of treatment adherence, symptom control, and complication prevention. This forms the basis for continuous, personalized rehabilitation that encompasses all components of recovery–biological, motor, cognitive, emotional, and social.

Despite these substantial advantages, limitations, implementation challenges, and economic aspects must be taken into account. Although the number of studies is growing, many still involve small samples, short follow-up periods, and heterogeneous protocols and populations, which complicates extrapolation of the findings to routine clinical practice. Staff training, equipment procurement, integration with existing clinical systems, and technical support all create financial and organizational barriers. Economic evaluations show that remote and technology-enhanced rehabilitation models can be cost-effective–in several studies, reduced per-patient costs or equivalent effectiveness at lower cost have been reported. For example, a 2022 systematic review found that in 64% of studies telerehabilitation was more cost-effective than traditional care[59]. At the same time, further long-term economic and clinical research is required, especially for fully fledged multimodal high-technology programs rather than telerehabilitation alone.

In conclusion, multimodal high-technology rehabilitation provides a comprehensive impact on the human body and psyche, combining neuroplastic, behavioral, psychological, and systemic mechanisms. Its effectiveness is grounded in the synergy of physical and psychotherapeutic components and in expanded possibilities for personalization and accessibility, making such interventions one of the most promising directions in contemporary restorative medicine.

CONCLUSIONS

Synthesizing the theoretical and evidence-based analysis, it can be concluded that multimodal rehabilitation emerges as an integrated, structurally organized, and scientifically grounded system capable of combining biomedical, psychosocial, cognitive, and technological interventions into a unified recovery model. Its conceptual foundation lies in the biopsychosocial approach and contemporary recommendations from

[59] Kenea C.D., Abessa T.G., Lamba D., Bonnechère B. Immersive virtual reality in stroke rehabilitation: a systematic review and meta-analysis of its efficacy in upper limb recovery. *Journal of Clinical Medicine*. 2025. 14(6). 1783.

Cochrane Rehabilitation, which define rehabilitation as a *multimodal, person-centred, collaborative process*, where functional recovery is inseparable from the development of activity, participation, and sustainable behavioural change. This methodological perspective provides a solid basis for integrating advanced digital technologies without compromising the coherence of psychotherapeutic, educational, and social components.

The analysis of current research demonstrates that the inclusion of VR/AR environments, multichannel sensor systems, and biofeedback modules substantially enhances the effectiveness of rehabilitation by means of gamification, contextualization of tasks, expanded sensory stimulation, and real-time adaptive feedback. The combination of motor, cognitive, and psycho-emotional stimuli activates extensive neural networks and promotes the formation of new functional connections within the CNS. These findings are consistent with meta-analytic evidence showing improvements in motor performance, balance, gait, cognitive flexibility, and emotional regulation. Importantly, the evidence also indicates that multimodal technological systems can be effectively transferred into home settings via telerehabilitation platforms, ensuring continuity of recovery and enabling objective monitoring.

A key outcome of this review is the confirmation that rehabilitation effectiveness is determined not by isolated methods, but by the systemic organization of the protocol: precise dosing, structured sequencing, multidimensional influence, and multidisciplinary coordination. Multimodal protocols that combine motor, cognitive-behavioural, psychosocial, and technological interventions consistently show superior clinical outcomes, better prevention of chronicity, enhanced motivation, and more durable effects compared to monotherapeutic approaches. Several studies demonstrate that integrated programmes accelerate functional recovery, reduce complication risks and shorten hospitalization, while in chronic and post-viral conditions they reduce fatigue, pain, and anxiety and improve quality of life and participation.

Despite substantial positive results, existing data point to several challenges: heterogeneity of protocols, insufficient large-scale studies–especially those examining integrated systems–and limited evidence for implementation in resource-constrained health-care settings. This highlights the necessity to standardize multimodal interventions, optimize loading parameters, develop unified pathways, and promote technologies adapted to the Ukrainian context, where war has significantly increased the need for highly effective rehabilitation for neurological, traumatic, post-stroke, and psychosocial conditions.

Overall, the findings allow us to conclude that multimodal rehabilitation enriched with VR/AR technologies, sensor systems, and biofeedback is

transitioning from an experimental concept into a new standard of high-technology, personalized, and evidence-based rehabilitation practice. It ensures synergy between motor, cognitive, and psycho-emotional recovery mechanisms, enhances motivation and engagement, supports neuroplasticity, and facilitates the development of lasting self-regulation skills. This approach opens pathways for building adaptive, scalable, multidisciplinary rehabilitation systems capable of responding effectively to modern clinical and societal challenges.

SUMMARY

This section presents a comprehensive analysis of the mechanisms underlying multimodal high-technology rehabilitation and its impact on the effectiveness of restorative treatment within the framework of contemporary evidence-based medicine. It elucidates the neurophysiological foundations of neuroplasticity, sensorimotor activation, and the influence of VR/XR technologies on the reorganization of functional brain networks. The significance of training intensity and task specificity–enabled by robotic systems and exoskeletons–is examined, along with behavioural mechanisms that enhance patient motivation through gamification, biofeedback, and interactive digital platforms. Particular attention is devoted to the psychological effects of high-technology interventions, including VR exposure therapy and telepsychology, which have demonstrated efficacy in PTSD, anxiety–depressive states, and trauma-related disorders. The section also discusses systemic physiological and cognitive changes accompanying intensive technological rehabilitation, as well as the organizational advantages of telerehabilitation models. Key limitations and implementation challenges are analyzed, including protocol variability, infrastructural demands, digital inequality, and the scarcity of long-term economic evaluations. It is emphasized that multimodal high-technology rehabilitation–owing to the synergy of physical, cognitive, and psychological mechanisms–has the potential to become a new standard in restorative medicine.

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