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The use of innovative means and methods of rehabilitation intervention for upper limb injuries in military personnel (literature review)

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Abstract: *the article outlines the characteristics of upper limb injuries in military personnel caused by gunshot and shrapnel wounds, fractures, neuropathies, and soft tissue injuries. Special attention is given to innovative rehabilitation approaches that promote the recovery of mobility, coordination, and limb functionality. The effectiveness of modern developments and methodologies in robotics and virtual reality for upper limb rehabilitation, as presented in scientific literature from 2021 to 2024, is analyzed concerning various types of injuries and recovery periods. These technologies demonstrate high potential in physical therapy by ensuring controlled and repetitive movements to activate muscle memory, stimulating sensorimotor functions, and creating a motivational environment. The necessity for further research is substantiated to confirm their clinical significance and long-term effectiveness. The summarized comparative information will serve as a valuable tool for physical therapists in selecting the most optimal innovative means and methods, as well as in developing more effective individualized rehabilitation programs for military personnel with upper limb injuries.*

Key words: Evidence-Based Medicine; Military Personnel; Physical Therapy; Quality of Life; Rehabilitation; recovery, robotic systems, upper limb injuries, vr, innovative methods, innovative tools.

Introduction

Upper limb injuries are one of the most common issues among military personnel, who endure significant physical strain, especially in combat conditions. Such injuries can significantly impact the combat readiness and effectiveness of the Armed Forces of Ukraine. They range from fractures and soft tissue injuries to severe cases requiring amputation [1].

Statistics indicate that approximately 25,7–42% of all injuries sustained during combat involve arm and shoulder injuries. Compared to other body parts, these areas are less protected, often resulting in temporary or permanent disability [1,2]. The most frequently encountered injuries include fractures, dislocations, and muscle tears. Their complications involve delayed consolidation of upper limb long bone

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fractures and the development of post-traumatic and post-immobilization contractures [1].

Practical specialists emphasize the undeniable impact of upper limb injuries on quality of life and functionality, as they limit the ability to perform daily tasks and professional duties. Therefore, they highlight that physical therapy (PT) in such cases aims not only to restore mobility and strength in the affected limb but also to reintegrate the servicemember into full-fledged life and military service [2].

An analysis of recent research by Ukrainian and international experts on rehabilitation recovery issues demonstrates that PT for these patients remains highly relevant. Existing comprehensive programs require new approaches, particularly the use of innovative technologies such as virtual reality and robotic therapy.

Aim

To characterize the structural and functional changes in upper limb injuries among military personnel, analyze the effectiveness of applying advanced rehabilitation technologies based on robotics and virtual reality (VR), and summarize information on their practical application in the recovery treatment of these patients.

Materials and Methods

A literature review was conducted using scientometric databases such as the Cochrane Library, PEDro, Google Scholar, PubMed, Oxford Academic, SpringerLink, and MDPI, as well as specialized Ukrainian medical journals. Publications from 2021 to 2024 were selected. The search included articles containing information on upper limb injuries, the use of robotic and VR therapy in PT, and their effectiveness, confirmed by clear functional recovery outcome criteria. Due to the limited number of studies involving military personnel, data from research on stroke rehabilitation and orthopedic conditions were also considered. Given the similarity in the clinical presentation of upper limb injuries, these findings can be extrapolated to military personnel, taking into account the individual characteristics of their trauma, physical and psychological condition, and the specific demands of military service. The collected information allowed for a comparative analysis of the potential use of robotic therapy and virtual reality technologies for specific impairments and at various stages of rehabilitation. Conclusions were drawn regarding their evidence-based effectiveness and the necessity for further research.

Review and Discussion

Combat-related upper limb injuries include gunshot and shrapnel wounds, bone fractures, amputations, neuropathies, arterial and venous injuries, as well as damage to soft tissues and the ligamentous apparatus. Military personnel may also sustain injuries not directly related to combat operations [3].

The main causes of combat-related upper limb injuries are mine-shrapnel, mine-explosive, and gunshot wounds [4]. They are characterized by multiplicity, varying depth, and wound surface area [5,6]. Mechanical injuries of the upper limbs in military personnel (mainly fractures and dislocations) result from impacts and compression by heavy objects, falls from heights, or movement across uneven terrain. Intense physical exertion during training or combat leads to ligament and muscle sprains [1].

A characteristic feature of combat trauma is the presence of combined complex polystructural wounds, where both soft tissues and bones are damaged, often accompanied by joint, vascular, and nerve destruction [7]. The high frequency of infectious-inflammatory complications exacerbates the injury course and necessitates long-term treatment and rehabilitation.

A primary injury in combat trauma is compartment syndrome, which arises due to increased pressure in muscle compartments. It is common in fractures and complex injuries. Neurotraumatic lesions of peripheral nerves, frequently observed in blast injuries, result in loss of sensation, motor dysfunction, and chronic pain. Vascular injuries contribute to serious ischemic complications, including contractures or even amputations. Combat-related upper limb injuries often involve open fractures, requiring multiple surgical interventions for bone stabilization and subsequent prolonged physical therapy [1].

The rehabilitation of military personnel with upper limb injuries is particularly important due to the complex anatomical structure of these body parts, as they play a crucial role in military tasks, including weapon handling and executing complex technical and tactical operations [7].

The development of individualized PT programs should consider the affected upper limb segments, the number of injuries, and the severity of damage. Rehabilitation should engage the entire upper limb, while focusing specifically on the injured structures. Even an uninjured joint is prone to pathological changes due to inactivity, so controlled loading of the entire limb improves functional outcomes and shortens the rehabilitation period [8].

Rehabilitation for upper limb injuries and wounds is crucial, as its key objectives are restoring functionality – mobility, strength, and coordination – to facilitate daily activities and return to professional duties; reducing pain and swelling to accelerate recovery; preventing complications such as contractures, muscle atrophy, and chronic pain; providing psychological support and motivation to help military personnel cope with stress and trauma-related depression; and improving overall quality of life [3].

The restoration of motor functions and reintegration of wounded personnel into professional duties depends on several key factors: the type of injury, the effectiveness of treatment, and the successful application of rehabilitation interventions. Physical therapy should begin with an assessment of the patient's needs [9]. To achieve its goals, it is advisable to use not only traditional but also innovative rehabilitation tools and methods [8]. Rehabilitation technologies are rapidly evolving, opening up new possibilities for robotic therapy and virtual reality (VR) in PT.

Understanding the correct application of robotics in medicine can enhance treatment methods, making them more individualized and effective [10].

Robotic therapy, particularly involving exoskeletons and end-effector devices, is promising in post-stroke rehabilitation. The effectiveness of these devices in restoring upper limb functions varies in real clinical practice, defining their specific applications. These technologies are recommended as an adjunct to standard rehabilitation programs. Calabrò R.S. et al. studied the effectiveness of Armeo Power and Armeo Spring exoskeletons compared to InMotion 2, Armotion, Motore, and ReoGo end-effector devices. After completing the rehabilitation course, both groups showed significant improvement in upper limb functional status. In the exoskeleton group, the mean FMA-UE score increased by 11 points (60% improvement). In the end-effector group, the mean FMA-UE score increased by 7 points (30% improvement). In both groups, $p < 0.0001$, indicating strong clinical significance. These findings suggest that exoskeletons are preferable in the acute phase for patients with severe impairments, as they provide greater support and enable more complex movements. Meanwhile, end-effector devices, which focus on precise and functional movements, are more suitable in the chronic phase for patients with residual motor impairments. This study highlights the need for further research on the long-term effects of these two innovative technologies and the personalization of their application in rehabilitation programs [10].

Tseng K.C. et al. studied modern approaches to the use of portable robotic devices in PT. The results of the analysis of various recovery parameters, such as mobility, muscle strength, and functional independence, indicate that their use contributes to a significant improvement in motor functions, especially in post-stroke patients with moderate motor impairments. According to the FMA scale, an increase of 0,696 standard deviation was recorded compared to those who underwent only traditional therapy, reflecting a significant clinical effect. Among the advantages of portable devices are repetitive and intensive tasks, convenience for outpatient and home rehabilitation, and compactness. At the same time, their effectiveness may vary depending on the nature and severity of the disease, as well as the overall physical condition of the patient. The combination of such portable devices with network communication technologies opens up prospects for expanding home rehabilitation [11].

Spits A.N. et al. recommend the modern MERLIN system for home PT in stroke patients

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with upper limb impairments. It consists of the ArmAssist robotic assistive device (which monitors and collects biomechanical data) integrated with the Antari Homecare home telerehabilitation platform (which provides communication between the patient and therapist). It is worth noting that this study is qualitative and does not contain a large number of statistically significant results. The focus is on patient experience and their perception of the telerehabilitation process. Nevertheless, an improvement in motor functions was observed: on the FMA scale – by 6,8 points, the ARAT test – by 4,4 points, and the Wolf test – by 5 points, indicating a reduction in motor impairments. Qualitative results suggest improvements in cognitive functions, particularly memory, as well as increased self-confidence. However, the home telerehabilitation process faces challenges such as technical difficulties and training organization, which in some cases may cause stress due to disruption of the usual daily routine. Despite this, motivation for rehabilitation remains high. Information about patient experiences is an important addition to quantitative results. In the future, large-scale studies will allow for an assessment of the clinical effectiveness of the proposed method, determine its long-term impact, and optimize training protocols [12].

Singh N. et al. developed a prototype of an electromechanical robotic exoskeleton for the rehabilitation of the hand and metacarpophalangeal joint. The device can synchronize wrist extension with finger flexion and vice versa in post-stroke patients. It reduces spasticity through a synergistic approach, supporting patient-initiated therapy by engaging residual muscle activity. A randomized controlled trial showed that patients undergoing robotic therapy with the developed exoskeleton achieved significant hand function improvement compared to those receiving standard treatment. A significant reduction in wrist joint spasticity was observed in the robotic therapy group (RTG) – from 1,75 ± 0,2 to 1,29 ± 0,3 (p = 0,0009), improvement in active range of motion (AROM) – from 15° ± 9,7° to 34,6° ± 14,5° (p = 0,0004), sensorimotor hand control (FMU/L) – from 36 ± 7,7 to 50,2 ± 6,5 (p = 0,0004), and distal hand function (FMW/H) – from 9,7 ± 2,7 to 16,6 ± 4,3 (p = 0,0004). These indicators were lower in the control group. Significant intergroup differences (p = 0,01) indicate the effectiveness of this robotic therapy in restoring fine motor skills. This study is important as it confirms neuroplasticity (the brain's ability to recover under the influence of robotic PT): functional MRI results showed positive changes in increased cortical excitability in the ipsilesional hemisphere in the robotic group. Further studies are needed to examine the long-term effects of PT using the device, testing it on other patient groups, including military personnel [13].

Virtual environments that incorporate key elements of neuroplasticity have significant potential to enhance the effectiveness of physical therapy, especially for patients with prolonged and severe orthopedic impairments [14].

Soleimani et al., in their meta-analysis, investigated the effectiveness of virtual reality systems for upper limb rehabilitation in stroke patients. VR is divided into three levels of immersion: full (completely blocking perception of the real world), semi-immersive (using screens or headsets), and non-immersive VR (allowing the combination of real and virtual environments). The application of VR therapy requires an individualized approach, as different types of VR have specific advantages for motor recovery. Fully immersive VR provides the greatest improvement in motor function, particularly in gross motor skills. The FMA scale scores increased by an average of 5.4 points (95% CI 5,02–5,77), and ARAT by 7,08 points (95% CI 6,67–7,49) compared to conventional therapy. It proved to be the most effective due to its ability to create a realistic environment that activates neuroplastic processes and ensures high patient engagement in the rehabilitation process. Semi-immersive and non-immersive VR (e.g., Microsoft Kinect or Nintendo Wii) are recommended for developing fine motor skills, which involve active hand manipulations. The analysis highlighted the supportive role of VR in restoring motor function, improving functional independence, dexterity, and patient quality of life. It is recommended to use VR in combination with traditional therapy to achieve maximum

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therapeutic effect. However, further research is needed to optimize VR rehabilitation protocols and adapt them to patient needs [15].

Side effects of full immersion, such as cybersickness and balance issues, may hinder rehabilitation sessions, especially in patients with brain injuries, movement disorders, and cognitive impairments, which are common among military personnel [15, 16].

For patients with upper limb immobilization, where performing physical exercises is challenging, VR embodiment in a virtual body is recommended. This allows patients to simultaneously imagine and observe virtual limb movements while performing various rehabilitation tasks, perceiving the immobilized limb as their own. Studies have shown that this method improves the functional capabilities of the affected upper limb and accelerates recovery during conservative treatment of distal radius fractures in the immobilization period. In a randomized controlled trial conducted by Matamala-Gomez et al., based on the criterion of achieving good hand function recovery (FMA $\geq$ 57), 85% of patients in the VR immersion group with virtual body embodiment achieved success, which was statistically significantly higher than the results of the traditional finger mobilization group (25%) and the non-immersive VR group (0%) ($p < 0{,}0001$). At the same time, this method significantly reduces pain levels, fear of movement, and improves psycho-emotional state. Minimizing the negative effects of immobilization and enhancing neuroplasticity is facilitated by the activation of neural connections responsible for movement planning and action observation. The positive impact on the autonomic system occurs through improved blood circulation and muscle tone, creating an engaging motivational environment that reduces stress and accelerates recovery [17].

VR embodiment in a virtual body has also proven effective in the rehabilitation of patients experiencing movement-related pain, which impedes recovery and is associated with kinesiophobia in many orthopedic disorders. This method is recommended for inclusion in physical therapy programs; however, research on its effectiveness in combination with other rehabilitation interventions requires further study [18].

The effectiveness of VR for upper limb rehabilitation beyond neurological disorders remains insufficiently studied. Comprehensive research is needed due to differences in treatment goals for such patients, particularly military personnel [19]. Combalia A et al. described the advantages of VR rehabilitation for orthopedic disorders, including an individualized approach, real-time feedback, a motivating environment, remote monitoring capabilities, and the ability to tailor treatment plans. Future studies should focus on the synergy of VR rehabilitation and artificial intelligence to create a personalized and adaptive VR experience using machine learning, computer vision, and natural language processing to enhance therapy effectiveness [14].

The integration of robotics and VR into clinical rehabilitation requires strategic planning, including assessing strategy effectiveness, developing standards and protocols, and customizing interventions based on individual patient needs, considering symptoms, impairment levels, functional capabilities, and personal preferences [6, 16].

The results of our study have been summarized for comparison (Table 1). They will help physical therapists select the most effective innovative tools and rehabilitation methods for specific upper limb impairments in military personnel during the recovery period.

The obtained results indicate that innovative methods and tools for upper limb disorders in military personnel have varying effectiveness, as confirmed by research. When selecting them for PT, this aspect must be taken into account. Exoskeletons demonstrate clinically significant effectiveness in restoring strength, coordination, and hand functionality in the acute phase, while end-effectors and portable robotic systems show their efficacy in the subacute and chronic phases. VR therapy with different levels of immersion has high effectiveness in restoring both gross and fine motor skills. The effectiveness of prototype electromechanical robotic exoskeletons for hand and metacarpophalangeal joint rehabilitation lies in significant improvements in hand and

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Table 1. Comparative table of innovative means and methods of rehabilitation interventions for upper limb injur

Innovative tool, method, technique	Application			Efficiency
	Impairments	At the period of PT / phase of the disease	Method of application	
Exoskeletons	Severe	Acute phase	No specific recommendations were given	Clinically significant
End effectors	Residual	Chronic phase		
Portable robotic devices	Moderate (restoration of strength, amplitude of movements, coordination and functionality of the hand	Home and outpatientperiod	Additions to standard PT methods	Clinically significant
Prototype electromechanical robotic exoskeleton for hand and carpophalangeal joint rehabilitation	Dysfunction of the wrist and hand	Subacute, chronic phase	Additions to standard PT methods	Significant improvement of functions
MERLIN system	Motor impairment	Home period	Additions to standard PT methods	Qualitative research, patient perception experience
Fully immersive VR	Gross motor skills impairment	All periods	Supplement to traditional therapy, although in some cases can be used as the main method in the last stages to support motor activity	Clinically significant
Semi-immersive, non-immersive VR	Fine motor skills impairment	All periods	Additions to standard PT methods	Clinically significant
Semi-immersive, non-immersive VR	Orthopedic injuries (fractures, surgical interventions)	Period of immobilization	Additions to standard PT methods	Statistically significant changes

wrist functions, but there is currently no data on clinically significant outcomes of their application in PT. Although VR with embodiment in a virtual body is recommended for use in PT, the studies conducted so far demonstrate only statistically significant changes. The MERLIN system positively affects motor functions in home conditions, but its effectiveness is mainly based on patient feedback and requires further research. Overall, combining robotic technologies and VR methods with standard PT significantly enhances rehabilitation effectiveness, particularly for military personnel, but requires an individualized approach for patient.

Robotic technologies and virtual reality systems, by increasing motivation, help overcome post-traumatic stress in military personnel, restore self-confidence, and facilitate adaptation to life after injuries [12, 19].

Conclusions

Injuries to the upper limbs of military personnel require a comprehensive approach to treatment and rehabilitation. The main challenges in the recovery process include the complexity of combined polystructural injuries, which may involve damage to nerves, blood vessels, bones, and soft tissues, as well as a high risk of developing post-traumatic stress disorder and other psychological complications. The use of such innovative technologies in physiotherapy (PT) as robotic and virtual systems demonstrates high effectiveness at various stages of recovery. Successful implementation into practice requires integration into comprehensive rehabilitation programs, taking into account the individual needs of military personnel. In the early stages of PT, the use of exoskeletons is advisable, as they provide support for active movements and stimulate initial functional recovery. During the residual phase, devices with end-effectors, portable robotic devices, and robotic technologies combined with telerehabilitation should be applied. VR technologies can complement the rehabilitation process at all stages. An important aspect is the inclusion of innovative tools and methods in individual PT programs that align with the principles of evidence-based medicine. Further research should focus on assessing the long-term effectiveness of these technologies, personalizing rehabilitation approaches, and adapting them for the recovery of military personnel, as well as a detailed and in-depth study of the latest PT technologies—combining robotics, VR, and artificial intelligence.

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Conflict of interest

The authors declare no conflict of interest.

Consent to publish

Since this study involves the analysis and generalization of published literary sources and did not involve the involvement of patients, consent for publication was not obtained. All authors have read the text of the manuscript and have given their consent for its publication.

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A – Research concept and design, B – Collection and/or assembly of data, C – Data analysis and interpretation, D – Writing the article, E – Critical revision of the article, F – Final approval of article.

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Використання інноваційних засобів та методів реабілітаційного втручання при пошкодженнях верхніх кінцівок у військовослужбовців (огляд літератури)

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Анотація: *у статті окреслено особливості пошкодження верхніх кінцівок у військовослужбовців при вогнепальних та осколкових пораненнях, переломах, невропатіях та травмах м'яких тканин. Увагу приділено інноваційним реабілітаційним підходам, які сприяють відновленню рухливості, координації та функціональності кінцівок. Проаналізовано ефективність запропонованих у науковій літературі протягом 2021-2024 років сучасних розробок і методик робототехніки та віртуальної реальності для реабілітації верхніх кінцівок при різних видах їх пошкодження та періодах відновлення. Такі технологій демонструють високий потенціал у фізичній терапії, забезпечуючи контрольовані та повторювані рухи для активації м'язової пам'яті, стимулюючи сенсомоторні функції, формуючи мотиваційне середовище. Обумовлено причини необхідності проведення додаткових досліджень, які дадуть змогу підтвердити їх клінічну значущість або довгострокову результативність. Узагальнена порівняльна інформація для фізичних терапевтів стане важливим інструментом у виборі найоптимальніших інноваційних засобів та методів і розробки ефективніших індивідуалізованих реабілітаційних програми для військових із пошкодженнями верхніх кінцівок.*

Ключові слова: фізична терапія, доказова медицина, пошкодження верхніх кінцівок, відновлення, військовослужбовці, віртуальна реальність, інноваційні методи, роботизовані системи, інноваційні засоби, якість життя.