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PHYSICAL REHABILITATION IN HANDBALL: MODERN APPROACHES AND PRACTICAL SIGNIFICANCE

Veritov O. I.
Doctor of Pedagogical Sciences,
Associate Professor at the Department of Physical Culture and Sports
Zaporizhzhia National University
Universytetska str., 66, Zaporizhzhia, Ukraine
orcid.org/0000-0002-3793-3010
kop230405@gmail.com

Skrypchenko I. T.
PhD, Associate Professor,
Associate Professor at the Department of Theory and Methods of Physical Culture and Sports
Kherson State Agrarian and Economic University
Stritenska str., 23, Kherson, Ukraine
orcid.org/0000-0001-5895-3099
sit71@ukr.net

Bessarabova O. V.
Candidate of Pedagogical Sciences, Associate Professor,
Associate Professor at the Department of Therapy and Rehabilitation
Zaporizhzhia National University
Universytetska str., 66, Zaporizhzhia, Ukraine
orcid.org/0000-0002-9193-4241
bessarabova217@gmail.com

Key words: *handball, physical rehabilitation, sports injuries, shoulder joint, ankle instability, anterior cruciate ligament (ACL), proprioceptive training, HRV monitoring, biofeedback, VR/AR technologies, sporting longevity.*

Physical rehabilitation in handball is a key area of sports medicine since the high incidence of injuries in this sport is caused by its intensive, contact-based, and speed-strength character. Modern research confirms that the most frequent injuries involve the shoulder joint, ankle complex, and anterior cruciate ligament, requiring targeted and evidence-based recovery programs. The analysis shows that the most effective are personalized and functionally oriented protocols that consider the athlete's individual characteristics, the specificity of game activity, and the clinical profile of the injury. The medical rationale for personalization lies in the variability of tissue regeneration rates, the influence of age, gender, and hormonal factors, as well as the need to monitor neuromuscular imbalances and psychophysiological state. Functional orientation of programs follows the SAID principle of specificity and ensures restoration of kinetic chains, intermuscular coordination, and game-related movement patterns, which are critical for preventing reinjury. Technological support is based on the use of HRV monitoring, GPS and inertial sensors for load control, biofeedback for developing self-regulation, and VR/AR technologies for stimulating neuroplasticity. Comprehensive programs combining proprioceptive training, plyometric drills, strength exercises, breathing techniques, and psycho-emotional support have proven

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effective in reducing the risk of recurrent injuries, accelerating return to play, and supporting athletic longevity. The practical significance of the study lies in substantiating evidence-based models for integrating rehabilitation protocols into the training structure of handball players. Future research prospects include standardizing assessment methods for rehabilitation effectiveness, analyzing causal mechanisms of interaction between cognitive, emotional, and physiological factors, and developing personalized programs for athletes of different age groups through the use of digital technologies.

ФІЗИЧНА РЕАБІЛІТАЦІЯ В ГАНДБОЛІ: СУЧАСНІ ПІДХОДИ ТА ПРАКТИЧНЕ ЗНАЧЕННЯ

Верітов О. І.
доктор педагогічних наук,
доцент кафедри фізичної культури і спорту
Запорізький національний університет
вул. Університетська, 66, Запоріжжя, Україна
orcid.org/0000-0002-3793-3010
kop230405@gmail.com

Скрипченко І. Т.
кандидат наук з фізичного виховання та спорту, доцент,
доцент кафедри теорії та методики фізичної культури та спорту
Херсонський державний аграрно-економічного університет
вул. Стрітенська, 23, Херсон, Україна
orcid.org/0000-0001-5895-3099
sit71@ukr.net

Бессарабова О. В.
кандидат педагогічних наук, доцент,
доцент кафедри терапії та реабілітації
Запорізький національний університет
вул. Університетська, 66, Запоріжжя, Україна
orcid.org/0000-0002-9193-4241
bessarabova217@gmail.com

Ключові слова: *гандбол, фізична реабілітація, спортивні травми, плечовий суглоб, гомілковостопна нестабільність, передня хрестоподібна зв'язка (ACL), пропріоцептивний тренінг, HRV-моніторинг, біологічний зворотний зв'язок, VR/AR-технології, спортивне довголіття.*

Фізична реабілітація у гандболі є ключовим напрямом спортивної медицини, оскільки високий рівень травматизму в цьому виді спорту зумовлений його інтенсивним, контактним та швидкісно-силовим характером. Сучасні дослідження підтверджують, що найчастіше ушкоджуються плечовий суглоб, гомілковостопний комплекс і передня хрестоподібна зв'язка, що вимагає цілеспрямованих, науково обґрунтованих програм відновлення. Мета дослідження – проаналізувати сучасні підходи до фізичної реабілітації гандболістів після травм та обґрунтувати ефективність інтеграції відновлювальних програм у тренувальний процес. Об'єкт дослідження – процес фізичної підготовки та відновлення спортсменів. Предмет дослідження – методи та засоби фізичної реабілітації, спрямовані на відновлення функціональної готовності гандболістів і профілактику повторних травм. Результати аналізу свідчать, що найбільш ефективними є персоналізовані та функціонально орієнтовані протоколи, які враховують індивідуальні особливості спортсмена, специфіку ігрової діяльності та клінічний

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профіль ушкодження. Медичне підґрунтя персоналізації полягає у варіативності темпів регенерації тканин, впливі вікових, гендерних і гормональних факторів, а також у необхідності контролю нейром'язового дисбалансу й психофізіологічного стану. Функціональна спрямованість програм відповідає принципу специфічності SAID і забезпечує відновлення кінетичних ланцюгів, міжм'язової координації та ігрових рухових патернів, критично важливих для запобігання повторним травмам. Технологічна підтримка базується на використанні HRV-моніторингу, GPS та інерційних сенсорів для контролю навантажень, біологічного зворотного зв'язку для розвитку саморегуляції та VR/AR-технологій для стимуляції нейропластичності. Комплексні програми, що поєднують пропріоцептивний тренінг, plyometric drills, силову підготовку, дихальні техніки й психоемоційний супровід, довели свою ефективність у зниженні ризику повторних ушкоджень, пришвидшенні повернення до змагань і підтриманні спортивного довголіття. Практична значущість дослідження полягає в обґрунтуванні доказових моделей інтеграції реабілітаційних протоколів у структуру тренувального процесу гандболістів. Перспективи подальших робіт пов'язані зі стандартизацією методик оцінювання ефективності реабілітації, аналізом каузальних механізмів взаємодії когнітивних, емоційних і фізіологічних факторів та розробкою персоналізованих програм для спортсменів різних вікових груп із використанням цифрових технологій.

Introduction. Handball, as a highly dynamic team sport, is characterized by significant speed-strength loads, a high level of contact, and intense changes in game situations, which together create a high risk of musculoskeletal injuries. Among the most common are injuries of the knee and ankle joints, ligament damage, and shoulder girdle injuries. In modern sport, the performance of a team largely depends on the ability of athletes to quickly restore their functional state and return to full competitive activity.

Physical rehabilitation is considered a comprehensive process aimed at restoring physical performance, reducing the risk of recurrent injuries, and prolonging athletic longevity. Modern programs combine methods of therapeutic physical training, kinesitherapy, sensorimotor and proprioceptive training, the use of physiotherapeutic technologies, and psychological support. The relevance of the topic is determined by the necessity of implementing evidence-based, individualized rehabilitation programs integrated into the training structure of handball players.

Purpose of the study – to analyze modern approaches to the physical rehabilitation of handball players after injuries and to substantiate the effectiveness of integrating recovery programs into the training process.

Object of the study – the process of athletes' physical preparation and recovery.

Subject of the study – methods and means of physical rehabilitation aimed at restoring the functional readiness of handball players and preventing recurrent injuries.

Analysis of contemporary literature sources. Epidemiological data confirm that handball belongs to sports disciplines with a high risk of injuries – predominantly to the lower limbs, knee, and shoulder – which necessitates effective rehabilitation strategies [Hadjisavvas et al., 2022]. A cluster randomized controlled trial among 660 elite handball players revealed that the implementation of the OSTRC Shoulder Injury Prevention Programme significantly reduced the incidence of shoulder injuries. The program included strengthening of the rotator cuff, thoracic mobility, and kinetic chain exercises during warm-up [Andersson, Bahr, Clarsen, & Myklebust, 2017]. A subsequent study demonstrated positive attitudes of coaches and team captains toward this program, although it also identified low compliance due to time constraints and motivational barriers [Andersson, Bahr, Olsen, & Myklebust, 2019].

A well-designed non-randomized trial involving 22 handball players with chronic ankle instability showed that proprioceptive exercises significantly improved postural control and reduced the number of sprains [Antohe & Panaet, 2024]. Systematic reviews highlight the necessity of a comprehensive approach to rehabilitation after anterior cruciate ligament ruptures, including the assessment of limb function symmetry and the use of objective functional tests such as the Limb Symmetry Index and hop tests [Fredriksen et al., 2020; Aasheim et al., 2018]. The application of combined external (GPS, inertial sensors) and internal (HR, RPE) load parameters, along with subjective well-being indicators, has proven effective in reducing the risk of overuse

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injuries in team sports, including handball [Milić et al., 2025].

Research Results. The analysis of current research in the field of physical rehabilitation of handball players confirms that the most effective approaches are comprehensive, multilevel programs that combine the restoration of functional capacity with the prevention of recurrent injuries.

Shoulder injuries account for up to 20–25% of all injuries in handball, particularly among throwing-position players (defenders, backcourt players). It has been demonstrated that the implementation of the OSTRC Shoulder Injury Prevention Programme reduces the prevalence of shoulder injuries by 28% among elite handball athletes [Andersson et al., 2017]. The effectiveness of this program is explained by the activation of the kinetic chain: exercises targeting the rotator cuff, scapular stabilizers, and thoracic spine reduce overload on the shoulder joint by redistributing forces along the entire upper limb. This is consistent with biomechanical models, which show that dysfunction in proximal segments (core, thoracic spine) significantly increases the risk of microtrauma in the shoulder.

Ankle instability is the most common consequence of acute injuries in handball. Clinical studies (Antohe & Panaet, 2024) demonstrated that a 6-week proprioceptive training program improves postural control and reduces the risk of recurrent sprains. Physiologically, this is explained by the activation of the sensorimotor system – balance training stimulates ligament and muscle receptors, enhances the responsiveness of the neuromuscular apparatus, and is critically important during jumping and rapid changes of direction.

Anterior cruciate ligament (ACL) rupture is one of the most severe injuries in handball, often leading to long-term loss of playing activity. Meta-analyses (Aasheim et al., 2018; Fredriksen et al., 2020) emphasize that criterion-oriented rehabilitation, based on objective functional tests (Limb Symmetry Index, hop tests, isokinetic testing), reduces the risk of reinjury by 30–40%. Biomechanical studies indicate that after ACL reconstruction, deficits in neuromuscular control and lower-limb asymmetries are the main risk factors for recurrent rupture, which justifies the integration of plyometric drills and load monitoring.

The use of GPS and inertial sensors makes it possible to quantify external load (number of jumps, accelerations, impact forces), while HRV monitoring provides an assessment of internal adaptation. Research (Milić et al., 2025) has shown that systematic use of HRV biofeedback reduces fatigue levels and accelerates recovery, directly correlating with more stable performance across the competitive cycle.

Generalized data demonstrate that rehabilitation programs combining therapeutic exercise, physiotherapy, psychological support, and load monitoring ensure not only recovery after injuries but also provide a preventive effect, reducing the likelihood of reinjury. This approach is based on the modern concepts of the *injury prevention continuum*, where rehabilitation is not regarded as the final stage, but as an integrated part of the training process.

Thus, the findings confirm that physical rehabilitation in handball must be personalized, functionally oriented, and technologically supported (Table 1). This approach not only accelerates return to sport but also fosters athletes' adaptability, stress resilience, and responsibility for their own health.

Functional orientation corresponds to the principle of specificity (SAID) and reflects the need to restore precisely those motor and physiological qualities that are critical for handball: speed-strength characteristics, jumping ability, and throwing coordination. The use

Table 1

Medical and physiological principles of personalized rehabilitation in handball

Principle	Medical and physiological rationale	Tools / Methods	Expected effects
Personalization	Tissue regeneration rates depend on age, sex, hormonal profile, previous injuries. In female athletes after ACL reconstruction, the risk of reinjury is 20–25% higher.	Individual therapeutic exercise protocols; gender-specific programs; consideration of comorbidities	Reduced risk of reinjury; optimized recovery duration
Functional orientation	SAID principle: the body adapts to specific demands (jumps, throws, changes of direction).	Plyometric drills, proprioceptive training, sport-specific movement patterns	Restoration of neuromuscular control; improved kinetic chain function; safe return to play
Technological support	HRV reflects autonomic balance; GPS/inertial sensors monitor external load; VR/AR stimulate neuroplasticity.	HRV monitoring, biofeedback, GPS trackers, VR rehabilitation	Objective readiness control; prevention of overload; accelerated motor recovery
Energy progression	Recovery requires gradual engagement of energy systems: aerobic (early phase), anaerobic-alactic and glycolytic (game-specific loads).	Low-intensity aerobic exercise → interval protocols → sport-specific drills	Progressive restoration of energy systems; reduced risk of recurrence; improved functional readiness

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of plyometric drills, proprioceptive training, and exercises resembling game actions supports the restoration of the kinetic chain and creates a "bridge" between clinical rehabilitation and full competitive practice.

Technological support makes rehabilitation maximally evidence-based and controlled. Objective data from HRV, GPS, and inertial sensors provide physicians and coaches with quantitative indicators of the athlete's state, while VR/AR technologies enhance neuroplasticity and motivation during the recovery process, opening a new level of integration of sports medicine with digital technologies (Figure 1).

Energy progression highlights the necessity of a gradual transition from aerobic to anaerobic energy supply. Such an approach ensures that the body restores both the basic mechanisms of tissue regeneration (aerobic system) and the explosive movement patterns specific to handball (anaerobic alactic and glycolytic systems).

Overall, the model presented in the table demonstrates that effective rehabilitation in handball cannot be limited to the restoration of an isolated function or segment. It must be comprehensive, combining medical, biomechanical, and technological approaches while simultaneously focusing on the specificity of game activity. Such integration ensures not only an accelerated return to play but also a reduced risk of recurrence and enhanced sporting longevity.

Medical research clearly shows that the course of recovery after injury largely depends on the individual characteristics of the athlete: age, sex, level of physical fitness, comorbidities, type of injury, and psycho-emotional state. For example, after ACL reconstruction, women face a 20–25% higher risk of reinjury compared to men of the same age, which justifies the necessity of gender-specific protocols. A personalized approach allows for optimal load dosing, consideration of individual deficits (strength, balance, neuromuscular control), and the stepwise design of a rehabilitation plan – from clinical recovery to functional readiness.

Modern medical and biomechanical approaches emphasize the importance of shifting from passive treatment methods (physiotherapy, immobilization) to active, functionally oriented rehabilitation. This implies the use of exercises closely resembling handball-specific demands: jumping actions, rapid changes of direction, and throwing movements. Functional orientation enables the restoration of kinetic chains and intermuscular coordination, which is critical for reducing the risk of reinjury. Scientific evidence confirms that isolated training of individual muscle groups does not guarantee a safe return to play, whereas comprehensive functional programs reduce the likelihood of recurrent injuries by 30–40% (Figure 2).

Medical practice in the 21st century is actively integrating digital and biotechnological tools into the rehabilitation process. Heart rate variability (HRV) monitoring enables the assessment of athletes' recovery capacity and the identification of optimal moments for increasing training loads. The use of GPS and inertial sensors provides precise control of external load (number of jumps, accelerations, impact forces), while biofeedback promotes self-regulation and prevents overtraining. In clinical centers and sports clubs, virtual and augmented reality (VR/AR) are increasingly being applied to restore motor functions, demonstrating effectiveness in accelerating

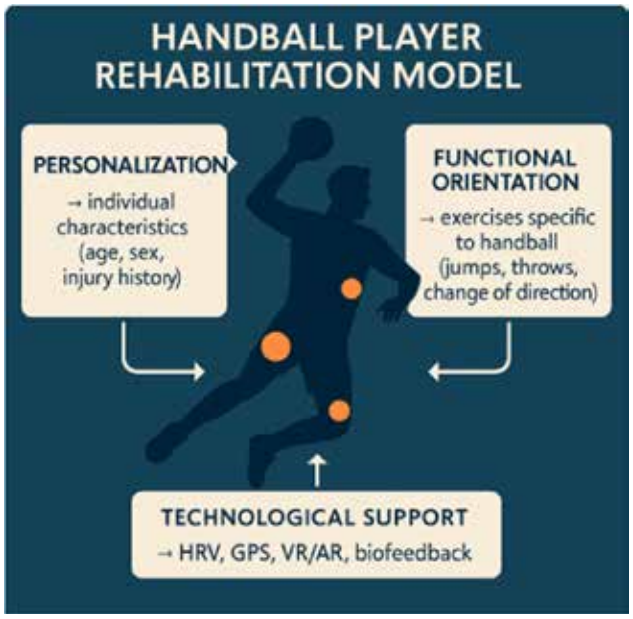

Fig. 1. Handball player rehabilitation model

PRINCIPLES OF HANDBALL REHABILITATION

Principle	Tools	Expected outcomes
• Personalization	Individual characteristics (age, sex, injury history	Optimization of recovery and avoidance premaun
• Functionalnal orientation	Plyometric drills, proprioceptive exercises	Restoration of handball-specific abilities
• Technological support	HRV GRS VR/AR Biofiedbeck	Monitoring and stimulation of recovery processes
• Energetic phasing	From aerobic to anaerobic –alactic	Physiological readiness for play

Fig. 2. Principles of handball rehabilitation

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neuroplastic processes and enhancing athletes' motivation for recovery.

Thus, personalization ensures the alignment of rehabilitation with the athlete's medical and functional needs; functional orientation restores sport-specific skills; and technological support makes the process more precise, controlled, and evidence-based. The combination of these approaches forms a modern medical-rehabilitation standard that not only accelerates handball players' return to play but also significantly reduces the risk of reinjury and enhances the quality of sporting longevity.

Each athlete recovers within different physiological timeframes, which are determined by individual differences in tissue regeneration rates, hormonal profile, immune system condition, and aerobic-anaerobic potential. For example, microtrauma of muscles typically requires 48–72 hours for recovery, whereas ligament and cartilage damage may take weeks to months due to lower tissue vascularization. Therefore, personalization allows practitioners to avoid both premature return to play and excessive immobilization, which may lead to muscle atrophy and reduced neuromuscular control.

The physiology of movement confirms that recovery should be based on the principle of *specific adaptation to imposed demands (SAID)*: the body adapts precisely to the loads it is exposed to. For handball, these include explosive jumps, rapid changes of direction, and high-intensity throws. Exercises that closely resemble game-specific actions contribute to: the activation of fast motor units (type IIb), the restoration of intermuscular coordination, and the reduction of imbalances in the kinetic chain.

Thus, functional orientation not only restores strength or mobility but also re-establishes the energy and neuromuscular mechanisms specific to handball.

Technological support and control of physiological markers are central to this process: HRV monitoring reflects the balance of the sympathetic and parasympathetic nervous systems, allowing an objective assessment of fatigue and readiness for training; GPS and inertial sensors provide quantitative indicators of jumping activity, impact loads, and accelerations, which correlate with tissue microtrauma; biofeedback (e.g., respiratory or muscular) facilitates conscious activation or relaxation of specific groups, reducing the risk of reinjury; VR/AR protocols stimulate neuroplasticity, as visuomotor imagery activates the same brain regions as real movement execution, thereby accelerating the restoration of motor functions after injury.

Energy mechanisms of rehabilitation include the following: in the early phases, the aerobic component dominates, providing tissue nourishment and oxygenation for recovery. In functionally specific exercises, the anaerobic alactic and glycolytic systems are activated, which are essential for jumping and explosive actions. Such a gradual progression guarantees the physiological readiness of the athlete for the full spectrum of game activities.

Personalization makes it possible to take into account regeneration rates and individual biological characteristics; functional orientation restores the energy and neuromuscular mechanisms specific to handball; and technological support ensures objective monitoring and stimulates neuroplastic processes. Together, these factors form a modern rehabilitation model that is medically safe, physiologically sound, and sport-effective.

Conclusions. Physical rehabilitation in handball is a key component for maintaining athletes' working capacity and sporting longevity. The high injury rate, caused by the dynamic and contact nature of the game, requires the integration of systematic recovery programs into the training process.

The personalization of rehabilitation protocols is justified by medical and physiological differences between athletes (age, sex, injury history, level of physical preparedness). An individually oriented approach allows optimization of recovery timelines and minimization of the risk of reinjury.

The functional orientation of programs ensures the restoration of motor and energy mechanisms specific to handball. The inclusion of plyometric drills, proprioceptive training, and exercises closely resembling game activity helps to restore kinetic chains, improve intermuscular coordination, and enhance the safety of return to competition.

Technological support (HRV monitoring, GPS/inertial sensors, biofeedback, VR/AR technologies) makes the rehabilitation process more precise and controlled. This allows the adaptation of loads to the athlete's actual condition, stimulation of neuroplasticity, and reduction of overtraining risks.

The systemic and multilevel structure of rehabilitation programs is consistent with the concepts of the *injury prevention continuum* and creates a dual effect – both restorative and preventive. Rehabilitation is not viewed as the final stage after injury, but as an integrated part of preparation that builds resilience against recurrent injuries.

Promising directions for future research include: the standardization of rehabilitation and injury prevention protocols in handball; the investigation of psychophysiological factors in recovery; and the application of digital technologies (mobile applications, VR/AR, sensor systems) for individualized monitoring of the rehabilitation process.

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