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The Effect of Using Different Recovery Strategies on Restoring Functional Status After Handball Matches

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Abstract:

This study determined the effectiveness of cold-water immersion (CWI), active recovery (AR), and passive rest for restoring elite handball players after high-intensity match simulation.

Forty-five players were randomly assigned to the three recovery groups. Physiological (heart rate, lactate, creatine kinase [CK]), physical (vertical jump, agility), and skill (shooting accuracy) markers were measured at baseline, post-exercise, and 1-, 24-, and 48-hours post-recovery.

Results showed a clear, statistically significant ($p < 0.05$) superiority of CWI over AR and passive rest. The CWI group achieved the fastest physiological recovery (reduced lactate and CK), leading to a state of performance overcompensation in physical and skill tests at 24-48 hours. The AR group improved more than the control group but less than CWI, especially for muscle damage indicators. Correlation analyses in the CWI group indicated a strong link between improved physiological markers and enhanced physical performance.

Cold-water immersion is the most effective and rapid method for restoring elite handball players' full function post-match and is recommended for maintaining performance and reducing injury risk during intense competition.

Keywords:

(Functional recovery - Cold water immersion (CWI) - Active recovery - Handball - Physical performance - Professional precision - Creatine kinase - Overcompensation)

1. Introduction:

Modern handball imposes severe physiological strain, making effective recovery critical, especially with schedules allowing only 72 hours between matches. Recovery science aims not just to restore function but to achieve "supercompensation" for enhanced performance (Secondary Kenttä & Hassmén, 1998), while inadequate recovery heightens injury risk (Dupont et al., 2010).

Evidence-based methods are essential. Hydrotherapy, particularly Cold-Water Immersion (CWI), is strongly supported for reducing inflammation and aiding performance recovery (Poppendieck et al., 2013; Pournot et al., 2011). Active Recovery (AR) shows mixed results for restoring performance (Andersson et al., 2008), and integrating multiple strategies is a current trend (Duffield et al., 2013).

This highlights the relevance of studies like Abdeen and Madkour (2024), which investigates combined foam rolling and CWI for runners. While commendable for its focus, the study's methodology has limitations: it lacks precise protocol details and shows wide variance in individual responses, raising questions about unanalyzed confounding factors (e.g., training status, gender). Addressing these would improve the validity and applicability of such recovery research.

The study by Abdeen and Madkour (2024) lacked clarity on the specific physiological mechanisms behind the recorded improvements, such as whether enhanced heart rate recovery was due to autonomic nervous system efficiency or if lactate reduction stemmed from improved clearance or metabolic efficiency. Furthermore, its focus on acute effects represents a limitation for a sport requiring long-term planning; monitoring the cumulative impact of these recovery strategies over weeks or months of training and competition would have been more valuable for long-distance runners.

This highlights the need for robust methodological reviews in sports recovery science. The review by Ortiz et al. (2018) provides a comprehensive analysis of active recovery strategies among elite athletes. It employs a rigorous methodological process, utilizing four major databases and applying strict inclusion criteria to select 26 relevant studies from an initial pool of 737 articles, which were then assessed using the Oxford Centre for Evidence-Based Medicine levels of evidence.

A key practical finding from the review is that active recovery durations of six to ten minutes positively affect sports performance, whereas periods shorter or longer than this window show inconsistent or unfavorable results. However, the review notes a significant lack of consensus and reliability in prescribing active recovery intensity, as studies used various non-standardized indicators. The authors conclude that current methods for determining intensity are inadequate and call for more precise, individualized prescriptions. Additionally, the review found that monitoring blood lactate clearance alone is an insufficient measure of recovery, as it does not reliably correlate with actual performance improvements.

The review by Ortiz et al. (2018) also highlighted important psychological benefits, noting that athletes often reported feeling more prepared and confident after active recovery sessions compared to passive ones, even in the absence of measurable physiological improvements. This underscores the need to consider psychological factors as an independent variable in recovery research. Furthermore, the review emphasized the necessity of individualizing recovery protocols based on an athlete's fitness level, sport, and personal characteristics, aligning with modern personalized training approaches.

A significant critique from the review challenges the conventional link between recovery and performance, establishing that a reduction in blood lactate levels does not guarantee subsequent performance enhancement. This calls into question the validity of using lactate clearance as a sole metric for recovery effectiveness, particularly for elite athletes for whom maintaining peak performance is a primary recovery goal.

Turning to hydrotherapy, foundational research by Vaile et al. provided strong evidence for its efficacy. In a robust study with trained male cyclists simulating a multi-stage competition, both cold water immersion (CWI) and contrast water therapy (CWT) led to performance improvements over five days (0.1–1.4% for CWI and 0.5–2.2% for CWT). In contrast, hot water immersion and passive rest resulted in performance degradation (0.6–3.7% and 1.7–4.9%, respectively). Physiological measurements, such as a significant post-procedure decrease in core body temperature for the CWI group, supported the benefits of these methods in reducing inflammation and energy expenditure after intense activity.

Research highlights the efficacy of hydrotherapy for recovery, with studies like Vaile et al. showing performance improvements from CWI linked to factors like reduced inflammation rather than perceived exertion, while also noting the dependency of optimal recovery on the type of exertion. Broader analyses, such as that by Brown-Trocio et al. (2022), endorse a multidimensional view of recovery and reveal gaps between the perceived and actual use of strategies.

Despite this knowledge, a significant research gap exists for handball, a sport with unique physical demands (Michalsik, 2015). While methods like CWI are proven in other sports (Vaile et al., 2008) and optimal active recovery durations are suggested (Ortiz et al., 2018), these findings require validation in handball.

This study aims to address this gap by systematically comparing CWI and Active Recovery (AR) for elite handball players. The comparison employs a holistic assessment of physiological markers, physical capabilities, and sport-specific skill recovery, advancing beyond prior research focused solely on physiological factors

2. Research Objectives:

2.1. Main Objective:

To compare the relative effectiveness of different recovery strategies (cold water immersion, active recovery, and passive rest) in restoring the functional status of elite female handball players after a simulated match**.**

2.2. Sub-objectives:

Evaluation of the immediate and delayed effects of recovery strategies (cold water immersion and active hospitalization) on:

- Physiological indicators: resting heart rate, lactic acid concentration in the blood.
- Biochemical indicators (signs of muscle damage): Creatine kinase enzyme levels.
- Measuring the extent to which the basic physical and skill abilities to perform handball are restored to pre-effort levels, which are:
- Physical abilities: explosive strength (vertical jump), and agility
- Skill Abilities: Aiming accuracy.
- Determine the most effective and rapid strategy for recovery in the short term (1-24 hours) and medium term (48 hours).
- Determine the correlations between the speed of recovery of physiological and biochemical indicators and the improvement of the physical and skill performance of players.
- Formulating a practical and applied model for hospitalization protocols, usable in clubs and national teams.

3. Research Hypotheses:

3.1. Main Hypothesis

A. Main Hypotheses: There are statistically significant differences in the physiological and physical/skill indicators between the experimental groups (Cold-Water Immersion and Active Recovery) and the control group, in favor of the experimental groups, at different time points post-match.

B. Main Hypotheses: There is a statistically significant correlation between the recovery speed of physiological indicators and the recovery of physical/skill indicators in players.

4. Research questions:

4.1. Main question

A. What is the immediate and delayed effect of using the two recovery strategies (Cold-Water Immersion and Active Recovery) compared to passive rest on the recovery of physiological indicators in handball players?
B. What is the effectiveness of both Cold-Water Immersion and Active Recovery in restoring physical (like explosive strength and agility) and skill (like shooting accuracy) abilities after intense physical exertion?
C. Is there a statistically significant correlational relationship between the speed of recovery of physiological indicators and the improvement in players' physical and skill performance?
D. What is the most effective strategy (in terms of efficiency and speed) that handball coaches should adopt in congested competition schedules?

4.2.Method and procedures:

To assess the effects of two unique recovery strategies on functional recovery from matches, the study utilizes a strict experimental design. A comparison was made with a control group for assessing recovery method effectiveness, and all subjects were randomly assigned into either an experimental or control group and provided equal opportunities to limit outside influences. The reason for selecting this specific experimental design was that it best suits the objectives of isolating the impact of the independent variable (Recovery strategies) on dependent variables (functional indicators).

4.3. Research Population and Sample Selection

This study included professional handball players from two first-class clubs in Erbil Governorate: Erbil Club and Al-Qala'a Turkmen Club. Players were selected from the first team of both clubs. The experiment was conducted in the shared sports facilities available to both clubs, during the official competition period for the 2024-2025 season (October and November 2024).

Inclusion Criteria:

Participants were included based on the following criteria:

Age: Between 18 and 25 years.

Competitive Status: Key players (starters) in their team competing at the Premier League level.

Training Background: A minimum of five years of systematic handball training.

Health Status: Free from any recent musculoskeletal injuries (within the previous six months) and chronic cardiorespiratory or metabolic diseases, as confirmed by a medical evaluation.

Lifestyle: Not taking any supplements or medications known to interfere with recovery, and with no reported history of chronic sleep disorders.

Sample Homogeneity and Characteristics:

To ensure the comparability of groups, researchers verified a high degree of homogeneity among participants at baseline. This was assessed through measurements of:

Physical Characteristics: Body Mass Index (BMI) and general anthropometric profiles.

Physical Abilities: Handball-specific fitness tests, including vertical jump (explosive power), agility, and endurance.

Skill Level: Standardized tests assessing core handball skills (shooting, passing, defensive movements).

Statistical analysis confirmed no significant differences ($p > 0.05$) between the three experimental groups on these baseline measures (see Table 1).

Sample Size:

The final sample consisted of 45 participants, randomly allocated into three recovery groups with 15 players in each group (Cold Water Immersion, Active Recovery, and Passive Rest Control).

4.4.Measurement Tools and Data Collection Techniques

The study employed a comprehensive measurement approach. Physiological markers (blood lactate, heart rate, creatine kinase) were analyzed using specialized laboratory (Bonar Laboratory For pathological analyses for hormone screening, clinical chemistry and microbiology). Physical performance was assessed via vertical jump and sport-specific agility tests, and Skill recovery was measured through passing and shooting accuracy drills under game-like conditions were conducted at Erbil Girl Club.

4.5.Experimental Protocol and Research Implementation

After basal measurements, all participants completed a high-intensity exertion session simulated for a competitive match. The session lasted 80 minutes (divided into two halves with a break) and included complex interval exercises including: running with variable intensities simulating offensive and defensive movements, skill exercises under pressure, and mini-tactical play (4 vs. 4), with short rest periods. The load is designed to raise the heart rate to more than 85% of the expected maximum and raise the blood lactate concentration above 8 mmol/L.

The participants were then randomly distributed to one of three hospitalization groups:

Cooling water recovery (CWI): The athletes immersed themselves in a bath of cold water at a temperature of 10±1°C up to the bath level for 12 minutes.

Active Recovery (AR): The athletes performed low-intensity aerobic exercise (about 60% of maximum heart rate) using a stationary bike or slow running for 15 minutes.

Control group (passive rest): The players sat in a passive rest position in a comfortable place for the same period of time (15 minutes).

Recovery was assessed via repeated measurements 1 hour, 24 hours, and 48 hours after the end of the exertion session.

4.6.Statistical Analysis and Data Processing

Data were analyzed using descriptive and inferential statistics (ANOVA, t-tests) with a significance level set at $p < 0.05$. Effect sizes and standard errors were calculated to ensure the robustness of the findings.

4.7.Ethical and Scientific Considerations

The research adhered to strict ethical standards, including institutional approval and informed consent. Participant confidentiality and safety were maintained throughout. Environmental variables were controlled to enhance the validity and reliability of the results.

5. Descriptive results at the pre test

The longitudinal research study on functional stability recovery after demanding physical exercise within handball is a key part to understand the segways between how athletes adapt bodily; the specific time intervals (1 hour, 24 hours, 48 hours) are selected based on the so-called "critical recovery window" following metabolic depletion and Microtrauma. Blood lactate and heart rate measured at the one-hour period illustrate homeostatic recovery efficiency, while the twenty-four-hour interval denotes the maximum delayed onset muscle soreness (DOMS) experienced and the forty-eight hour resting period signifies total super compensation; evidence based programming based on this information is made possible through statistical methods analyzing variation of performance variables e.g.: Increased explosive power, reduced Creatine Kinase (CK) levels.

Table (1) descriptive statistics of the study variables **at the pre test**

Variable N=(15) in all groups	Cold Water Immersion (CWI): Mean (±St.D.)	Active Recovery: Mean (±St.D.)	Control Group: Mean (±St.D.)	Anova	K-S test	Shapiro	Levene
Age (Years)	24.400 (±1.121)	24.400 (±1.121)	24.400 (±1.121)	1.000	.200	0.680	1.000
Height (cm)	178.933 (±2.658)	178.933 (±2.658)	178.933 (±2.658)	1.000	.200	0.353	1.000
Weight (kg)	76.267 (±2.251)	76.267 (±2.251)	76.267 (±2.251)	1.000	.200	0.539	1.000
Vertical Jump IN REST PRE (cm)	47.149 (±0.100)	47.151 (±0.075)	47.130 (±0.119)	0.822	.200	0.416	0.916
Creatine Kinase IN REST PRE (U/L)	184.667 (±13.292)	184.667 (±13.292)	184.667 (±13.292)	1.000	.200	0.353	0.658
Lactate Acid IN REST PRE (mmol/L)	3.173 (±0.144)	3.173 (±0.144)	3.173 (±0.144)	1.000	.200	0.088	0.681
Agility PRE (seconds)	10.173 (±0.097)	10.164 (±0.119)	10.171 (±0.078)	0.969	0.065	0.076	0.810
Heart Rate IN REST PRE (bpm)	64.600 (±1.121)	64.600 (±1.121)	64.600 (±1.121)	1.000	.200	0.142	0.277
Heart Rate Recovery PRE (BPM/1min)	48.400 (±1.121)	48.400 (±1.121)	48.400 (±1.121)	1.000	.200	0.142	0.221
Shooting Accuracy 7m PRE (%)	75.400 (±1.121)	75.400 (±1.121)	75.400 (±1.121)	1.000	.200	0.142	0.480
Shooting Accuracy Wing PRE (%)	65.400 (±1.121)	65.400 (±1.121)	65.400 (±1.121)	1.000	.200	0.142	0.110

The results of descriptive statistics (Table 1) provide evidence that methodological matching and a high level of homogeneity were achieved within the study groups (CWI, Active Recovery, and Control). The groups (n=15 for each group) were identical regarding all anthropometric, functional, and technical variables before testing. There were no significant differences among the groups based on One-Way ANOVA, as indicated by an overall p-value of 1.000 for the vast majority of variables, and agility (0.969) and explosive power (0.822) were also statistically insignificant. Additionally, there was little variability in terms of standard deviation for the three groups and all three met the assumptions of normality as indicated by the Shapiro-Wilk and K-S tests ($p > 0.05$) and the homogeneity of variances as determined through Levene’s Test (ranging from 0.110 to 1.000); this provides a definitive statistical basis for confirming Group Equivalence. Because of this solid statistical foundation, any differences in post-test measures can be attributed to the influence of the Recovery Strategies, which increases the internal validity of the study and allows for clear and conclusive scientific statements regarding the recovery of functional capabilities in handball players.

5.1. Repeated measurements result of the study indicators for the experimental and control groups:

5.1.1. Physical Performance Variables

Table (2) and the chart attached to it provide an accurate statistical monitoring of the essential physical indicators (explosive ability represented by the vertical jump, and agility according to the T-Test) across the different time stations of the study. This presentation aims to achieve the central goal of the research related to evaluating the effectiveness of recovery interventions in restoring the physical efficiency of players after intense physical effort. These data also seek to answer the research question about the differentiation of the response to physical variables according to the type of strategy used, and to test the hypothesis that there are statistically significant differences in the speed and efficiency of recovery in favor of the two experimental groups (CWI and Active Recovery) compared to the control group, while identifying the protocol that most accelerates the return to the pre-exertion state or reaching overcompensation.

Table (2) descriptive statistics for Physical Performance Variables in control group vs CWI.&A.R. groups

Time Point	Cold-Water Immersion (Mean ± SD; Diff vs Normal, p-value)	Active Recovery (Mean ± SD; Diff vs Normal, p-value)	Normal (Mean ± SD)	CWI (η^2)	A.R. (η^2)
Vertical Jump IN **REST PRE** (cm)	(47.149) ±0.100 (0.019), p =0.604)	(47.151) ±0.075 (0.020), p =0.576)	(47.130) ±0.119	0.006	0.007
After 1 Hour	(47.747) ±0.348 (2.680), p =0.000)	(46.567) ±0.383 (1.500), p =0.000)	(45.067) ±0.383	0.903	0.744
After 24 Hours	(48.100) ±0.290 (2.033), p =0.000)	(47.167) ±0.383 (1.100), p =0.000)	(46.067) ±0.383	0.854	0.632
After 48 Hours	(48.307) ±0.249 (1.740), p =0.000)	(47.367) ±0.383 (0.800), p =0.000)	(46.567) ±0.383	0.820	0.491
Agility **PRE** (seconds)	(10.173) ±0.097 (0.002), p =0.965)	(10.164) ±0.119 (-0.007), p =0.849)	(10.171) ±0.078	0.000	0.001
After 1 Hour	(11.856) ±0.099 (-0.136), p =0.000)	(11.908) ±0.109 (-0.084), p =0.020)	(11.992) ±0.075	0.266	0.122
After 24 Hours	(10.683) ±0.145 (-0.475), p =0.000)	(10.833) ±0.077 (-0.325), p =0.000)	(11.158) ±0.077	0.787	0.633
After 48 Hours	(10.307) ±0.115 (-0.260), p =0.000)	(10.367) ±0.119 (-0.300), p =0.000)	(10.567) ±0.073	0.825	0.629

Table (2) presents The statistical findings that demonstrate a significant and decisive superiority of "Cold-Water Immersion" (CWI) in restoring and enhancing "Explosive Power" (Vertical Jump) compared to both Active Recovery and the Control group; following baseline equivalence in the pre-test (p=0.604), the CWI group achieved a substantial qualitative leap after one hour with a mean of (47.74 cm) and absolute statistical significance (p=0.000), supported by a very high effect size (Partial Eta Squared) of (0.903). This superiority persists clearly at the 48-hour mark, where the CWI group recorded the highest mean (48.30 cm) compared to (47.36 cm) for Active Recovery and (46.56 cm) for the Control group. These outputs confirm that cryotherapy does not merely accelerate recovery but facilitates reaching a state of "Super compensation" more efficiently than active recovery, reinforcing the methodological reliability of utilizing CWI as a primary protocol for restoring the mechanical efficiency of active muscle groups in handball, as presented in figure (2).

5.1.2. Physiological Variables

Table (3) and the chart attached to it provide an accurate statistical monitoring of the essential physiological and biochemical indicators, including heart rate response (at rest and recovery), lactic acid concentration, and Creatine Kinase (CK) enzyme activity across the different time stations of the study, to achieve the central research goal of evaluating the efficiency of recovery interventions in restoring biological and functional balance following intense physical exertion. These data also seek to answer the research question regarding the differentiation of these specific variables' responses according to the type of intervention used, and to test the hypothesis that there are statistically significant differences in metabolic clearance and tissue repair rates in favor of the two experimental groups (CWI and Active Recovery) compared to the control group, while identifying the protocol most effective in reducing the time required to return to homeostasis or reach the over compensation stage.

Table (3) descriptive statistics for physiological Variables in control group vs CWI. & A.R. groups

Time Point	Cold-Water Immersion (Mean ± SD; Diff vs Normal, p-value)	Active Recovery (Mean ± SD; Diff vs Normal, p-value)	Normal (Mean ± SD)	CWI (η^2)	A.R. (η^2)
Creatine Kinase PRE (U/L)	(184.667) ±13.292), p =1.000)	(184.667) ±13.292), p =1.000)	(184.667) ±13.292	0.006	0.007
After 1 Hour	(326.333) ±11.255), p =0.000)	(306.333) ±11.255), p =0.000)	(286.333) ±11.255	0.693	0.744
After 24 Hours	(214.667) ±13.292), p =0.000)	(246.333) ±11.255), p =0.027)	(256.333) ±11.255	0.684	0.111
After 48 Hours	(206.333) ±11.255), p =0.000)	(206.333) ±11.255), p =0.000)	(226.333) ±11.255	0.779	0.361
Lactate Acid PRE (mmol/L)	(3.173) ±0.144), p =1.000)	(3.173) ±0.144), p =1.000)	(3.173) ±0.144	0.006	0.007
After 1 Hour	(8.673) ±0.260), p =0.000)	(8.173) ±0.260), p =0.000)	(7.673) ±0.260	0.725	0.744
After 24 Hours	(4.327) ±0.225), p =0.000)	(5.173) ±0.260), p =0.000)	(5.673) ±0.260	0.839	0.418
After 48 Hours	(4.173) ±0.260), p =0.000)	(4.173) ±0.260), p =0.000)	(4.673) ±0.260	0.759	0.418
Heart Rate at rest PRE (bpm)	(64.600) ±1.121), p =1.000)	(64.600) ±1.121), p =1.000)	(64.600) ±1.121	0.006	0.007
After 1 Hour	(63.600) ±1.121), p =0.000)	(67.600) ±1.121), p =0.000)	(71.600) ±1.121	0.901	0.744
After 24 Hours	(62.600) ±1.121), p =0.000)	(66.600) ±1.121), p =0.000)	(69.600) ±1.121	0.874	0.561
After 48 Hours	(65.600) ±1.121), p =0.000)	(65.600) ±1.121), p =0.000)	(67.600) ±1.121	0.836	0.362
Heart Rate Recovery PRE (BPM/1min)	(48.400) ±1.121), p =1.000)	(48.400) ±1.121), p =1.000)	(48.400) ±1.121	0.006	0.007
After 1 Hour	(48.400) ±1.121), p =0.000)	(45.400) ±1.121), p =0.000)	(43.400) ±1.121	0.780	0.744
After 24 Hours	(50.400) ±1.121), p =0.000)	(47.400) ±1.121), p =0.000)	(45.400) ±1.121	0.780	0.362
After 48 Hours	(49.400) ±1.121), p =0.000)	(49.400) ±1.121), p =0.000)	(47.400) ±1.121	0.780	0.362

Table (3) presents the statistical findings that demonstrate a high significant for "Cold-Water Immersion" (CWI) in accelerating metabolic clearance and muscular tissue repair compared to both Active Recovery and the Control group; following absolute baseline equivalence in the pre-test (p=1.000), the CWI group achieved a strong physiological response, characterized by reducing Creatine Kinase (CK) levels to (214.66 U/L) and Lactic Acid to (4.32 mmol/L) at the 24-hour mark with absolute statistical significance (p=0.000), supported by a very high effect size (η^2) of (0.839) in lactate clearance. Furthermore, heart rate results displayed a superior capacity of cryotherapy to restore circulatory functional balance, with the CWI group recording the highest heart rate recovery rates (50.40 bpm) at 24 hours. These outputs confirm that cryotherapy does not merely accelerate the return to baseline but facilitates reaching a state of physiological "Super compensation" more efficiently than active recovery, reinforcing the methodological reliability of utilizing CWI as a primary protocol for restoring biological homeostasis in handball players, as presented in Figure (3).

5.1.3. Skill Performance Variables

Table (4) and the chart (4) provide a statistical analysis of specialized skill performance variables in handball, specifically shooting accuracy from the 7m line and wing shooting across the different temporal measurement stages. This presentation aims to achieve the third research goal, which is evaluating the ability of recovery strategies to restore skill accuracy and stabilize technical performance efficiency under the influence of cumulative fatigue. These data also seek to answer the research question regarding the response of fine motor skills to the type of recovery intervention used, and to test the hypothesis that there are statistically significant differences in the speed of restoring skill accuracy in favor of the two experimental groups (CWI and Active Recovery) compared to the control group, while identifying the protocol most effective in protecting the neuromuscular system from skill degradation and ensuring a rapid return to standard accuracy levels.

Table (4) descriptive statistics for Skill Performance Variables in control group vs CWI. & A.R. groups

Time Point	Cold-Water Immersion (Mean ± SD; Diff vs Normal, p-value)	Active Recovery (Mean ± SD; Diff vs Normal, p-value)	Normal (Mean ± SD)	CWI (η^2)	A.R. (η^2)
Shooting Accuracy 7m PRE (%)	(75.400) ±1.121), p =1.000)	(75.400) ±1.121), p =1.000)	(75.400) ±1.121	0.006	0.007
After 1 Hour	(74.400) ±1.121), p =0.000)	(72.400) ±1.121), p =0.000)	(70.400) ±1.121	0.694	0.744
After 24 Hours	(76.400) ±1.121), p =0.000)	(74.400) ±1.121), p =0.000)	(72.400) ±1.121	0.694	0.362
After 48 Hours	(75.400) ±1.121), p =0.000)	(75.400) ±1.121), p =0.000)	(73.400) ±1.121	0.694	0.362
Shooting Accuracy Wing PRE (%)	(65.400) ±1.121), p =1.000)	(65.400) ±1.121), p =1.000)	(65.400) ±1.121	0.006	0.007
After 1 Hour	(64.400) ±1.121), p =0.000)	(62.400) ±1.121), p =0.000)	(60.400) ±1.121	0.694	0.744
After 24 Hours	(66.400) ±1.121), p =0.000)	(64.400) ±1.121), p =0.000)	(62.400) ±1.121	0.694	0.362
After 48 Hours	(65.400) ±1.121), p =0.000)	(65.400) ±1.121), p =0.000)	(63.400) ±1.121	0.694	0.362

The statistical findings in Table (4) demonstrate the effectiveness of recovery strategies in protecting and stabilizing "Shooting Accuracy" (7m and Wing) against skill degradation caused by physical fatigue, with a clear and early advantage for the "Cold-Water Immersion" (CWI) group. Following baseline equivalence (p=1.000), the CWI group exhibited higher technical resilience one-hour post-exertion with means of (74.40% and 64.40%) compared to the other groups, supported by a high effect size (η^2) of (0.694), The efficiency of CWI was further evident in reaching a state of "Skill Supercompensation" at the 24-hour mark, where shooting accuracy surpassed pre-exertion levels (76.40% for 7m and 66.40% for Wing) with absolute statistical significance (p=0.000). This superiority suggests that cooling effectively contributes to the rapid restoration of neuromuscular readiness and the mental focus required for precision skills, making it the most reliable protocol for stabilizing the technical efficiency of handball players during congested schedules, as presented in Figure (4).

5.1.4. Study relationships and regression

This study utilized a participant tracking methodology with measurements at 1-, 24-, and 48-hours post-exertion to analyze relationships and regression. The aim was to calculate the "net change" at each stage, examining the link between metabolic accumulation and overall recovery. A correlation matrix encompassing all three time points was developed to test the hypothesis of a "temporal correlation" between functional recovery and on-court performance.

The selection of variables for analysis—such as lactate and creatine kinase (CK) for metabolic stress, vertical jump for mechanical efficiency, and shooting accuracy for neuromuscular readiness—was purposeful. This approach was designed to construct an explanatory model linking fatigue causes to performance effects, while avoiding statistical redundancy (Type I error). The analysis revealed that the increased clearance speed of metabolic waste was the most significant contributor to restoring the motor coordination and mental focus required for skilled performance. This methodology provides a credible metric for coaches to estimate a player's level of recovery and competitive readiness.

Table (5) relationships between the study variables

Group	variable	VJ1_Pre	VJ24_Pre	VJ48_Pre	CK1_Pre	CK48_Pre
CWI	VJ1_Pre	1	.997	.977	.582	.656
	VJ24_Pre	.997	1	.985	.572	.651
	VJ48_Pre	.977	.985	1	.638	.723
	CK1_Pre	.582	.572	.638	1	.674
	CK48_Pre	.656	.651	.723	.674	1

Group comparisons revealed distinct recovery dynamics. For the Cold-Water Immersion (CWI) group, a strong and progressive correlation was observed, peaking at 48 hours between the reduction in creatine kinase (CK) and improvement in vertical jump performance ($r = 0.723$, $p < 0.01$). This indicates CWI initiated a non-linear recovery pathway that enhanced the functional link between physiological repair (reduced muscle damage) and physical super compensation (explosive power).

In contrast, the Active Recovery and Control groups displayed static, near-perfect correlations ("monotonic synchrony"), showing their physiological and physical functions recovered at the same rate without an enhanced functional connection. This confirms CWI's unique role in strengthening the interdependence between the body's systems.

To build on this, linear regression analysis was used to develop a predictive model. This addresses the research objective by quantifying to what extent physiological indicators (like CK levels) can serve as reliable scientific bases for predicting a player's on-court readiness, providing coaches with a data-driven tool to estimate safe return-to-competition time.

Table (6): Simple linear regression analysis for predicting Vertical Jump by CK

Model	R	R Square	Adjusted R Square	F	Sig.
1	.723a	.522	.485	14.205	.002
Unstandardized Coefficients			Standardized Coefficients Beta	t	Sig.
	B	Std. Error			
(Constant)	1.917	.209		9.153	.000
CK48_Pre	.091	.024	.723	3.769	.002

Simple linear regression analysis revealed a statistically significant effect ($p = 0.002$) of creatine kinase (CK) levels at 48 hours on explosive power recovery (vertical jump). The coefficient of determination ($R^2 = 0.522$) indicates that 52.2% of the variance in jump recovery can be explained by changes in CK levels alone. The resulting predictive equation shows that for every one-unit decrease in CK, vertical jump performance improves by 0.091 cm. This model provides coaching staff with a practical tool to predict player readiness using biochemical data, helping to regulate training loads and mitigate injury risks from inadequate tissue recovery. This fulfills the study's fifth objective and confirms the Cold-Water Immersion (CWI) protocol's effectiveness in enhancing the functional connection between the body's systems.

$$VJ\ Recoveryafter48h(cm) = 1.917 + 0.091CK\ Reductionafter48h$$

6. Discussion:

This study confirms the clear superiority of cold-water immersion (CWI) overactive recovery (AR) and passive rest for restoring elite handball players. Data showed CWI enabled the fastest physiological recovery, with significant, rapid reductions in lactate and creatine kinase (CK) levels by 24 hours, aligning with the vasoconstriction mechanism described by Vaile et al. (2008) and the performance recovery linked to lower CK as shown by Pournot et al. (2011).

CWI uniquely facilitated a state of "super compensation," where players' vertical jump and shooting accuracy not only returned to baseline but surpassed it at 24 and 48 hours. A strong correlation ($r = 0.723$) between reduced CK and improved jump performance in the CWI group indicated an enhanced functional link between physiological repair and physical output, a connection absent in the other groups.

While AR was more effective than passive rest in clearing lactate, it was less effective than CWI at mitigating muscle damage (CK) and achieving performance supercompensation. This helps explain conflicting findings in literature, such as those by Andersson et al. (2008). The study also supports the psychological benefits of recovery noted by Ortiz et al. (2018), with CWI aiding the restoration of fine motor skills like shooting accuracy.

The findings underscore the unique demands of handball highlighted by Michalsik (2015) and provide a practical solution to injury risks associated with congested schedules, a concern raised by Dupont et al. (2010). By integrating physiological, physical, and skill-based metrics over time, this research validates prior foundational work and extends it into a comprehensive, evidence-based recovery model for handball, directly informing coaching practice. This research directly addresses the unique demands of handball (Michalsik, 2015) and provides a practical, evidence-based protocol to mitigate the injury risks associated with congested fixtures (Dupont et al., 2010).

6.1 Study Limitations and Future Considerations

While the results support the short-term efficacy of CWI for post-match recovery, certain limitations must be acknowledged. This study did not investigate the long-term effects of repeated CWI use on chronic training adaptations, such as hypertrophy or aerobic capacity—an area of ongoing scientific debate. Furthermore, the theoretical framework mentioned psychological readiness; however, this study did not include direct measures of perceptual (e.g., rating of perceived recovery) or psychological states (e.g., motivation, focus), which could provide a more comprehensive understanding of recovery. Future research should incorporate such measures to disentangle physiological from psychological effects. Despite these limitations, the integrated assessment of physiological, physical, and skill-based metrics over a 48-hour period provides valuable applied insights for handball practitioners.

7. Results:

Utilizing an experimental design, this study examined the effects of different recovery techniques on elite handball players. The findings indicate that cold-water immersion (CWI) was more effective than both active recovery (AR) and passive rest under the conditions of this study. CWI was associated with a faster return to baseline for heart rate, blood lactate, and creatine kinase levels, and coincided with functional "overcompensation" where performance in explosive power and shooting precision exceeded pre-exercise levels at 24-48 hours. AR showed some physiological benefits over passive rest, particularly in lactate clearance, but appeared less effective than CWI in mitigating muscle damage markers. Notably, moderate to strong correlations observed within the CWI group suggest a potential link between the reduction in biochemical markers of fatigue and the improvement in motor and skill performance.

These findings support the inclusion of CWI in post-competition protocols during congested schedules, though its long-term impact on training adaptations warrants further investigation.

8. Recommendations

Based on the findings from this investigation, the following recommendations are given to the practitioners of handball training and sports science:

1. The CWI protocol should be included in the core of a recovery strategy in handball training programs and intense periods of competition, as this modality accelerates physiological, physical, and technical recoveries, and can contribute to reducing the risk of fatigue accumulation and injuries.
2. Coaches and the scientific support staff should routinely conduct assessment of biochemical markers, such as creatine kinase, and physical performance measurements, such as vertical jump, to objectively monitor players' recovery status with a view to predicting their readiness to matches a head and aid in training load modulation.
3. In cases where CWI is not feasible, active recovery can be prescribed as a practical alternative. The prescription for this type of recovery is based on low-intensity modes (jogging or stationary cycling) for 6-10 minutes. It is useful to consider that its effectiveness may be limited to accelerating the removal of metabolic by products, while the reduction of muscle damage is not equally extended.
4. Individual recovery plans should be developed in a flexible way, considering the differences in the players' response, the nature of their playing position, the intensity of the previous match, and the time available until the next match.
5. It is important that players and sports managers understand the need for systematic recovery as an integral pillar of high performance and longevity in the sport, and not a luxury or subsidiary routine.

9. Future Studies

On the basis of the results and limitations of this investigation, the following five areas for future research are recommended:

1. It is important to evaluate how effective these recovery methods are for both young players and female players, and therefore identify if there are any physiological differences in responses to the recovery methods.

2. This research may lead to the discovery of the cumulative effect of continually implementing the recovery protocols for weeks/months/a full season has on a player's overall performance, injury rate and levels of psychological stress.
3. To study the molecular and cellular explanations for an increase in performance following the use of cold-water immersion and the measurement of micro-inflammation markers, cytokines and cellular muscle repair mechanisms.
4. To determine whether a combination of various recovery strategies may lead to an increased level of recovery (decreased soreness) than using either cold-water immersion or compression alone. For example, include the combination of cold-water immersion, compression therapy, specialized nutrition and improved quality of sleep (as was done in the study conducted by Duffield et al. in 2013).
5. To develop and/or standardize more specialized and standardized skills and physical performance tests that better replicate the physical demands of the sport of handball; allowing for a more thorough assessment of the functional components of performance, including frequency, maximal strength and kinesthetic awareness during a player's recovery period.
6. Conduct comparative studies on other high-contact (i.e., rugby, basketball) sports to identify/clarify the uniqueness of the sport, as compared to handball.

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