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Emerging Technologies in Aquatic Physical Therapy and Rehabilitation: A Systematic Review

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Abstract

Aquatic rehabilitation has evolved substantially from conventional hydrotherapy to encompass technology-enhanced interventions including underwater treadmills, pneumatic partial weight-support systems, water-jet resistance gait training, structured aquatic high-intensity interval training (AHIIT), and imaging-supported outcome assessment. Despite increasing clinical use across musculoskeletal and neurological rehabilitation, no focused synthesis has systematically evaluated the evidence specific to these emerging aquatic rehabilitation technologies. This systematic review aimed to identify, critically evaluate, and synthesize the clinical evidence for technology-enhanced aquatic rehabilitation interventions across musculoskeletal and neurological conditions. Adhering to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines, systematic searches were conducted across PubMed/MEDLINE, Scopus, Web of Science, Cochrane Library, and Embase from database inception to July 12, 2026. Eligible studies were randomized controlled trials (RCTs) evaluating technology-enhanced or structured aquatic rehabilitation in human participants. Completed trials were included in the qualitative outcome synthesis. Methodological quality of completed randomized trials was appraised using the Cochrane Risk of Bias 2 (RoB 2) tool. Owing to clinical and methodological heterogeneity, a thematic narrative synthesis was performed. Eleven studies met the eligibility criteria, comprising 11 completed randomized trials. The strongest completed clinical evidence concerned underwater treadmill interventions for knee osteoarthritis (KOA) and chronic stroke, pneumatic partial weight-support treadmill systems, water-jet resistance gait training, aquatic high-intensity interval training in rheumatic and musculoskeletal disease, and structured aquatic therapy for chronic low back pain (CLBP). Across studies, these interventions improved pain, physical function, gait, balance, quality of life, and, in some cases, muscle morphology. RoB 2 assessments indicated predominantly “some concerns” or “low risk” judgements across domains, with limitations primarily related to a lack of participant and therapist blinding. However, the evidence base remains constrained by modest sample sizes, inconsistent reporting of technological parameters, heterogeneous comparators, and limited long-term follow-up. Technology-enhanced aquatic rehabilitation appears effective across several conditions, particularly knee osteoarthritis, chronic low back pain, and post-stroke gait dysfunction. Current evidence most strongly supports a limited set of clinically implemented technologies, especially underwater treadmill-based systems and resistance-modulated aquatic gait training. More advanced technologies such as exoskeleton-integrated, sensor-driven, and computationally assisted aquatic systems remain promising but lack sufficient clinical trial validation.

Categories: Physical Medicine & Rehabilitation, Orthopedics, Healthcare Technology
Keywords: aquatic rehabilitation, emerging technologies, hydrotherapy, systematic review, underwater treadmill

Introduction And Background

Musculoskeletal and neurological disorders collectively represent some of the most prevalent and burdensome categories of non-communicable disease worldwide. According to the Global Burden of Disease 2021 study, musculoskeletal conditions alone account for a substantial and growing proportion of years lived with disability globally, with projections indicating further increases through 2050 [1]. The World Health Organization similarly identifies musculoskeletal conditions as a leading global cause of disability [2]. Chronic low back pain, knee osteoarthritis, rheumatic and musculoskeletal diseases, and post-stroke mobility impairment are among the most clinically significant rehabilitation targets, owing to their long-term consequences for physical function, independence, psychosocial wellbeing, and healthcare resource utilization. The cumulative economic and societal burden of these conditions, encompassing direct treatment costs, productivity losses, and caregiver dependency, underscores the urgency of developing more effective, accessible, and precisely targeted rehabilitation strategies.

Aquatic rehabilitation has long been recognized as a clinically valuable therapeutic approach, exploiting the unique physical properties of water to facilitate movement, reduce pain, and improve functional capacity in individuals for whom land-based exercise may be poorly tolerated or contraindicated. The principal mechanisms through which water exerts its therapeutic effects are well established. Buoyancy reduces effective body weight and mechanical joint loading, thereby decreasing compressive forces across weight-bearing joints and enabling earlier mobilization in post-injury or post-surgical populations. Hydrostatic

pressure acts uniformly across immersed body segments, assisting venous return, reducing dependent edema, and supporting cardiovascular responses to exercise. Viscosity provides graded resistance to movement in all directions, enabling progressive muscle strengthening without the need for external resistance equipment. Thermal properties of heated water may additionally contribute to analgesia, muscle relaxation, and reduced tissue stiffness, thereby lowering the perceived effort and pain associated with therapeutic exercise [3].

These combined properties render aquatic exercise particularly appropriate for individuals who have difficulty tolerating conventional land-based rehabilitation because of pain, obesity, neuromuscular weakness, postural instability, fear of falling, or reduced exercise tolerance. By reducing mechanical loading while providing multidirectional resistance and environmental support, the aquatic setting can facilitate therapeutic movement and exercise participation when equivalent land-based activities are difficult to perform or poorly tolerated. In patients with knee osteoarthritis, for example, buoyancy-mediated unloading of the tibiofemoral joint allows repetitive gait-specific practice at a lower pain threshold than equivalent land-based walking, potentially enabling training volumes that would otherwise be unattainable. In post-stroke patients, the hydrostatic support of water may reduce fall risk during gait retraining while preserving the task-specific nature and intensity of the practice. In chronic low back pain populations, the aquatic environment may simultaneously reduce pain, movement fear, and biomechanical loading of sensitized lumbar structures, thereby facilitating engagement with therapeutic exercise programs that patients might otherwise avoid or prematurely discontinue. A recent systematic review and meta-analysis confirmed the effectiveness of aquatic exercise across chronic musculoskeletal disorders [4], and bibliometric evidence indicates that aquatic exercise therapy has become one of the most rapidly expanding fields within rehabilitation research [5].

However, aquatic rehabilitation is not a uniform therapeutic modality. In recent years, the field has undergone a substantial transition from traditional pool-based free exercise toward a more diverse and technology-enriched landscape of structured intervention models. Clinically implemented technologies now include underwater treadmills [5,6], pneumatic partial weight-support treadmill systems, water-jet resistance gait training, intensity-regulated aquatic high-intensity interval training, and imaging-guided evaluation of morphological change following aquatic interventions [6,7]. These technologies represent a qualitative advancement over conventional aquatic exercise, as they enable more precise control of training load, progression parameters, task specificity, resistance magnitude, and outcome monitoring. The underwater treadmill, for instance, not only provides buoyancy-mediated joint unloading but also enforces a specific locomotor pattern and speed, enabling consistent, reproducible training stimuli that free-water walking cannot guarantee. Pneumatic partial weight-support systems provide an alternative mechanical unloading mechanism on land, raising important questions about the relative efficacy of aquatic and terrestrial unloading approaches. Water-jet resistance systems add a directional challenge to underwater gait training, potentially increasing neuromotor demand and proprioceptive stimulation in ways that conventional ankle weights cannot replicate [7]. The conceptual relationship between aquatic rehabilitation technologies, loading modification, and clinical applications is illustrated in Figure *1*.

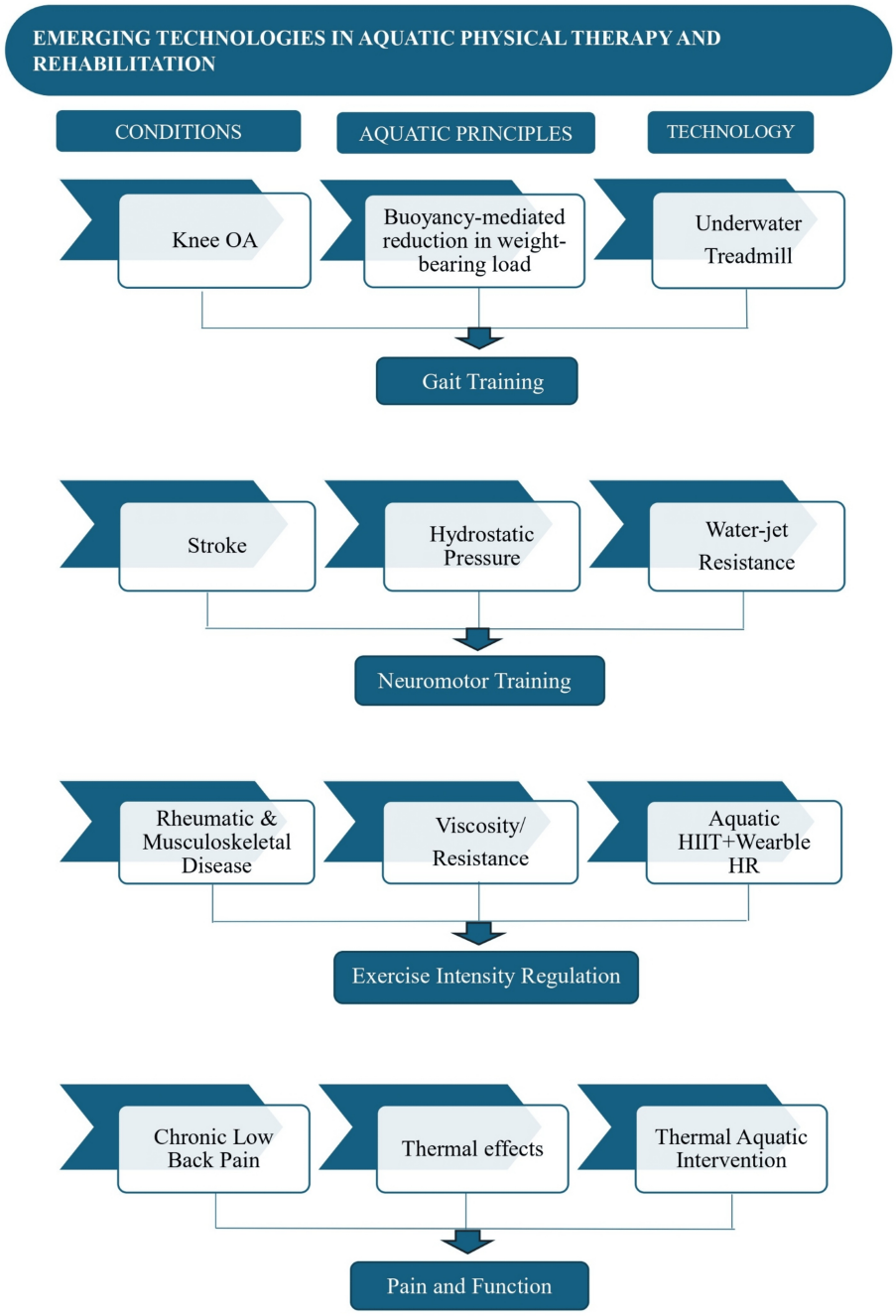


FIGURE 1: AquaRehab technology integration framework

The framework illustrates the relationship between clinical conditions, aquatic therapeutic principles, technology-enhanced interventions, and rehabilitation outcomes. Buoyancy-mediated reduction in weight-bearing load refers to the decrease in effective body-weight loading during immersion, which may facilitate supported gait training and functional exercise. Hydrostatic pressure, water viscosity, thermal effects, and technology-assisted exercise are linked to gait training, neuromotor training, exercise-intensity regulation, and improvements in pain and physical function.

OA: osteoarthritis, HIIT: high-intensity interval training, HR: heart rate

Image credits: Created by the authors using Microsoft Word (Microsoft Corp., WA, USA)

These developments are clinically relevant because technology-assisted systems may allow therapists to standardize and progressively modify exercise intensity, mechanical loading, resistance, gait speed, and task demands in ways that are difficult to achieve consistently with conventional free-water exercise.

At the same time, the broader rehabilitation technology literature has proposed additional emerging and

future directions, including wearable sensor-driven feedback systems, proprioceptive technologies, exoskeleton integration into rehabilitative environments, virtual reality platforms, and computationally enhanced rehabilitation planning and load modeling. However, the critical distinction must be drawn between technologies that are supported by controlled clinical outcome data and those that remain largely theoretical, preclinical, or insufficiently tested within structured aquatic rehabilitation trial designs. As Willingham et al. [6] and Cook et al. [7] have separately noted, the proliferation of new rehabilitation technologies frequently outpaces the generation of robust clinical trial evidence, creating a landscape in which clinical enthusiasm may exceed the available scientific foundation. Several of these technologies have been conceptually applied to aquatic settings, most notably in discussions of exoskeleton-assisted aquatic therapy and sensor-integrated aquatic training systems [8].

A further consideration is the importance of distinguishing between technological innovation as hardware the physical devices and systems used to deliver aquatic interventions and technological innovation as methodology the structured design of exercise protocols, intensity-monitoring procedures, and data-driven outcome-assessment frameworks.

Despite the clinical proliferation of these technologies, no focused systematic review has specifically examined the evidence base for technology-enhanced aquatic rehabilitation across musculoskeletal and neurological conditions. Existing reviews of aquatic exercise have tended to address the modality broadly, without specifically distinguishing between conventional aquatic therapy and technology-enhanced or structured aquatic interventions. This gap limits the ability of clinicians to make evidence-informed decisions about technology selection and limits researchers' ability to identify where the existing evidence is most robust and where critical gaps remain.

To address this gap systematically and rigorously, this review was conducted with the following specific objectives: (1) to identify the range of emerging and technology-enhanced interventions currently evaluated within aquatic rehabilitation, (2) to critically analyze their effectiveness across musculoskeletal and neurological conditions, (3) to assess the methodological quality of the existing clinical evidence using the validated RoB 2 tool, and (4) to identify current limitations and future priorities for research and clinical implementation.

Review

Methods

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement [9]. A pre-defined review protocol was developed prior to study selection and data extraction to ensure methodological rigor.

Literature Search

A systematic literature search was conducted in PubMed/MEDLINE, Scopus, Web of Science, Cochrane Library, and Embase from database inception to July 12, 2026, which was the final search date. The search strategy combined controlled vocabulary, where available, with free-text keywords related to aquatic rehabilitation, emerging rehabilitation technologies, and the target clinical populations. Search terms included "aquatic rehabilitation", "aquatic therapy", "hydrotherapy", "underwater treadmill", "water-jet resistance", "partial weight support", "aquatic high-intensity interval training", "technology", "knee osteoarthritis", "low back pain", "stroke", and "musculoskeletal disorders". Boolean operators AND and OR were used to combine search concepts.

The reference lists of all included studies and relevant review articles were also screened manually to identify additional eligible studies not captured by the electronic database searches. The search results were exported, and duplicate records were removed before title and abstract screening.

The complete database-specific search strategies, including the search strings, controlled vocabulary, Boolean operators, and database-specific filters or limits, are provided in the Appendix to facilitate reproducibility of the literature search.

Selection Criteria

Inclusion criteria: We included English-language full-text studies involving human participants of any age or sex. Eligible studies were completed randomized controlled trials (RCTs) evaluating a technology-enhanced or structured aquatic rehabilitation intervention, as defined a priori below. Studies were required to include a comparator group and to report at least one quantifiable clinical outcome related to pain, physical function, gait, balance, quality of life, disability, or morphology.

Exclusion criteria: We excluded non-English studies, animal studies, studies without a comparator group, case reports, case series, conference abstracts lacking full-text access, systematic reviews, bibliometric

analyses, narrative reviews, and RCT protocol papers. Studies evaluating only conventional aquatic exercise without a distinct technological or structured technology-enhanced component where the intervention could not reasonably be classified within the review scope were also excluded. Duplicate publications and overlapping datasets were removed.

Detailed eligibility criteria are presented in Table 1.

Criteria	Inclusion	Exclusion
Study population	Human participants (all genders and ages)	Animal studies
Study design	Completed randomized controlled trials (RCTs)	RCT protocol papers, reviews, bibliometric studies, abstracts without full text, case reports, case series
Intervention	Technology-enhanced or structured aquatic rehabilitation	Conventional aquatic exercise without a distinct structured or technology-related component
Comparator	Active comparator, standard care, home exercise, land-based care, or alternative aquatic technology	No comparator group
Outcomes	Pain, function, gait, balance, quality of life, disability, morphology	No relevant quantifiable clinical outcomes
Language	English full text	Non-English
Data integrity	Primary original datasets	Duplicate publications and overlapping cohorts

TABLE 1: Eligibility criteria for inclusion and exclusion of studies

RCT, randomized controlled trial

For this review, technology-enhanced aquatic rehabilitation was defined as aquatic rehabilitation incorporating a device or technology that directly modified exercise delivery, loading, resistance, gait training, or exercise intensity. This included underwater treadmill systems, pneumatic partial weight-support systems, water-jet resistance systems, and other technology-assisted aquatic exercise modalities. Structured aquatic rehabilitation was defined as a prespecified, protocolized aquatic exercise program with a clearly defined therapeutic target, exercise content, intervention frequency, and duration, even when no specialized technological device was used. Conventional aquatic exercise was therefore considered eligible only when it met the predefined characteristics of a structured rehabilitation protocol; studies involving nonspecific conventional aquatic exercise without a distinct structured or technology-related component were excluded.

Study Selection and Data Extraction

Two reviewers independently screened all titles and abstracts according to the predefined eligibility criteria. Potentially relevant studies then underwent independent full-text assessment. Disagreements were resolved through consensus discussion and, where necessary, adjudication by a third reviewer. Data extraction was performed using a standardized form capturing study design, population characteristics, intervention details, comparator, outcome measures, follow-up duration, and principal findings.

Quality Assessment

The methodological quality of the 11 completed randomized trials was assessed using the Cochrane Risk of Bias 2 (RoB 2) tool [10]. Assessments were conducted across five domains: (1) bias arising from the randomization process, (2) bias due to deviations from intended interventions, (3) bias due to missing outcome data, (4) bias in the measurement of the outcome, and (5) bias in the selection of the reported result. Overall risk-of-bias (RoB) judgments were assigned according to the Cochrane RoB 2 algorithm.

Data Synthesis

Given substantial clinical and methodological heterogeneity across included studies encompassing differences in populations, technologies, comparators, outcome measures, and intervention duration, a quantitative meta-analysis was considered inappropriate. A thematic narrative synthesis was therefore

performed. Where individual studies reported effect estimates, 95% confidence intervals (CIs), or P-values, these were extracted and reported as presented in the original studies; no pooled effect estimates were calculated. Extracted data were organized into the following clinical domains: (1) underwater treadmill-based technologies, (2) pneumatic partial weight-support systems, (3) resistance-modulated aquatic gait training, (4) structured aquatic high-intensity exercise, (5) technology-supported aquatic rehabilitation for chronic low back pain, and (6) future technologies with limited or no current clinical outcome evidence [11,12].

Results

Study Selection

The database search identified 192 records: PubMed (n = 33), Scopus (n = 119), Embase (n = 23), Cochrane Library (n = 4), and Web of Science (n = 13). After removal of 39 duplicate records, 153 records underwent title and abstract screening, of which 124 were excluded. Twenty-nine full-text reports were assessed for eligibility, and 18 were excluded for the following reasons: conventional aquatic exercise without a distinct technology component (n = 5), no comparator group (n = 3), wrong study design (n = 4), review or bibliometric paper (n = 3), and non-English language (n = 3). Eleven studies met the eligibility criteria and were included in the review, all of which were completed randomized trials and were included in the qualitative outcome synthesis. The included interventions comprised both technology-enhanced modalities and structured aquatic rehabilitation programs. Technology-enhanced interventions included underwater treadmill systems, pneumatic partial weight-support systems, and water-jet resistance, whereas structured interventions included protocolized aquatic exercise, aquatic high-intensity interval training, aquatic trunk-stabilization exercise, and thermally enhanced aquatic rehabilitation. Each included intervention met the predefined technology-enhanced or structured eligibility definition described in the Methods. The study selection process is presented in the PRISMA 2020 flow diagram (Figure *2*).

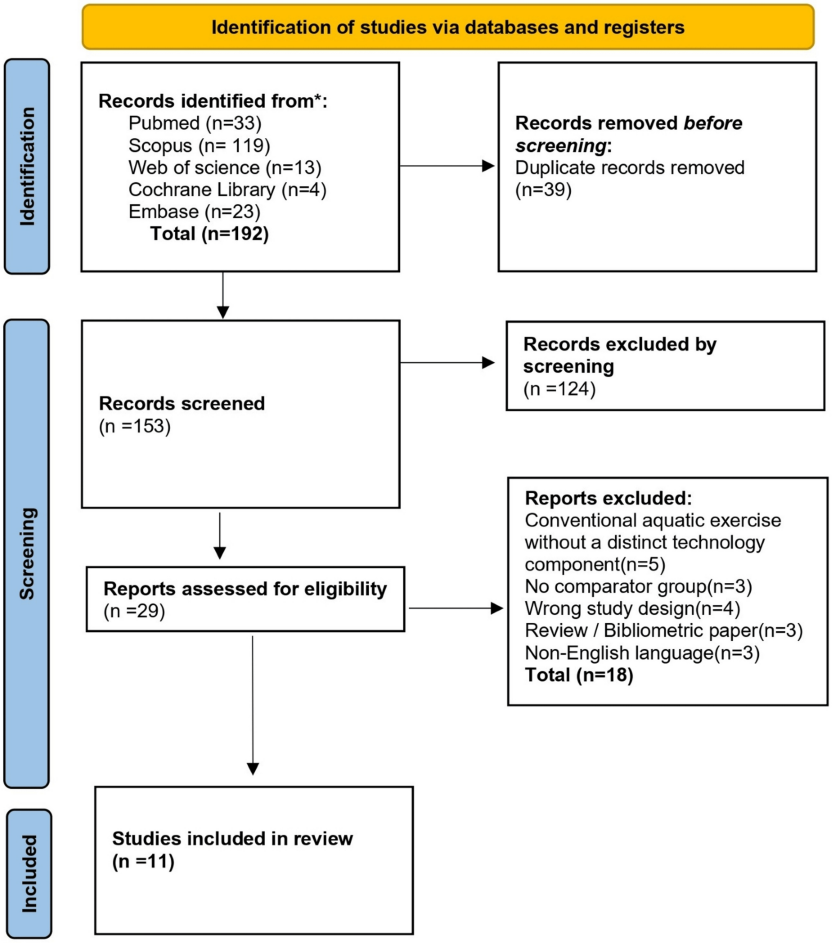


FIGURE 2: PRISMA 2020 flow diagram

PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses

A full summary of study characteristics is presented in Table 2.

S. No.	Author (Year)	Population	Design	Groups (n)	Intervention	Classification / rationale
1	Dias JM, Cisneros L, Dias R, et al. (2017) [13]	Knee OA (elderly women)	RCT	Education + hydrotherapy (n = 36) vs. education alone (n = 37)	Education + hydrotherapy	Structured aquatic rehabilitation: protocolized hydrotherapy delivered at a defined frequency and duration for knee OA
2	Kuptniratsaikul V, Kittichaikarn C, Suntornpiyapan P, Kovintaset K, Inthibal S. (2019) [14]	Knee OA, obese (BMI ≥25)	Single-blind RCT	UTM + home exercise (n = 40) vs. home exercise alone (n = 40)	Underwater treadmill + home exercise	Technology-enhanced: underwater treadmill directly modifies aquatic gait training and loading
3	Assar S, Gandomi F, Mozafari M, Sohaili F. (2020) [15]	Knee OA (female)	Single-blind RCT (3-arm)	TRX exercise (n = 12) vs. aquatic exercise (n = 12) vs. passive drug-only control (n = 12)	Aquatic exercise	Structured aquatic rehabilitation: prespecified aquatic exercise program with defined treatment duration and frequency
4	Azizi S, Dadarkhah A, Rezasoltani Z, Raeissadat SA, Mofrad RK, Najafi S (2020) [16]	Knee OA (male only)	Single-blind RCT	Aquatic exercise vs. acetaminophen/lifestyle control (n = 16/group planned)	Aquatic exercise	Structured aquatic rehabilitation: protocolized aquatic exercise delivered as a defined rehabilitation intervention
5	Lim CG. (2020) [17]	Chronic stroke	Single-blind RCT (pilot)	UTM + water-jet resistance (n = 11) vs. UTM + ankle weights (n = 11)	Underwater treadmill + water-jet resistance	Technology-enhanced: combines underwater treadmill gait training with water-jet resistance
6	Moreira NB, da Silva LP, Rodacki ALF. (2020) [18]	Older adults with MSDs and fall risk	Single-blind RCT	Aquatic exercise (n = 75 allocated, 60 completed) vs. control (n = 70 allocated, 60 completed)	Aquatic exercise	Structured aquatic rehabilitation: defined aquatic exercise program delivered over a prespecified treatment period
7	Kuptniratsaikul V, Chaiworapuek W, Kovintaset K, Meesawang M, Chinsawangwatanakul P, Danoi A. (2022) [19]	Knee OA, overweight	Non-inferiority RCT	Pneumatic partial weight-support treadmill vs. UTM (n = 55/group planned)	Pneumatic partial weight-support treadmill	Technology-enhanced: pneumatic partial weight support directly modifies loading during aquatic treadmill exercise
8	Bunæs-Næss H, Nilsson BB, Kvæl LAH, Heywood SE, Gerritsen RBTW, Heiberg KE. (2025) [20]	Rheumatic/musculoskeletal disease	Secondary analysis of RCT	AHIIT (n = 44) vs. aquatic moderate-intensity continuous training (n = 45); target 84	AHIIT	Structured aquatic rehabilitation: prespecified high-intensity aquatic interval training protocol with defined exercise intensity and duration
9	Rosenstein B, Montpetit C, Vaillancourt N, et al. (2025) [21]	Chronic non-specific LBP	RCT	Aquatic trunk-stabilization exercise (n = 18) vs. land-based standard care (n = 16)	Aquatic trunk-stabilization exercise	Structured aquatic rehabilitation: targeted, protocolized aquatic exercise directed toward trunk stabilization
10	Vaillancourt N, Montpetit C, Rosenstein B, Fortin M. (2026) [22]	Chronic non-specific LBP	RCT (secondary psychological-outcomes analysis)	Aquatic therapy (n = 18) vs. standard care (n = 16)	Aquatic therapy	Structured aquatic rehabilitation: defined aquatic therapeutic exercise program delivered over a prespecified treatment period
11	Qin L, Dong N, Zhao Y, et al. (2026) [23]	Chronic LBP (male)	RCT	Conventional rehab + aquatic exercise/hot-spring bathing (n = 18) vs. conventional rehab alone (n = 18)	Aquatic exercise + hot-spring bathing	Structured/thermally enhanced aquatic rehabilitation: predefined aquatic rehabilitation combined with a specified thermal component

TABLE 2: Characteristics of the included studies

RCT, randomized controlled trial; OA, osteoarthritis; LBP, low back pain; UTM, underwater treadmill; AHIIT, aquatic high-intensity interval training; TRX, total resistance exercise; MSD, musculoskeletal disorder; BMI, body mass index

The baseline attributes and key findings of all included studies are presented in Table *3*.

Author (year)	Total participants	Outcome measures	Intervention	Key results	Main conclusion
Dias JM, Cisneros L, Dias R, et al. (2017) [13]	73 (37 hydrotherapy; 36 education only)	Pain (VAS, WOMAC), function (WOMAC), muscle performance	Education + hydrotherapy vs. education alone; 2×/week, 6 weeks	Hydrotherapy significantly improved pain and physical function vs. education alone	Hydrotherapy is beneficial for pain and function in elderly women with KOA
Kuptniratsaikul V, Kittichaikarn C, Suntornpiyapan P, Kovintaset K, Inthibal S. (2019) [14]	80 randomized (33 UTM completed; 37 control completed)	Pain (VAS), TUG, 5×STS, 10MWT, quadriceps strength, WOMAC	Underwater treadmill exercise vs. home exercise; 30 min/session, 3×/week, 4 weeks	UTM group showed significantly greater improvement in pain (VAS) and physical function (TUG, 10MWT) vs. home exercise	Underwater treadmill exercise is superior to home exercise for pain and function in obese KOA patients
Assar S, Gandomi F, Mozafari M, Sohaili F. (2020) [15]	36 (12/group, 3-arm)	Knee instability (VAS), pain (VAS), WOMAC stiffness subscale, static and dynamic balance	Aquatic training vs. TRX exercise vs. passive drug-only control; 3×/week, 8 weeks	Aquatic training improved self-reported knee instability, pain, and stiffness comparably to TRX; both active groups outperformed passive control	Aquatic training addresses perceptual and biomechanical KOA dimensions; comparable efficacy to land-based TRX
Azizi S, Dadarkhah A, Rezasoltani Z, Raeissadat SA, Mofrad RK, Najafi S (2020) [16]	32 (16/group)	Pain (VAS), gait parameters, balance	Aquatic exercise vs. acetaminophen + lifestyle advice; 3×/week, 8 weeks	Aquatic exercise produced significantly greater improvements in pain, gait, and balance vs. pharmacological comparator	Aquatic exercise can outperform pharmacological management for pain, gait, and balance in elderly men with KOA
Lim CG. (2020) [17]	22 (11/group)	Balance (BBS), gait (10MWT, TUG)	UTM + water-jet resistance vs. UTM + ankle weights; 30 min conventional PT + 30 min UTM, 5×/week, 4 weeks	Water-jet resistance group showed significantly greater improvement in BBS, 10MWT, and TUG vs. ankle weights	Water-jet resistance is a promising aquatic technology for neurological gait and balance rehabilitation in chronic stroke
Moreira NB, da Silva LP, Rodacki ALF. (2020) [18]	145 randomized; 120 analyzed (60/group)	SPPB, TUG, BBS, handgrip strength, fear of falling (FES-I), SF-36	Aquatic exercise program vs. control; 45 min/session, 2×/week, 16 weeks	Aquatic exercise significantly improved functional capacity, balance, fear of falling, and QoL vs. control	Aquatic exercise benefits older adults with mixed musculoskeletal disorders; effects sustained at 16 weeks
Kuptniratsaikul V, Chaiworapuek W, Kovintaset K, Meesawang M, Chinsawangwatanakul P, Danoi A. (2022) [19]	55/group planned	Pain (NRS), quadriceps strength (isokinetic dynamometry), 6MWT, QoL	Pneumatic partial weight-support treadmill vs. underwater treadmill; 30 min/session, 3×/week, 8 weeks; follow-up at 12 weeks	Both interventions improved pain and function; pneumatic system showed greater quadriceps strength gains; UTM showed comparable pain reduction	Both unloading technologies are effective; mechanism-specific benefits differ; technology selection should be guided by treatment priority
Bunæs-Næss H, Nilsson BB, Kvæl LAH, Heywood SE, Gerritsen RBTW, Heiberg KE. (2025) [20]	89 (44 AHIIT; 45 AMICT)	PROMs, QALYs	Aquatic HIIT vs. aquatic moderate-intensity continuous training; 2×/week, 12 weeks	No significant between-group difference in PROMs or QALY-related estimates (AHIIT vs. AMICT) at 3 or 6 months	The aquatic environment can support delivery of high-intensity conditioning in RMD populations
Rosenstein B, Montpetit C, Vaillancourt N, et al. (2025) [21]	34 (18 aquatic exercise; 16 standard care)	MRI paraspinal morphology (multifidus, erector spinae), pain (NRS), ODI, QoL, PCS	Aquatic trunk-stabilization exercise vs. land-based standard care; 2×/week, 10 weeks	Aquatic exercise produced significant improvements in paraspinal muscle morphology, pain, and disability vs. standard care	Aquatic exercise supports structural paraspinal muscle adaptation in CLBP

Vaillancourt N, Montpetit C, Rosenstein B, Fortin M. (2026) [22]	34 completed (18 aquatic therapy; 16 standard care)	Pain (NPRS), ODI, SF-12, PCS, HADS, TSK-11, ISI	Aquatic therapy vs. standard care; 2×/week, 10 weeks	Both groups improved in pain and disability; only aquatic therapy group showed significant within-group reductions in kinesiophobia (TSK-11: MD = −4.84, p = .002) and sleep disturbance (ISI: MD = −5.06, p = .001)	Aquatic therapy confers psychological and sleep benefits beyond standard care, particularly for kinesiophobia and sleep disturbance in CLBP
Qin L, Dong N, Zhao Y, et al. (2026) [23]	36 (18/group); no attrition	Pain (VAS), ODI, FMS, lumbar muscle strength	Conventional rehab + aquatic exercise/hot-spring bathing vs. conventional rehab alone; 3×/week, 4 weeks	Combined intervention produced significantly greater reduction in pain (VAS; p < .001; ΔVAS = 2.56 ± 0.92 vs. 0.94 ± 0.54) and improvements in motor function vs. control	Thermal-aquatic combination adds analgesic and functional benefit beyond conventional rehabilitation alone

TABLE 3: Baseline attributes and key findings of the included studies

VAS, visual analog scale [24]; TUG, timed up-and-go [25]; 5×STS, five-times sit-to-stand [26]; 10MWT, ten-metre walk test [27]; WOMAC, Western Ontario and McMaster Universities Osteoarthritis Index [28]; NRS, numeric rating scale [29]; 6MWT, six-minute walk test [30]; QoL, quality of life; BBS, Berg Balance Scale [31]; PROMs, patient-reported outcome measures; QALYs, quality-adjusted life-years; AHIIT, aquatic high-intensity interval training; AMICT, aquatic moderate-intensity continuous training; RMD, rheumatic and musculoskeletal disease; MRI, magnetic resonance imaging; ODI, Oswestry Disability Index [32]; PCS, Pain Catastrophizing Scale [33]; SPPB, Short Physical Performance Battery [34]; SF-12, Short Form-12 [35]; SF-36, Short Form-36 [36]; FES-I, Falls Efficacy Scale–International [37]; NPRS, numeric pain rating scale [29]; HADS, Hospital Anxiety and Depression Scale [38]; TSK-11, Tampa Scale of Kinesiophobia [39]; ISI, Insomnia Severity Index [40]; FMS, Functional Movement Screen; KOA, knee osteoarthritis; CLBP, chronic low back pain; UTM, underwater treadmill; TRX, total resistance exercise

Risk-of-Bias Assessment

The RoB 2 assessment of the 11 included randomized trials is summarized in Table *4*. Overall, 10 studies were judged to have some concerns regarding RoB, while one study (Assar et al., 2020) [15] was judged to have a high overall RoB. None of the included studies was judged to have a low overall RoB. The principal concerns were related to deviations from intended interventions and measurement of outcomes, particularly because blinding of participants and treating therapists is generally not feasible in exercise-based and aquatic rehabilitation interventions.

Author (year)	Domain 1: Randomization Process	Domain 2: Deviations from Intended Interventions	Domain 3: Missing Outcome Data	Domain 4: Measurement of Outcome	Domain 5: Selection of Reported Result	Overall risk of bias
Dias JM, Cisneros L, Dias R, et al. (2017) [13]	Low	Some concerns	Low	Some concerns	Low	Some concerns
Kuptniratsaikul V, Kittichaikarn C, Suntornpiyapan P, Kovintaset K, Inthibal S. (2019) [14]	Low	Some concerns	Low	Some concerns	Low	Some concerns
Assar S, Gandomi F, Mozafari M, Sohaili F. (2020) [15]	Low	Some concerns	High	Some concerns	Low	High
Azizi S, Dadarkhah A, Rezasoltani Z, Raeissadat SA, Mofrad RK, Najafi S (2020) [16]	Low	Some concerns	Low	Some concerns	Low	Some concerns
Lim CG. (2020) [17]	Some concerns	Some concerns	Low	Some concerns	Low	Some concerns
Moreira NB, da Silva LP, Rodacki ALF. (2020) [18]	Low	Some concerns	Low	Low	Low	Some concerns
Kuptniratsaikul V, Chaiworapuek W, Kovintaset K, Meesawang M, Chinsawangwatanakul P, Danoi A. (2022) [19]	Low	Some concerns	Low	Low	Low	Some concerns
Bunæs-Næss H, Nilsson BB, Kvæl LAH, Heywood SE, Gerritsen RBTW, Heiberg KE. (2025) [20]	Low	Some concerns	Low	Some concerns	Low	Some concerns
Rosenstein B, Montpetit C, Vaillancourt N, et al. (2025) [21]	Low	Some concerns	Low	Some concerns	Low	Some concerns
Vaillancourt N, Montpetit C, Rosenstein B, Fortin M. (2026) [22]	Low	Some concerns	Low	Low	Low	Some concerns
Qin L, Dong N, Zhao Y, et al. (2026) [23]	Low	Some concerns	Low	Some concerns	Low	Some concerns

TABLE 4: Risk of Bias 2 (RoB 2) assessment

Judgments: Low risk; Some concerns; High risk. Domain definitions per Cochrane Handbook for Systematic Reviews of Interventions, version 6.3, 2022. The main source of "some concerns" across studies was the lack of blinding of participants and therapists, which is practically unavoidable in exercise-based rehabilitation interventions.

In Domain 1 (bias arising from the randomization process), 10 studies were judged to have a low RoB, whereas Lim et al. (2020) [17] was judged to have some concerns because of insufficient reporting of the randomization and allocation procedures. Overall, the randomization process was adequately reported in most studies.

In Domain 2 (bias due to deviations from intended interventions), all 11 studies were judged to have some concerns. The principal limitation was the inability to blind participants and treating therapists to intervention allocation, which is inherent to most exercise-based and aquatic rehabilitation interventions. Although no major deviations from the assigned interventions were identified, awareness of treatment allocation may have influenced participant expectations, adherence, or engagement with the intervention.

For Domain 3 (bias due to missing outcome data), 10 studies were judged to have a low RoB. Participant retention was generally adequate, and missing outcome data were either minimal or sufficiently explained. By contrast, Assar et al. (2020) [15] was judged to have a high RoB because of substantial missing outcome data and insufficient evidence that the missingness was unlikely to influence the estimated intervention effect.

For Domain 4 (bias in measurement of the outcome), three studies were judged to have a low RoB, while

eight were judged to have some concerns. The main concerns related to subjective or participant-reported outcomes, particularly pain and perceived functional status, in the context of unblinded interventions. However, several studies also used objective performance-based measures, including walking tests, balance assessments, gait parameters, and muscle-strength measurements.

For Domain 5 (bias in selection of the reported result), all 11 studies were judged to have a low RoB. No clear evidence of selective reporting or substantial discrepancies between the stated study objectives and reported outcomes was identified.

Overall, the RoB 2 assessment indicates that the included evidence was characterized predominantly by some concerns rather than high RoB. The most frequent limitation was the inability to blind participants and treating therapists, while substantial missing outcome data represented the principal concern in Assar et al. (2020) [15]. These methodological limitations were considered when interpreting the findings of the review.

Discussion

Principal Findings

This systematic review synthesized evidence from 11 completed RCTs evaluating structured or technology-enhanced aquatic rehabilitation in musculoskeletal and neurological populations. Overall, the evidence suggests that aquatic rehabilitation incorporating underwater treadmill training, pneumatic partial weight support, water-jet resistance, structured high-intensity exercise, conventional aquatic exercise, and thermally enhanced aquatic interventions can improve selected clinical outcomes, including pain, physical function, gait, balance, strength, aerobic capacity, and quality of life [13-23,41,42]. However, the evidence does not establish consistent superiority of technology-enhanced aquatic rehabilitation over conventional aquatic exercise, land-based rehabilitation, home exercise, or standard care. Rather, the findings indicate that aquatic rehabilitation may provide a clinically useful environment for modifying mechanical loading, resistance, exercise intensity, and task difficulty according to individual rehabilitation needs.

The interpretation of these findings should remain cautious because the included trials differed substantially in diagnosis, participant characteristics, intervention characteristics, comparator conditions, treatment duration, and outcome measures. In addition, most trials had some concerns regarding RoB, and one trial was judged to have a high RoB. Therefore, the overall evidence is more appropriately interpreted as supportive of potential clinical benefit than as definitive evidence of treatment superiority.

Interpretation of the Findings

The observed benefits are biologically plausible and may arise from the interaction between buoyancy, hydrostatic pressure, viscosity, and structured therapeutic exercise. Buoyancy reduces effective weight-bearing demands and may allow individuals with pain, weakness, obesity, impaired balance, or reduced exercise tolerance to perform repetitive movements with less mechanical stress. At the same time, water resistance provides a multidirectional training stimulus that can be progressively modified according to movement velocity, body position, and exercise design. These properties may permit patients to achieve an adequate exercise dose while maintaining greater movement tolerance.

The knee osteoarthritis studies provide the clearest evidence for this therapeutic model. Dias et al. [13] reported improvements in pain and physical function following hydrotherapy in older women with knee osteoarthritis. Similarly, aquatic exercise in older adults was associated with reductions in pain and improvements in static and dynamic balance and gait-related parameters in the trial by Azizi et al. [16]. Moreira et al. [18] further demonstrated that a 16-week aquatic exercise programme improved functional capacity, balance-related outcomes, perceptual aspects, and quality of life in older adults with musculoskeletal disorders and elevated fall risk. Collectively, these findings support the role of aquatic exercise as a potentially well-tolerated strategy for individuals in whom pain, impaired balance, fear of falling, or reduced weight-bearing tolerance limits participation in conventional exercise.

However, the evidence does not indicate that an aquatic intervention is consistently superior to another exercise approach. Kuptniratsaikul et al. [14] found significant improvements in both underwater treadmill and home-exercise groups among obese individuals with knee osteoarthritis, but no statistically significant between-group differences in pain, six-minute walking distance, quadriceps strength, or body weight. Although participants receiving underwater treadmill training reported greater global improvement and satisfaction, the primary clinical outcomes did not demonstrate clear superiority. This finding is important because it suggests that the aquatic environment may enhance exercise acceptability and tolerability without necessarily producing greater clinical effects than an appropriately designed home exercise programme.

A similar pattern was observed by Assar et al. [15], in which both aquatic and total-resistance exercise improved pain, balance, and self-reported knee instability. However, improvements in knee stiffness, quadriceps strength, and knee flexion range of motion were more pronounced with total-resistance exercise.

These findings indicate that aquatic rehabilitation should not be regarded as universally superior to land-based resistance exercise. Instead, the relative effectiveness of aquatic and land-based approaches may depend on the impairment being targeted and the characteristics of the exercise programme.

Technology-Specific Effects

An important finding of this review is that the effects of aquatic rehabilitation may be technology-specific rather than uniform across all aquatic interventions. Lim demonstrated that underwater treadmill gait training incorporating water-jet resistance produced greater improvements in several measures of static and dynamic balance and gait performance than underwater treadmill training using ankle weights in individuals with chronic stroke [17]. These findings suggest that water-jet resistance may provide a task-specific method of increasing resistance while retaining the supportive characteristics of the aquatic environment.

The comparison between pneumatic partial weight-support treadmill training and underwater treadmill training provides further evidence for technology-specific treatment selection. Kuptniratsaikul et al. [19], reported that pneumatic partial weight-support treadmill training was non-inferior to underwater treadmill training for pain reduction and produced significantly greater improvement in quadriceps strength in overweight individuals with knee osteoarthritis. These findings suggest that the clinical value of partial-weight-support technologies may not depend solely on their ability to reduce loading, but also on their capacity to facilitate progressive strengthening while maintaining exercise tolerance.

Accordingly, technology selection should be based on the primary rehabilitation objective rather than on the assumption that one aquatic technology is intrinsically superior. Underwater treadmills may be particularly appropriate for repetitive gait practice and graded weight-bearing; water-jet resistance may be useful for task-specific resistance and balance training; and pneumatic partial-weight-support systems may facilitate controlled progression of loading and strengthening. This technology-specific perspective is more clinically defensible than treating all forms of aquatic technology as a single intervention category.

Exercise Intensity Does Not Necessarily Translate Into Greater Clinical Benefit

The AquaHigh trials provide important evidence concerning exercise intensity. In the primary RCT, aquatic high-intensity interval training produced a greater improvement in aerobic capacity than moderate-intensity continuous aquatic training after 12 weeks [41]. However, this difference was not maintained at six months, and no significant between-group difference was observed in lower-limb functional strength [41]. These findings suggest that higher-intensity aquatic exercise can produce additional short-term physiological benefits, but the persistence and clinical relevance of these effects remain uncertain.

The secondary analysis of the same AquaHigh trial provides an important complementary finding. Despite the physiological improvement in aerobic capacity, no significant between-group differences were observed in patient-reported outcomes or quality-adjusted life-years between aquatic high-intensity interval training and moderate-intensity continuous aquatic exercise [20]. Taken together, these findings indicate that greater physiological intensity does not necessarily result in greater improvements in pain, fatigue, disease activity, health-related quality of life, or overall patient-reported benefit.

Therefore, exercise intensity should be individualized according to symptom severity, baseline functional capacity, treatment goals, adherence, safety, and patient preference. The most effective aquatic programme may not necessarily be the most intensive programme, particularly when the primary objective is symptom management rather than improvement in aerobic capacity.

Chronic Low Back Pain and Broader Rehabilitation Applications

The more recent chronic low back pain literature expands the potential clinical relevance of aquatic rehabilitation beyond knee osteoarthritis and neurological rehabilitation. Rosenstein et al. investigated aquatic exercise compared with standard care using both patient-oriented outcomes and MRI-based assessment of paraspinal muscle morphology and composition [21]. This study provides an important methodological contribution because imaging-based outcomes allow researchers to investigate structural and physiological adaptations that may not be captured by pain and disability questionnaires alone.

Vaillancourt et al. [22] similarly compared aquatic therapy with standard care in individuals with chronic low back pain. Both groups demonstrated significant improvements in pain, disability, and physical quality of life, but no significant between-group differences were observed for the primary patient-reported outcomes. Interestingly, aquatic therapy was associated with significant reductions in kinesiophobia and sleep disturbance, suggesting that the aquatic environment may provide additional benefits for selected psychological or behavioral factors even when conventional clinical outcomes are comparable between treatment approaches.

Qin et al. [23] reported a different pattern when aquatic exercise was combined with hot-spring bathing and compared with conventional physical therapy. The combined intervention produced greater improvements in pain, disability, functional movement, and lumbar and back-muscle strength than conventional therapy alone. However, this intervention included both aquatic exercise and thermal exposure; therefore, the observed effect cannot be attributed exclusively to aquatic exercise. The study nevertheless suggests that thermally enhanced aquatic rehabilitation may represent a potentially useful multimodal approach for selected individuals with chronic low back pain.

The most recent evidence from Montpetit et al. [42] further strengthens the importance of objective muscle outcomes. Aquatic therapy was associated with reductions in intramuscular fat in the gluteus maximus and gluteus medius and significant increases in gluteal strength, although significant increases in gluteal muscle volume were not demonstrated. Both aquatic therapy and standard care improved gluteal strength. These findings suggest that changes in muscle composition and strength may occur without measurable increases in muscle volume and that muscle quality may therefore represent an important outcome domain for future aquatic rehabilitation research.

Relationship Between Treatment Effects and Risk of Bias

The favorable findings across several outcomes should be interpreted in the context of methodological limitations identified by the RoB 2 assessment. Ten of the 11 trials were judged to have some concerns overall, whereas one trial was judged to have a high RoB because of missing outcome data. The most frequent concern related to deviations from intended interventions.

Blinding presents a particular challenge in rehabilitation trials because participants and therapists can rarely be blinded to the exercise environment or treatment allocation. Nevertheless, the absence of participant or therapist blinding does not automatically invalidate a trial. Greater concern arises when knowledge of treatment allocation may influence adherence, co-interventions, expectations, or subjective outcome reporting. This issue is especially relevant for pain, disability, quality of life, and psychological outcomes.

Consequently, greater confidence should be placed in findings that demonstrate consistency across subjective and objective outcomes. For example, improvements in gait performance, balance, strength, aerobic capacity, or imaging-based muscle characteristics may provide complementary evidence to patient-reported outcomes [17,21,41,42]. Conversely, isolated improvements in subjective outcomes should be interpreted cautiously when methodological concerns or substantial differences in intervention exposure exist.

The high RoB identified in Assar et al. [15] further reduces confidence in the precision of that individual study's effect estimates. However, the presence of one high-risk trial does not negate the broader evidence base. Instead, it emphasizes the need for replication using adequately powered randomized trials with robust retention strategies, transparent reporting of missing data, and prespecified methods for handling attrition.

Clinical Implications

The findings support the selective integration of aquatic rehabilitation into individualized rehabilitation programmes rather than routine replacement of conventional land-based therapy. Aquatic interventions may be particularly valuable for patients whose symptoms or functional limitations make conventional weight-bearing exercise difficult, including individuals with painful osteoarthritis, obesity, impaired balance, fear of falling, neurological gait impairment, or reduced exercise tolerance [13-19].

Clinicians should select the aquatic technology according to the patient's primary impairment and treatment goal. Underwater treadmill training may facilitate repetitive gait practice under reduced loading, water-jet resistance may permit progression of task-specific resistance, and pneumatic partial-weight-support systems may allow controlled progression of loading and strengthening [17,19]. Conventional aquatic exercise may remain appropriate when the primary objective is general conditioning, mobility, balance, or symptom management [13,16,18].

The evidence also suggests that exercise intensity should be prescribed individually. High-intensity aquatic interval training can improve aerobic capacity [41], but higher intensity did not produce superior patient-reported outcomes or quality-adjusted life-years compared with moderate-intensity aquatic exercise [20]. Thus, clinicians should avoid equating exercise intensity with therapeutic superiority and instead consider the patient's tolerance, goals, adherence, safety, and functional status.

Objective muscle assessment may also have future clinical value. The findings from Rosenstein et al. and Montpetit et al. indicate that aquatic rehabilitation may influence muscle composition and strength in chronic low back pain [21,42]. However, these findings remain preliminary and do not establish that aquatic therapy produces superior structural adaptations compared with standard care.

Importantly, the available evidence does not justify replacing conventional land-based rehabilitation with aquatic technology in all patients. Rather, aquatic rehabilitation should be considered a complementary intervention that can modify loading conditions, facilitate movement practice, improve exercise tolerance, and provide an alternative training environment when conventional exercise is difficult to perform or poorly tolerated.

Overall, the findings suggest that the clinical role of aquatic rehabilitation is condition- and impairment-specific, with potential advantages related primarily to reduced loading, supported movement, adjustable resistance, and exercise tolerance rather than consistent superiority over conventional land-based rehabilitation.

Strengths of the Evidence

A major strength of the evidence base is that all included studies used randomized controlled designs. Furthermore, the trials evaluated a broad range of clinically relevant outcomes, including pain, physical function, gait, balance, strength, aerobic capacity, quality of life, psychological outcomes, and imaging-based muscle characteristics [13-23, 41, 42].

Another strength is the inclusion of technology-specific interventions. Rather than evaluating aquatic exercise as a completely homogeneous intervention, the included trials provide information regarding underwater treadmill systems, water-jet resistance, pneumatic partial weight support, high-intensity aquatic exercise, conventional aquatic training, and thermally enhanced aquatic rehabilitation [14,17,19,20,23,41]. This allows a more clinically meaningful interpretation of which components may be useful for particular rehabilitation objectives.

The incorporation of objective outcomes in recent trials is also important. MRI-based assessments of paraspinal and gluteal muscle characteristics and objective strength or gait measures provide complementary evidence to subjective outcomes and may help clarify the physiological mechanisms underlying clinical improvement [17,19,21,41,42].

Limitations of the Evidence

Several limitations should be considered when interpreting the findings. First, sample sizes were frequently modest, and intervention durations ranged from relatively short programmes to approximately 16 weeks. Long-term follow-up was uncommon. The AquaHigh study illustrates this limitation particularly well, because the improvement in aerobic capacity observed after 12 weeks was not maintained at six months [41].

Second, substantial clinical and methodological heterogeneity existed across the trials. Participants differed in diagnosis, age, body composition, functional impairment, and baseline exercise capacity. Intervention protocols also differed in water temperature, immersion conditions, exercise intensity, session frequency, treatment duration, treadmill characteristics, unloading percentage, resistance method, and progression strategy. Outcome measures varied similarly, limiting direct comparison between trials.

Third, comparator interventions were not uniform. Some studies compared aquatic interventions with home exercise [14], others with alternative aquatic or technology-assisted approaches [17,19], and others with standard care or conventional physical therapy [21-23,42]. Consequently, an improvement relative to one comparator cannot automatically be generalized to superiority over all conventional rehabilitation approaches.

Fourth, subjective outcomes represented an important component of the evidence base. Pain, disability, quality of life, psychological factors, and perceived improvement are clinically important, but they may be influenced by expectations and treatment experience, particularly when participant blinding is impossible. The inclusion of objective measures in several newer trials is therefore an important methodological development [17,19,21,41,42].

Finally, the evidence for technology-specific superiority remains limited. The available studies generally provide comparisons between selected technologies rather than comprehensive head-to-head comparisons across all available aquatic systems. Therefore, the present findings support individualized technology selection rather than a universal hierarchy of aquatic rehabilitation technologies.

Limitations of the Review Process

The review process has several limitations. The eligibility criteria were restricted to English-language full-text publications, which may have introduced language and publication-selection bias. Although 11 studies were included in the review, the relatively small number of eligible independent RCTs limited the amount of evidence available for synthesis. Although the search strategy was designed to identify relevant evidence

comprehensively, only a limited number of studies met the predefined eligibility criteria. This small evidence base limits the precision and generalizability of the findings and reduces the ability to draw firm conclusions regarding the comparative effectiveness of specific emerging technologies across different clinical populations. Therefore, the findings should be interpreted cautiously, and larger, adequately powered RCTs are needed to strengthen the evidence base.

The clinical and methodological heterogeneity prevented meaningful quantitative pooling. Consequently, a structured narrative synthesis was considered more appropriate than combining clinically incompatible interventions into a single summary effect. Although this approach avoids potentially misleading pooled estimates, it limits statistical precision and prevents direct estimation of an overall treatment effect.

The small number of independent trials also prevented meaningful subgroup analyses according to diagnosis, technology type, exercise dose, age, or treatment setting. Publication bias could not be assessed reliably because of the limited number of independent trials and the absence of sufficient comparable quantitative data.

The evidence base continues to expand beyond pain and functional outcomes. Vaillancourt et al. [22] reported improvements in kinesio phobia and sleep disturbance, Qin et al. [23] found additional benefits from aquatic exercise combined with hot-spring bathing, and Montpetit et al. [42] demonstrated reductions in intramuscular fat and improved gluteal strength. Together, these findings broaden the potential effects of aquatic rehabilitation while supporting the need for continued evidence synthesis.

Implications for Future Research

Future research should prioritize adequately powered, multicentre RCTs with larger sample sizes and medium- and long-term follow-up of at least 12 months. Studies should use transparent reporting of allocation procedures, adherence, protocol deviations, missing data, adverse events, and co-interventions. Trials should also report sufficient intervention detail, including technological parameters and progression criteria, to allow replication and comparison across studies. Larger samples would improve statistical precision, enhance the generalizability of findings, and provide greater confidence in estimates of the effectiveness and safety of emerging aquatic rehabilitation technologies.

Standardized reporting of aquatic rehabilitation parameters is particularly important. Future studies should clearly describe water temperature, immersion depth, session duration, frequency, exercise intensity, treadmill speed, unloading percentage, resistance intensity, progression criteria, and adherence. Standardization would facilitate comparison between trials and increase the feasibility of future quantitative synthesis.

Future studies should combine patient-reported outcomes with objective measures. Pain and disability measures should ideally be accompanied by gait analysis, functional performance tests, dynamometry, wearable-sensor measurements, cardiopulmonary outcomes, or imaging where appropriate. The recent use of MRI-based assessment of paraspinal and gluteal muscle characteristics provides a useful model for investigating biological adaptations alongside conventional clinical outcomes [21,42].

Direct technology-to-technology comparisons are another priority. Future trials should determine whether underwater treadmill training, pneumatic partial weight support, water-jet resistance, high-intensity aquatic exercise, and thermally enhanced aquatic interventions produce superior, equivalent, or clinically distinct outcomes compared with conventional aquatic and land-based rehabilitation. Such studies should be adequately powered to test between-group differences rather than relying primarily on within-group changes.

Further research should also investigate treatment dose and patient selection. Important questions include which patients benefit most from aquatic rehabilitation, whether baseline obesity, pain severity, balance impairment, fear of movement, or muscle weakness modifies treatment response, and what duration and frequency of treatment are required to maintain benefits.

The relationship between changes in muscle morphology, muscle composition, strength, and functional outcomes also warrants further investigation. The findings of Rosenstein et al. and Montpetit et al. suggest that muscle composition and strength may change following aquatic rehabilitation without corresponding increases in muscle volume [21,42]. Longitudinal studies incorporating imaging, strength assessment, pain, disability, and functional performance could clarify whether improvements in muscle quality mediate improvements in patient-reported outcomes.

Finally, emerging approaches such as wearable-sensor-guided exercise prescription, artificial intelligence-assisted rehabilitation, virtual reality, robotic assistance, and sensor-integrated aquatic training warrant prospective clinical validation. These technologies should not be recommended routinely until adequately powered clinical trials establish their effectiveness, safety, feasibility, cost-effectiveness, and comparative clinical value.

Overall Interpretation

Overall, the randomized evidence suggests that aquatic rehabilitation is a promising and clinically relevant adjunct to conventional rehabilitation across selected musculoskeletal and neurological populations [13-23, 41, 42]. The most consistent evidence concerns improvements in pain, physical function, gait, balance, and selected measures of strength and aerobic capacity. However, the evidence does not demonstrate consistent superiority of technology-enhanced aquatic rehabilitation over conventional exercise or standard care.

The findings from the underwater treadmill, water-jet resistance, pneumatic partial-weight-support, and AquaHigh studies indicate that different technologies may influence different aspects of rehabilitation [17,19,20,41]. At the same time, the chronic low back pain studies demonstrate that aquatic rehabilitation may produce improvements in psychological outcomes, muscle composition, strength, and functional measures, although these effects are not uniformly superior to standard care [21-23,42].

Therefore, the most defensible clinical interpretation is that technology-enhanced aquatic rehabilitation should be viewed as an individualized and complementary rehabilitation strategy rather than a replacement for conventional therapy. Its principal value may lie in its ability to modify loading, resistance, exercise intensity, and movement conditions according to patient needs. Future research should move beyond the question of whether aquatic rehabilitation is effective and determine which technology is most appropriate for which patient, at what dose, for which impairment, and with what long-term clinical benefit.

Conclusions

Technology-enhanced aquatic rehabilitation demonstrates clinically meaningful benefits across a range of musculoskeletal and neurological conditions, with the strongest evidence supporting its use for knee osteoarthritis, chronic low back pain, and post-stroke gait dysfunction. Interventions supported by fair-to-good methodological quality (as assessed via RoB 2), specifically underwater treadmill exercise, pneumatic partial weight-support treadmill systems, water-jet resistance gait training, and structured aquatic high-intensity interval training approaches improve pain, physical function, gait, balance, quality of life, and, in select cases, objective paraspinal and gluteal muscle morphology. Additional benefits, including reductions in Kinesio phobia and sleep disturbance, have been documented in chronic low back pain populations.

However, the field remains constrained by modest sample sizes, predominant short-term intervention durations (four to 16 weeks), inconsistent reporting of technological parameters (pool temperature, immersion depth, resistance settings, and treadmill speeds), heterogeneous comparator conditions, and limited long-term follow-up data. More advanced technologies, including sensor-driven, exoskeleton-assisted, and computationally integrated aquatic rehabilitation systems, remain at the early stages of development and lack sufficient randomized controlled trial validation.

Future research must prioritize standardized technological parameter reporting, adequately powered trials with medium- and long-term follow-up (minimum 12 months), direct head-to-head comparative designs between active technologies, and prospective clinical validation of next-generation systems. Until these gaps are addressed, clinical implementation should focus on the technologies with existing trial validation underwater treadmills, pneumatic unloading devices, water-jet resistance systems, and structured aquatic high-intensity protocols while maintaining awareness of their context-specific advantages and limitations.

Appendices

Database-specific search strategies

Search concepts stated in the manuscript: aquatic rehabilitation; aquatic therapy; hydrotherapy; underwater treadmill; water-jet resistance; partial weight support; aquatic high-intensity interval training; technology; knee osteoarthritis; low back pain; stroke; and musculoskeletal disorders.

PubMed/MEDLINE

("Aquatic Therapy"[MeSH Terms] OR "Hydrotherapy"[MeSH Terms] OR "aquatic rehabilitation" [Title/Abstract] OR "aquatic therapy"[Title/Abstract] OR hydrotherapy[Title/Abstract] OR "underwater treadmill"[Title/Abstract] OR "water-jet resistance"[Title/Abstract] OR "partial weight support" [Title/Abstract] OR "aquatic high-intensity interval training"[Title/Abstract]) AND (technology[Title/Abstract] OR treadmill[Title/Abstract] OR resistance[Title/Abstract] OR structured[Title/Abstract] OR training[Title/Abstract]) AND ("knee osteoarthritis"[Title/Abstract] OR "low back pain"[Title/Abstract] OR stroke[Title/Abstract] OR "musculoskeletal disorders"[Title/Abstract])

Scopus

TITLE-ABS-KEY(("aquatic rehabilitation" OR "aquatic therapy" OR hydrotherapy OR "underwater treadmill" OR "water-jet resistance" OR "partial weight support" OR "aquatic high-intensity interval training") AND (technology OR treadmill OR resistance OR structured OR training) AND ("knee osteoarthritis" OR "low back

pain" OR stroke OR "musculoskeletal disorders"))

Web of Science

TS=(("aquatic rehabilitation" OR "aquatic therapy" OR hydrotherapy OR "underwater treadmill" OR "water-jet resistance" OR "partial weight support" OR "aquatic high-intensity interval training") AND (technology OR treadmill OR resistance OR structured OR training) AND ("knee osteoarthritis" OR "low back pain" OR stroke OR "musculoskeletal disorders"))

Embase

("aquatic rehabilitation" OR "aquatic therapy" OR hydrotherapy OR "underwater treadmill" OR "water-jet resistance" OR "partial weight support" OR "aquatic high-intensity interval training") AND (technology OR treadmill OR resistance OR structured OR training) AND ("knee osteoarthritis" OR "low back pain" OR stroke OR "musculoskeletal disorders")

Cochrane Library

("aquatic rehabilitation" OR "aquatic therapy" OR hydrotherapy OR "underwater treadmill" OR "water-jet resistance" OR "partial weight support" OR "aquatic high-intensity interval training") AND (technology OR treadmill OR resistance OR structured OR training) AND ("knee osteoarthritis" OR "low back pain" OR stroke OR "musculoskeletal disorders")

Database	Search strategy	Records identified (n)
PubMed/MEDLINE	("Aquatic Therapy"[MeSH Terms] OR "Hydrotherapy"[MeSH Terms] OR "aquatic rehabilitation"[Title/Abstract] OR "aquatic therapy"[Title/Abstract] OR hydrotherapy[Title/Abstract] OR "underwater treadmill"[Title/Abstract] OR "water-jet resistance"[Title/Abstract] OR "partial weight support"[Title/Abstract] OR "aquatic high-intensity interval training"[Title/Abstract]) AND (technology[Title/Abstract] OR treadmill[Title/Abstract] OR resistance[Title/Abstract] OR structured[Title/Abstract] OR training[Title/Abstract]) AND ("knee osteoarthritis"[Title/Abstract] OR "low back pain"[Title/Abstract] OR stroke[Title/Abstract] OR "musculoskeletal disorders"[Title/Abstract])	33
Scopus	TITLE-ABS-KEY(("aquatic rehabilitation" OR "aquatic therapy" OR hydrotherapy OR "underwater treadmill" OR "water-jet resistance" OR "partial weight support" OR "aquatic high-intensity interval training") AND (technology OR treadmill OR resistance OR structured OR training) AND ("knee osteoarthritis" OR "low back pain" OR stroke OR "musculoskeletal disorders"))	119
Web of Science	TS=(("aquatic rehabilitation" OR "aquatic therapy" OR hydrotherapy OR "underwater treadmill" OR "water-jet resistance" OR "partial weight support" OR "aquatic high-intensity interval training") AND (technology OR treadmill OR resistance OR structured OR training) AND ("knee osteoarthritis" OR "low back pain" OR stroke OR "musculoskeletal disorders"))	13
Embase	("aquatic rehabilitation" OR "aquatic therapy" OR hydrotherapy OR "underwater treadmill" OR "water-jet resistance" OR "partial weight support" OR "aquatic high-intensity interval training") AND (technology OR treadmill OR resistance OR structured OR training) AND ("knee osteoarthritis" OR "low back pain" OR stroke OR "musculoskeletal disorders")	23
Cochrane Library	("aquatic rehabilitation" OR "aquatic therapy" OR hydrotherapy OR "underwater treadmill" OR "water-jet resistance" OR "partial weight support" OR "aquatic high-intensity interval training") AND (technology OR treadmill OR resistance OR structured OR training) AND ("knee osteoarthritis" OR "low back pain" OR stroke OR "musculoskeletal disorders")	4
Total		192

TABLE 5: Database-specific search strategies

Search period: Database inception to July 12, 2026.

MeSH, Medical Subject Headings; TITLE-ABS-KEY, title, abstract, and keywords fields in Scopus; TS, Topic Search in Web of Science; AND, intersection of search concepts; OR, alternative search terms

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

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Acquisition, analysis, or interpretation of data: Sandeep Shinde, Amal P. Zacharia, David P. Binu, Mebin S. Thomas

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Conflicts of interest: In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

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