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Rehabilitation during extracorporeal membrane oxygenation: bridging the gap between life support and functional recovery

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Rehabilitation during extracorporeal membrane oxygenation (ECMO) has become a promising intervention to mitigate the profound physical and functional decline that occurs with prolonged critical illness. With the wider adoption of ECMO, interest has grown in integrating early mobilization into routine care practices to preserve muscle mass, reduce intensive care unit-acquired weakness, and improve long-term patient outcomes. Emerging observational data indicate that structured rehabilitation protocols—including passive and active mobilization—are feasible and safe, including for individuals undergoing femoral cannulation. Nevertheless, multiple obstacles, including patient instability, technical constraints, staffing limitations, and gaps in clinical knowledge, impede broader implementation. Although the theoretical rationale and initial data are compelling, further robust randomized controlled trials are essential to establish the definitive efficacy, best-practice protocols, and cost-effectiveness of rehabilitation interventions in ECMO-supported patients.

Key Words: early ambulation; extracorporeal membrane oxygenation; muscle weakness; physical therapy modalities; rehabilitation

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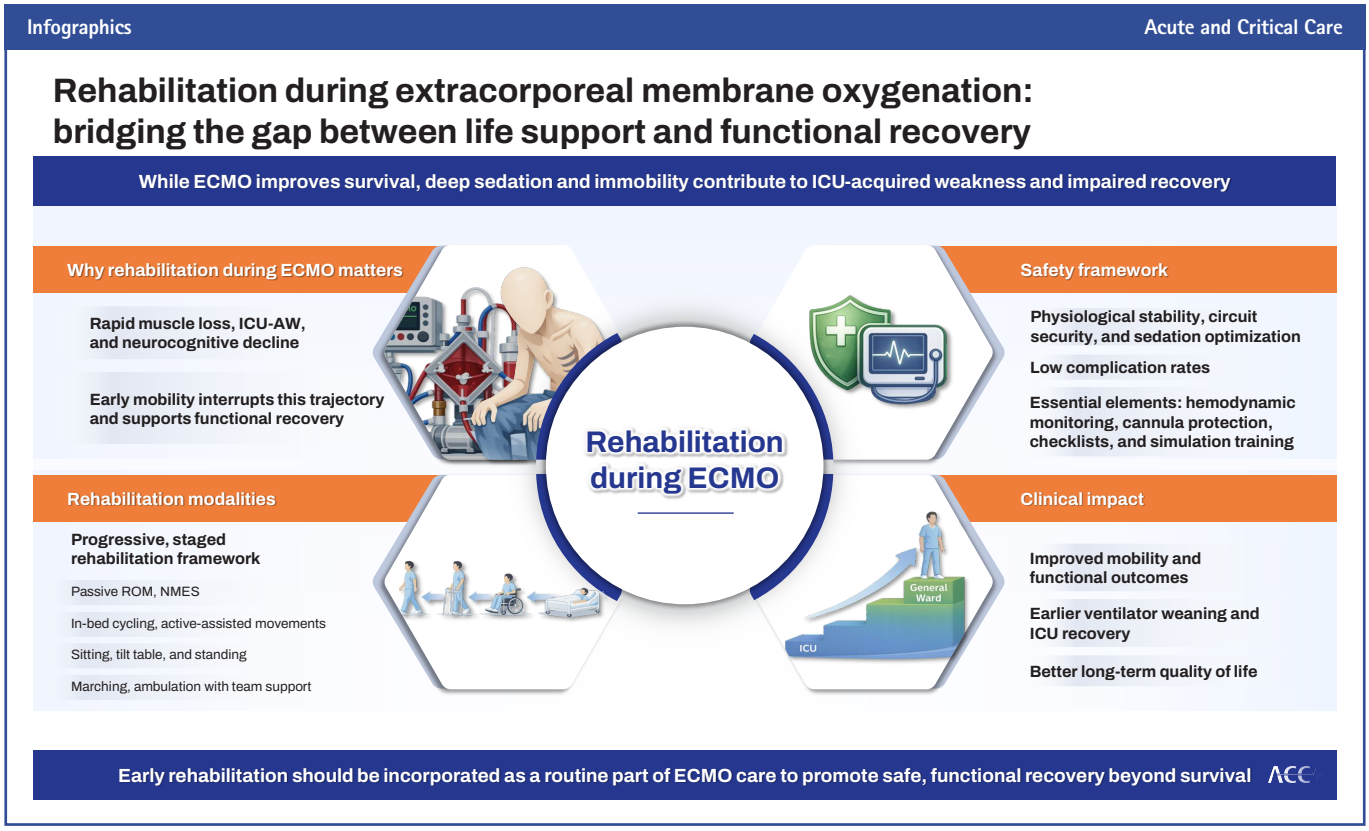
INTRODUCTION

Extracorporeal membrane oxygenation (ECMO) is a life-saving therapy that delivers temporary cardiopulmonary support to patients with refractory cardiac or respiratory failure. Its use has become increasingly common in intensive care units (ICU) worldwide [1-4]. While ECMO can improve survival rates in selected patients, it often necessitates deep sedation and prolonged immobilization, resulting in extended ICU stays. These factors contribute to severe muscle wasting, ICU-acquired weakness (ICU-AW), and post-intensive care syndrome [5-8],



which can impair functional outcomes, limit independence after discharge, and increase long-term morbidity [9-11].

Historically, patients supported by ECMO have been managed with strict bed rest and heavy sedation to minimize the risk of circuit interruption or cannula-related complications [12]. However, advancements in circuit stability and the adoption of "awake" critical care practices have led to a shift in management. Early mobilization is now recognized as a feasible and safe adjunct to ECMO support [13-16]. Building on early case reports of ambulation during ECMO, recent cohort studies and systematic reviews increasingly support a proactive approach to physical rehabilitation in this population [16-21].

This evolution in care reflects a broader understanding that survival alone is insufficient. Restoration of functional ability, cognition, and quality of life has become the central goal of ICU care. Accordingly, rehabilitation during ECMO is increasingly regarded as the standard of care for appropriately selected patients. International centers and consensus statements have begun to formalize early mobilization protocols, while accumulating evidence suggests potential benefits, including improvements in functional status, mechanical ventilation (MV) duration, and discharge outcomes [15,16,20,21].

This narrative review synthesizes current knowledge and practices related to rehabilitation during ECMO. It summarizes the underlying pathophysiologic rationale, reviews safety and feasibility data, outlines patient selection strategies, describes rehabilitation modalities and staged progression, and presents evidence for outcome benefits. Additionally, barriers to implementation are discussed, and future research priorities are identified to optimize and standardize ECMO rehabilitation across diverse clinical settings.

LITERATURE SEARCH STRATEGY

A structured literature search was performed in PubMed using two queries: (1) "Extracorporeal membrane oxygenation" AND "rehabilitation." (2) "Extracorporeal membrane oxygenation" AND "mobilization." Only English-language studies of adults (≥19 years) published from January 2014 to December 2024 were included. Reference lists of the retrieved articles were reviewed to identify additional studies. Two authors independently screened titles, abstracts, and the full text to

resolve discrepancies by consensus. Eligible studies reported clinical outcomes related to rehabilitation during ECMO, including randomized controlled trials (RCTs), observational studies, or case series. Pediatric studies, reviews, editorials, conference abstracts, and letters were excluded. This review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines; the selection process is detailed in Figure 1.

PATHOPHYSIOLOGIC RATIONALE FOR REHABILITATION DURING ECMO

Patients receiving ECMO therapy often experience profound physical deconditioning due to severe illness, prolonged immobility, deep sedation, and systemic inflammation [5,22-24]. Extended periods of immobility and MV rapidly lead to muscle atrophy, particularly of the postural and lower-limb musculatures, while sedatives further compromise voluntary muscle activation and neuromuscular function [25-27]. In addition, inflammation associated with ECMO and critical illness accelerates muscle breakdown via increased proteolysis, mitochondrial dysfunction, and insulin resistance [27-29]. Consequently, skeletal muscle catabolism is hastened, delaying the restoration of patient functional independence [30,31].

This constellation of physiologic disturbances contributes to ICU-AW, which affects up to 50% of critically ill patients and is associated with higher mortality, prolonged MV, and diminished post-discharge quality of life [7,8,32,33]. ICU-AW presents as diffuse muscle wasting and reduced contractility, placing patients on ECMO—especially those requiring prolonged MV support—at notably increased risk [34]. Diagnostic imaging, such as ultrasound or computed tomography (CT) scans, has documented substantial muscle loss within 5–10 days of critical illness, particularly without early mobilization or adequate nutrition [35-37].

Immobility also impairs cardiovascular and pulmonary function; sustained recumbency results in venous stasis, weakened respiratory musculature, and decreased cardiac preload, thereby complicating ECMO and MV weaning [38-40]. Restricted mobility predisposes patients to pressure injuries, joint contracture, and musculoskeletal stiffness, further hindering recovery post-decannulation [41,42]. While prolonged sedation and immobility increased the risk of delirium, cognitive impairment, and post-intensive care syndrome [43-46], early initiation of rehabilitation may mitigate neurocognitive complications. Specifically, it fosters wakefulness, establishes healthier sleep–wake cycles, and facilitates meaningful physical activity.

Overall, the rationale for rehabilitation during ECMO centers on addressing the multifactorial pathophysiology driving ICU-acquired debilitation. A recent expert consensus indicates

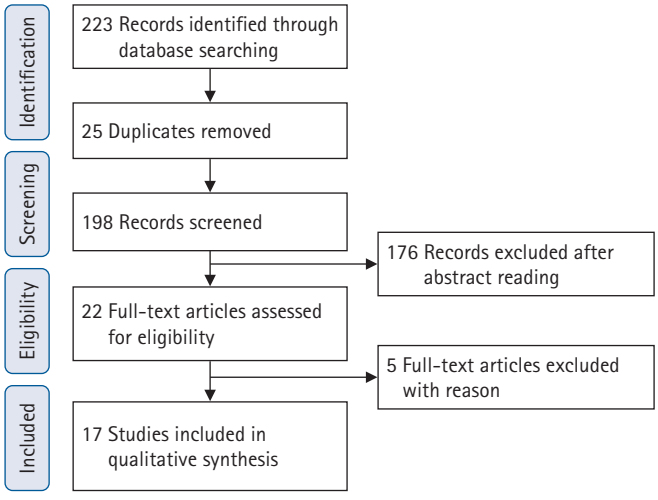


Figure 1. Study flow diagram of literature selection for extracorporeal membrane oxygenation rehabilitation studies. Flow diagram illustrating the structured literature search and selection process for studies on rehabilitation during extracorporeal membrane oxygenation.

KEY MESSAGES

- Early rehabilitation during extracorporeal membrane oxygenation (ECMO) is practical and safe when implemented by trained multidisciplinary teams, including in patients undergoing femoral cannulation, potentially reducing intensive care unit-acquired weakness and promoting functional recovery.
- Observational data suggest improved mobility, reduced intensive care unit stays, and improved discharge outcomes, although robust randomized trials are warranted.
- Structured rehabilitation protocols that integrate staged mobilization, sedation minimization, and patient-centered goals are becoming a widely accepted standard of care, bridging survival with long-term quality of life in ECMO-supported patients.

that even low-intensity, in-bed exercise can counteract functional decline [15,16]. Early intervention supports recovery by preserving muscle mass, range of motion (ROM), and pulmonary function.

Emerging evidence suggests that rehabilitation positively influences metabolic and inflammatory pathways. Studies in critically ill populations indicate that physical activity improves insulin sensitivity, reduces cytokine levels (e.g., interleukin [IL]-6, tumor necrosis factor-α), and stimulates anabolic signaling in skeletal muscle following physical activity [17,47-49]. Although ECMO-specific data remain limited, these findings suggest that early rehabilitation may help attenuate catabolism, inflammation, and mitochondrial dysfunction—key drivers of ICU-AW and delayed recovery.

FEASIBILITY AND SAFETY OF REHABILITATION DURING ECMO

Early rehabilitation for patients undergoing ECMO has evolved from an experimental approach to a structured clinical practice in specialized centers. Initial safety concerns about mobilizing these patients have been alleviated by studies showing that, with careful selection and coordinated teamwork, rehabilitation is feasible and safe [9,10,17,50-52]. Physical therapy interventions—ranging from passive ROM and in-bed exercises to sitting, standing, and selected ambulation—are associated with a low incidence of complications [17,53,54]. For example, one retrospective study of 607 physical therapy sessions among 167 patients on ECMO (80% with at least one femoral cannula and 40% with bifemoral cannulation) reported only three minor events (two arrhythmias and one transient hypotension) and no major events, such as cannula dislodgment or bleeding [53]. Similarly, a pilot randomized trial that initiated goal-directed physiotherapy within 72 hours of cannulation increased total mobilization time during the first week without serious adverse events and only infrequent minor events [54]. Another large cohort study found that 78% of the patients (138/177) achieved out-of-bed activity and 61% (108/177) ambulated during ECMO support, with adverse events occurring in only 2% of active rehabilitation sessions (54/2,700) and no documented cannula dislodgement [17].

The success and safety of rehabilitation are closely tied to the expertise of the multidisciplinary team, comprising intensivists, physiotherapists, perfusionists, ICU nurses, and respiratory therapists, each performing a predefined role during mobilization [15,55,56]. Implementing structured safety checklists ensures hemodynamic stability, maintains cannula security, and facilitates continuous monitoring of vital signs and ECMO circuit parameters [15,16,55]. Simulation-based training further strengthens team readiness for rare but potentially catastrophic events, such as cannula dislodgment or circuit failure, improving coordination and crisis management. Indeed, high-volume centers have reported thousands of successful mobilization sessions without catastrophic complications, even among patients undergoing venoarterial (VA) ECMO with femoral cannulation [16,17,53].

In summary, early rehabilitation during ECMO is achievable and safe when guided by structured protocols and experienced teams. While some cases warrant caution, such as those involving femoral cannulation or vasoactive therapy, these factors should not automatically preclude mobilization with appropriate adherence to safety criteria and continuous monitoring.

Quantitative Safety Evaluation

Upon mobilization initiation, ECMO rehabilitation safety must be assessed and documented using standardized quantitative metrics rather than descriptive reports. Key indicators should include the frequency of adverse events per 100 sessions stratified by the mobilization phase and cannulation configuration. Adverse events—such as transient desaturation, hypotension requiring vasopressor escalation, arrhythmia requiring intervention, or circuit-related incidents—should be graded as minor or major. Rates and specific reasons for terminating sessions, like physiologic instability, circuit alarms, bleeding, or agitation, must be thoroughly documented. Tracking physiological drifts during activity, such as an oxygen desaturation of 10% or more, mean arterial pressure (MAP) below 60 mm Hg, or new arrhythmias, offers useful real-time data regarding patient tolerance. Additional process indicators, such as checklist completion, staffing composition, and the frequency of device alarms per session, reflect team adherence to safety protocols. Consistent, reliable reporting across these parameters enables comparison among centers and supports a reproducible framework for evaluating ECMO rehabilitation safety.

PATIENT SELECTION AND SCREENING STRATEGIES

Not all patients receiving ECMO are eligible for active rehabilitation or mobilization. Careful patient selection and structured screening are essential to ensure safety and to achieve optimal outcomes. Research highlights the value of a gradual approach that starts with passive movements and slowly progresses toward active mobilization and ambulation [15,21,55].

Physiological Stability

Physiologic stability is the primary prerequisite for initiating rehabilitation during ECMO. Mobilizing patients without sufficient cardiovascular and respiratory stability may lead to hemodynamic collapse, severe hypoxemia, or circuit-related complications. Patients should demonstrate stable ECMO flow and sweep gas parameters to achieve adequate oxygenation and carbon dioxide clearance. Oxygen saturation levels should be maintained above institution-defined thresholds, generally exceeding 90%, although requirements may vary based on underlying pathology and specific circuit configurations [57]. Hemodynamic stability is also essential, and is most often achieved by maintaining MAP within an appropriate range, with low-to-moderate vasopressors support. Most centers consider norepinephrine doses of ≤0.1–0.2 μg/kg/min or equivalent to be acceptable [57,58].

Before mobilization, metabolic and hematological parameters—including hemoglobin, lactate, and electrolyte levels—must be optimized. Particular attention must be given to coagulation status; active bleeding or uncorrected coagulopathy are commonly regarded as absolute contraindications [15,57]. Due to the dynamic nature of patient stability, frequent reassessment is necessary. A patient deemed stable in the morning may become unstable due to bleeding, infection, arrhythmia, or circuit malfunction. Hence, reassessment before, during, and after mobilization procedures is integral to safe practice.

Cannulation Configuration

The cannulation site and type significantly influence rehabilitation outcomes. Jugular or subclavian cannulas, particularly dual-lumen options such as the Avalon Elite Bi-Caval Dual-Lumen Catheter (Maquet Cardiopulmonary), facilitate early rehabilitation as they do not restrict the lower extremities [59,60]. Traditionally, mobilization has been considered unsuitable in patients with femoral cannulation—particularly those with bifemoral VA-ECMO—due to concerns regarding dislodgement and limb ischemia. However, recent data challenge this assumption. Wells et al. [53] reported that among 167 patients on ECMO (80.2% with at least one femoral cannula), bed-to-chair transfer and ambulation were performed safely, with only minor events. Similarly, Pasrija et al. [61] found that 15/104 (14%) patients with femoral VA-ECMO ambulated without major complications, initiating mobilization at a median of 4 days post-cannulation. Thus, with meticulous cannula management, use of distal perfusion catheters, and close multidisciplinary coordination, active rehabilitation is achievable—even for patients traditionally considered high risk.

Neurological and Sedation Status

Neurological status and sedation depth decisively determine participation in rehabilitation. Although passive ROM exercises are possible in deeply sedated patients, active mobilization requires adequate alertness and cooperation. One international survey of venovenous (VV) ECMO centers found that 59% used deep sedation after cannulation, while only 25% aimed for patients to remain "calm and cooperative." Although 84% offered physical therapy, only 41% initiated it within 72 hours of cannulation [12]. Deep sedation tended to delay or prevent early rehabilitation; Abrams et al. [55] emphasized that "awake ECMO," which is characterized by lighter sedation, is critical for ambulation in conventional and transplant populations. Others observed that active mobilization—achieving an Intensive Care Unit Mobility Scale (IMS) score of at least 3—occurred in 37% of patients on extracorporeal life support (ECLS) and on 26.7% of total ECLS days, despite most having femoral cannulation (93.9%). Documented reasons for non-mobilization included sedation with a Richmond Agitation-Sedation Scale (RASS) ≤–2 (65.0%), coma without sedation (4.6%), and agitation with RASS ≥2 (2.7%), underscoring sedation depth and neurological dysfunction as key barriers to rehabilitation [62].

To address these challenges, many centers have adopted daily sedation minimization or interruption protocols that enable active patient participation while maintaining safety [6,63]. Overall, lighter sedation and preserved neurological responsiveness are prerequisites for successful ECMO rehabil-

itation. Regular sedation assessment and structured weaning protocols expand opportunities for active participation.

Multidisciplinary Screening Process

In established ECMO centers, patient rehabilitation is typically coordinated by a structured multidisciplinary team, including intensivists, ECMO specialists, physiotherapists, ICU nurses, respiratory therapists, and occupational therapists to ensure a holistic evaluation of each patient's readiness for activity. One study described a dedicated rehabilitation team that assessed ECMO patients daily, 6 days per week, and set individualized mobility targets ranging from passive exercises to ambulation [9]. Comparable benefits have been observed in mechanically ventilated cohorts, where structured multidisciplinary rounds increased early mobilization rates from 9.3% to 33.8%, and reduced the time to first activity from 6 days to 3 days [64]. During multidisciplinary rounds, the team collectively reviewed each patient's hemodynamic, respiratory, and neurological stability, along with other available resources, to determine suitable rehabilitation intensity. These coordinated rounds are critical to the success of ECMO rehabilitation. By integrating physiologic assessments, equipment checks, and logistic coordination, the team ensures safety, timeliness, and individualized progression.

Common Eligibility and Exclusion Criteria

Table 1 provides an overview of the prevailing eligibility criteria and both relative and absolute exclusion factors, derived from key studies and established guidelines [56,57]. This summary is designed to support clinical teams in conducting structured and standardized screening during daily rehabilitation assessments.

REHABILITATION MODALITIES AND STAGED PROGRESSION

Once a patient is deemed eligible for rehabilitation, focus shifts to choosing suitable interventions. For individuals on ECMO, rehabilitation typically follows a structured and staged approach, progressing from passive exercise to active mobilization depending on clinical stability and individual tolerance. This step-by-step progression supports personalized progress when minimizing risk, particularly for patients with limited physiological reserves.

Staged Rehabilitation Framework

Rehabilitation programs generally apply a stepwise framework (Table 2). They begin with passive or active-assisted ROM exercises and in-bed cycle ergometry. Once patients stabilize, rehabilitation advances to sitting at the edge of the bed (EOB), then standing, marching in place, and ambulating, if tolerated [57]. Session duration typically ranges from 20 to 60 minutes, depending on patient tolerance, with frequent rest periods [57,62]. Most centers provide daily or twice-daily sessions, adjusting activities based on hemodynamic, respiratory, and neurological feedback. This progressive framework is designed to optimize functional recovery while minimizing risk during rehabilitation. To enhance clinical applicability, the framework incorporates explicit entry criteria and predefined stop criteria for each stage. These safety checkpoints guide clinicians in safely progressing patients through each rehabilitation phase and determining when activities should be paused or stopped.

Passive and Assisted Interventions

Rehabilitation for sedated, critically ill patients typically begins with passive ROM exercises, continuous passive motion devices, limb positioning, and joint contracture prevention [51,62]. Assisted techniques, such as manual facilitation, positioning aids, and tilt adjustment, help promote circulation and joint mobility in patients incapable of independent, voluntary movements. Neuromuscular electrical stimulation (NMES) is a valuable adjunctive therapy for patients unable to engage in active rehabilitation. It delivers low-frequency electrical currents to the major muscle groups—typically the quadriceps, gastrocnemius, and gluteus maximus—to induce visible muscle contractions and preserve muscle mass [65-67]. Small clinical series have suggested that NMES during ECMO may reduce skeletal muscle atrophy, enhance local microcirculation, and improve tissue oxygen extraction without significantly affecting systemic hemodynamics. It can also serve as a bridge to active rehabilitation once patients regain consciousness or strength [68].

Despite these potential advantages, NMES usage varies across ECMO centers due to equipment availability, staff training, and access to standardized procedures. Larger multicenter studies are needed to define optimal stimulation parameters, treatment frequency, and candidate selection.

Table 1. Eligibility and exclusion criteria for ECMO rehabilitation

Category	Inclusion criteria	Exclusion criteria (relative or absolute)
Hemodynamic stability	1. Stable ECMO flow and sweep gas 2. Heart rate: 40–150 bpm 3. SBP: 80–180 mm Hg 4. MAP ≥65 mm Hg with low to moderate vasopressor support	1. Escalating vasopressor needs in the last 12 hr 2. High doses of inotropes and vasopressors 3. MAP persistently <65 mm Hg
Respiratory status	Acceptable oxygenation and ventilation 1. FiO_2 <0.6, PEEP <10 cm H_2O 2. SpO_2 >90% 3. pO_2 >60 mm Hg 4. pCO_2 <80 mm Hg (pH >7.25) 5. RR <30/min	Severe hypoxemia or hypercapnia unresponsive to ECMO adjustments
Neurological status	Arousable or awake for active rehabilitation; adequate response on sedation scales (e.g., RASS −1 to +1)	Deep sedation or coma preventing purposeful interaction; uncontrolled delirium
Cannulation status	Securely fixed cannulas; no signs of dislodgement or local complications	Cannula instability, recent cannulation without secure fixation, local infection, or active bleeding
Bleeding risk	No major active bleeding; stable anticoagulation profile	Active bleeding, recent high-risk procedures, or severe coagulopathy
Cardiopulmonary reserve	Adequate cardiac and pulmonary reserve to tolerate mild to moderate exercise demand	Uncontrolled arrhythmias, acute myocardial ischemia, severe pulmonary hypertension
Device compatibility	Compatible ventilator and ECMO equipment for mobilization; manageable number of infusion lines and devices	Multiple critical or unstable device making safe mobilization technically infeasible
Team and resources	Available multidisciplinary team including intensivists, nurses, physiotherapists, perfusionists; access to necessary equipment and monitoring resources	Lack of adequately trained staff, monitoring limitations, or absence of emergency preparedness protocol

ECMO: extracorporeal membrane oxygenation; SBP: systolic blood pressure; MAP: mean arterial pressure; PEEP: positive end-expiratory pressure; RR: respiratory rate; RASS: Richmond Agitation-Sedation Scale.

In-bed and Early Upright Mobilization

As patients stabilize, rehabilitation progresses to active-assisted and active exercises, including in-bed cycle ergometry and bedside sitting [53,57]. Integrating a cycle ergometer into ECMO care is increasingly common and has proven effective for mitigating lower limb muscle atrophy [53,57,69]. Ergometers can be used in passive, active-assisted, or active-resisted modes depending on the patient's condition, and can be initiated as early as the first few days of ECMO support. The device allows individualized adjustment of intensity and duration, targeting aerobic conditioning and muscle engagement without compromising hemodynamic stability [69].

Sitting at the EOB is one of the earliest upright activities in ECMO rehabilitation and is used to assess postural control, muscle strength, and hemodynamic tolerance [14,19,70]. This position promotes pulmonary expansion, facilitates secretion clearance, and helps recondition the trunk and lower limb muscles. Indeed, EOB sitting is achievable in most awake ECMO patients when a trained team applies careful cannula management and hemodynamic monitoring [39,53,61,62].

Once sitting balance is achieved, rehabilitation advances to balance training, weight-shifting, bed-to-chair transfers, and gradual weight-bearing exercises [15,16]. For patients unable to stand independently, tilt-table and assisted standing devices enable progressive verticalization and full weight-bearing while maintaining safety and comfort. Importantly, tilt table mobilization supports early upright posture and recovery without compromising ECMO circuits or cannula security [71,72]. In smaller or less-experienced centers, tilting beds offer a promising solution to overcome logistical barriers and promote early mobilization, thus improving outcomes across diverse ECMO settings.

Advanced Upright Mobilization and Ambulation

In selected patients undergoing ECMO, upright mobilization may progress to standing, marching in place, and ambulation. Turner et al. [19] reported three lung-transplant candidates who ambulated while on ECMO within one week post-surgery. Similarly, in a large observational study comprising 177 patients on ECMO and 2,700 active physical therapy sessions,

Table 2. Staged rehabilitation approach during ECMO

Stage	Rehabilitation target	Key intervention	Entry criteria	Stop criteria
Phase 1: Passive	Sedated or unconscious patients	Passive ROM, NMES, limb positioning, contracture prevention	· Hemodynamically stable (MAP ≥65 mm Hg with low-moderate vasopressor) · Ventilator FiO_2 ≤0.6 with SpO_2 ≥88% · RASS −5 to −2	· MAP <60 mm Hg or ≥ 20% drop · New arrhythmia · SpO_2 <85% or RR >40/min · ECMO flow fluctuation >0.5 L/min
Phase 2: Active-assisted	Patients emerging from sedation with preserved motor function and minimal cognitive responsiveness	In-bed cycle ergometry (passive/active), assisted sitting on edge of bed	· Able to follow simple commands · RASS −1 to +1 · Maintain MAP ≥65 mm Hg with stable vasopressor dose	· Increased work of breathing · Tachycardia >130/min · Patient distress or agitation
Phase 3: Early upright mobilization	Patients with sitting balance	Independent sitting on edge of bed, tilt-table, weight shifting, bed-to-chair transfers, assisted standing	· Able to maintain sitting balance ≥5 sec · No cannulation restriction	· Orthostatic hypotension symptoms · Cannula tension or oozing
Phase 4: Advanced upright mobilization	Fully awake, cooperative, hemodynamically stable patients	Standing, marching in place, ambulation with assistive devices	· Secure cannula (preferable non-femoral or single femoral) · Able to stand with minimal assistance	· Any sign of cannula traction · Chest pain, neurologic change

ECMO: extracorporeal membrane oxygenation; ROM: range of motion; NMES: neuromuscular electrical stimulation; MAP: mean arterial pressure; RASS: Richmond Agitation-Sedation Scale; RR: respiratory rate.

Abrams et al. [17] reported that 85% of patients stood at least once during ECMO support and 47% ambulated—including 34 with femoral cannulas—with a median maximum walking distance of 113 m. These findings demonstrate that meaningful upright activity is achievable with coordinated multidisciplinary supervision, meticulous cannula management, real-time hemodynamic and circuit monitoring, and assistive devices, such as harnesses or walkers, to reduce fall risk and cannula-related complications.

Safety-First Algorithm for ECMO Rehabilitation

Rehabilitation during ECMO should prioritize both patient and circuit safety. Using the defined determinants, a structured, safety-first algorithm integrates key parameters—including physiological stability, sedation depth, ECMO flow parameters, and cannulation configuration—and outlines the daily reassessment elements needed to determine when previously unsuitable patients have become stable enough to begin rehabilitation. This framework provides a practical guide for multidisciplinary teams to assess readiness, determine mobilization intensity, and identify the need to pause or stop activity in the event of hemodynamic, respiratory, or circuit instability (Figure 2).

EVIDENCE OF OUTCOME BENEFITS

Emerging evidence suggests early rehabilitation during ECMO may provide meaningful clinical and functional benefits. While high-quality RCTs are limited, a growing body of observational and cohort studies, along with systematic reviews, link early rehabilitation to improved functional recovery, reduced ICU-AW, shortened ICU and hospital stays, and improved discharge outcomes [18,51,71-80].

A recent cohort study of patients on VV-ECMO showed that those who achieved greater mobility by day 7 had substantially lower 30-day mortality rates than those with less mobility (29% vs. 48%, P<0.0001) [81]. While mobility may reflect better overall clinical stability, these findings reinforce the potential benefits of early activity. Similarly, Cerier et al. [18] reported that patients who began rehabilitation within 7 days achieved greater ambulation distances at discharge (mean, 49.3 m) than those who started rehabilitation later (mean, 21.4 m). Mayer et al. [74] observed that early rehabilitation enabled 86.2% of patients to sit on the EOB within 2 weeks. Likewise, Hayes et

al. [73] demonstrated that structured cardiac rehabilitation hastened initial sitting, standing, and walking milestones, with 1-hour daily exercise sessions achieving moderate intensity.

Beyond functional improvements, early rehabilitation may help improve resource utilization and postoperative recovery. For example, Bain et al. [76] observed shorter ICU stays, reduced MV duration after lung transplantation, and lower healthcare costs in patients on ECMO who received active rehabilitation before lung transplantation. Similarly, Bonizzoli et al. [51] noted a positive association between beginning physiotherapy within one week of ECMO initiation and shorter ECMO duration and ICU stay, although mortality benefits were not statistically significant.

A recent systematic review concluded that the effects of active rehabilitation on mortality, duration of MV, ICU and hospital length of stay, and quality of life remains unclear due to limited sample sizes, a high risk of bias, and potential confounding factors [20]. Existing data predominantly originate from observational or single-center cohort studies, which are often subject to selection and indication bias. Typically, patients considered suitable for rehabilitation represent those with less severe illness, potentially resulting in an overestimation of the benefits associated with early mobilization. Few studies have thoroughly controlled for factors such as illness severity, ECMO flow stability, or sedation depth, and long-term outcomes—including post-ICU survival or quality of life—remain insufficiently assessed.

Although ECMO-specific RCTs are scarce, evidence from a broader, critically ill population provides supportive context. In mechanically ventilated adults, protocolized early physical and occupational therapy has proven feasible and safe, capable of improving functional outcomes at discharge without increasing adverse events [82,83]. Meta-analysis data further reinforce the safety and feasibility of structured early rehabilitation, providing indirect justification for extending similar approaches to ECMO-supported patients [84]. Although the pathophysiological rationale for early rehabilitation remains unclear, it may reduce muscle wasting, joint contractures, and polyneuropathy—key factors contributing to long-term disability (Table 3). Additional multicenter RCTs are warranted to validate and refine implementation strategies.

POST-DISCHARGE FUNCTIONAL AND QUALITY-OF-LIFE OUTCOMES

ECMO survivors face substantial long-term functional and

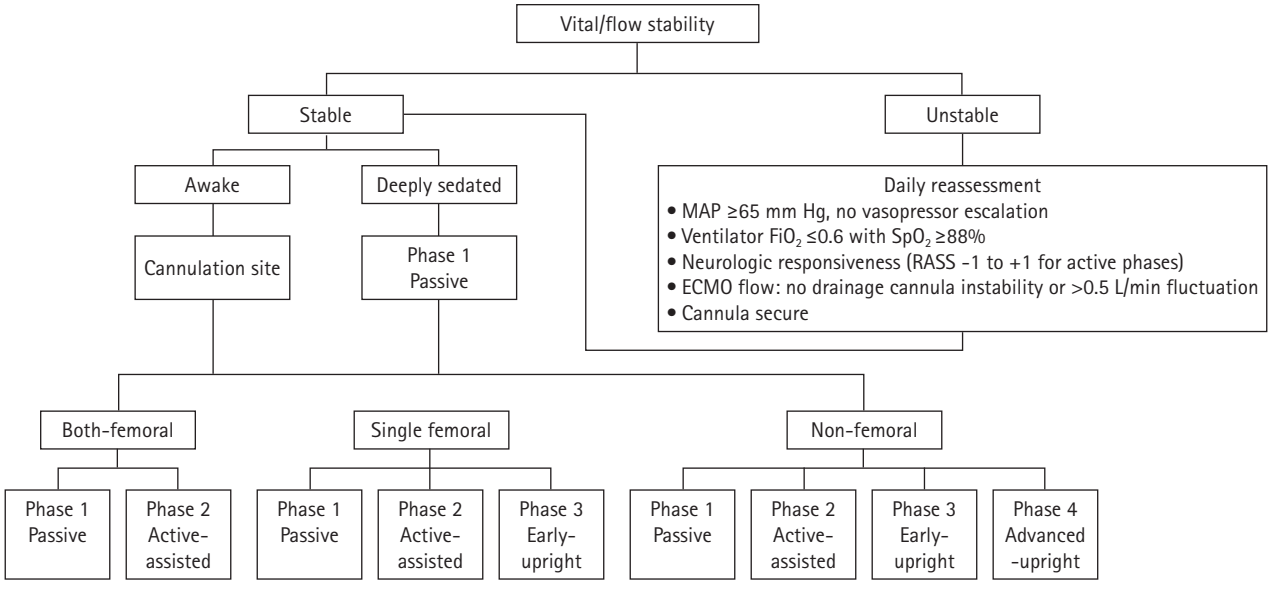


Figure 2. Safety-first algorithm for phase-specific rehabilitation during extracorporeal membrane oxygenation (ECMO). A structured, phase-based rehabilitation algorithm is presented according to patient stability, sedation depth, and cannulation configuration. Rehabilitation progresses sequentially from phase 1 (passive) to phase 4 (advanced upright) as physiologic tolerance and neurological function improve. MAP: mean arterial pressure; RASS: Richmond Agitation-Sedation Scale.

health-related quality of life (HRQoL) issues. In a single-center study of 370 adults supported with VA- or VV-ECMO, the overall 5-year survival rate was approximately 33%–36%, whereas the conditional survival rate among 30-day survivors exceeded 70%. Nevertheless, follow-up assessments have frequently documented limitations in daily basic and instrumental activities and high rates of posttraumatic stress symptoms, indicating considerable long-term morbidity [85].

A cross-sectional study of 106 ECMO survivors demonstrated that HRQoL metrics were generally lower than national population norms across multiple 36-Item Short Form Survey (SF-36) domains. The physical and mental component summary scores were 63.7 and 72.7, respectively, with significantly reduced values in physical dimensions ($P<0.05$). Both domains correlated positively with functional independence (Barthel Index) and negatively with post-traumatic stress and social isolation, underscoring the close interrelationship between physical and psychological recovery [86]. Data from a multicenter VA-ECMO registry indicated that approximately 30% of patients were alive without disability at 12 months, with most recoveries occurring within the first 6 months and persisting thereafter [87]. Another longitudinal study reported progressive improvement in the 6-minute walk distance and return-to-work rates by 12 months, although HRQoL scores remained below population averages [88].

In summary, although survival after ECMO has improved, persistent functional impairment and HRQoL deficits are observed frequently, particularly during the early post-discharge period. These findings support structured post-ICU rehabilitation and long-term follow-up. However, there is limited direct evidence that ECMO rehabilitation improves long-term outcomes, indicating a need for future prospective investigations.

BARRIERS AND IMPLEMENTATION CHALLENGES

Despite the growing support for early rehabilitation during ECMO, regular implementation faces obstacles in patient, organizational, technical, and cultural areas, with effects differing among institutions.

Patient-Related Barriers

Not all patients receiving ECMO are suitable candidates for rehabilitation. Profound hemodynamic instability, refractory hypoxemia, active bleeding, intracranial hypertension, and multi-organ failure can preclude safe mobilization, even with a multidisciplinary team in place [12,89]. Deep sedation, neurological impairment, and delirium further limit participation, underscoring the need for individual assessment and cautious progression.

Cannulation and Device Constraints

Despite advances in cannulation strategies, technical challenges remain the most frequently cited barriers. Recent research shows that with careful management, femoral cannulation does not necessarily prevent patient mobilization; however, many centers remain hesitant due to concerns regarding cannula dislodgement, bleeding, or limb ischemia, particularly where protocols and experience are limited [17,53,61].

Beyond cannulation, additional life-sustaining devices such as mechanical ventilators, continuous renal replacement therapy circuits, intra-aortic balloon pumps, and ventricular assist devices increases the complexity of mobilization efforts and the risk of line entanglement, accidental disconnection, and hemodynamic instability [90,91]. Consequently, physiologically eligible patients may only receive in-bed or passive rehabilitation, with upright mobilization rarely attempted.

Staffing and Resource Limitations

Safe rehabilitation during ECMO requires a highly trained multidisciplinary team including physiotherapists, ECMO specialists, ICU nurses, respiratory therapists, and intensivists [16,57,89]. Each session demands careful planning, clear role allocation, and continuous real-time monitoring of patient and ECMO circuits [13,15]. Many centers, especially those with low ECMO volumes or limited resources, struggle to allocate sufficient staff for these labor-intensive activities. Mobilizing patients receiving ECMO typically requires two to four extra personnel compared to standard ICU rehabilitation to manage cannulas, monitor hemodynamics, adjust ventilators, and physically support the patient [9,62].

Moreover, physiotherapy coverage may be limited to nighttime, weekends, or periods of high patient acuity [92]. Thus, even well-resourced centers may deprioritize rehabilitation due to competing priorities, such as emergency procedures or new admissions. Beyond staffing challenges, limited access to

Table 3. Summary of key clinical studies on early rehabilitation during ECMO

Study	Study design	ECMO configuration	Patient	Frequency and duration	Rehabilitation modality	Outcome	Adverse event
Abrams et al. (2014) [13]	Retrospective cohort study	VV (n=31) VA (n=4)	n=35 (out of 100 total ECMO patients who received active PT) - Patients receiving active PT: 35 (BTT: 19; BTR: 16)	1. Median time from ECMO initiation to first PT session: 2 days (IQR, 1–4.5) 2. PT sessions per week per patient: median, 2.8 (IQR, 0.5–7.8)	Active-assisted range of motion (32%), sitting in bed or at EOB (9%), standing (9%), ambulation (51%), cycle ergometer	1. Liberation from MV during ECMO: 66% (23/35) 2. Survival - BTT: 10/19 (53%) underwent transplant - BTR: 14/16 (88%) survived to discharge	No patient-related complications reported
Hermens et al. (2015) [77]	Retrospective case series	VV (n=9)	n=9 (all patients were awake and non-intubated as a bridge to lung transplantation	Unknown	1. Extensive sputum mobilization 2. Lower body muscle training 3. Bed-to-chair mobilization	1. Survivors (n=4): mean MRC score increased from 3.75 to 4.25 before transplant. 2. Non-survivors (n=5): only 1 patient could perform muscle training, with no improvement in strength.	Observed only in bifemoral cannulation cases: one large rectus hematoma and one obstructing thrombus in the return cannula
Ko et al. (2015) [14]	Retrospective case series	VV (n=7) VA (n=1)	n=8 - BTT (lung): 4 - BTT (heart): 1 - BTR: 3	Total PT sessions: 62	1. 31 sessions (50%): passive ROM + NMES 2. 17 sessions (27%): sitting 3. 2 sessions (3%): elastic band 4. 11 sessions (18%): standing or marching in place 5. 1 session (2%): walking	Study focused on feasibility and safety. No clinically significant adverse events were reported.	3 sessions (5%) were interrupted due to: 1 case of tachycardia (HR, 132/min) and 2 cases of tachypnea (RR, 46–47/min)
Bain et al. (2016) [76]	Retrospective cohort study	VV (n=9)	n=9 (all BTT on MV prior to ECMO) - Usual care: 4 - Active rehabilitation including ambulation: 5	Unknown	Progressive rehabilitation followed by ambulation	1. Post-transplant ICU stay was significantly shorter in the ambulatory group (median, 8 days vs. 45 days). 2. Total hospital stay was also shorter (median, 50 days vs. 94 days). 3. Post-transplant MV was shorter (median, 2 days vs. 29.5 days).	No specific adverse events during rehabilitation

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Table 3. Continued

Study	Study design	ECMO configuration	Patient	Frequency and duration	Rehabilitation modality	Outcome	Adverse event
Munshi et al. (2017) [50]	Retrospective cohort study	VV (n=57) VA (n=4)	n=61 (all ARDS, bridge to recovery) - Usual care: 11 - Active rehabilitation: 50	Number of PT days on ECMO: median, 3 days (IQR, 1–5).	1. Passive ROM 2. Active ROM 3. Sitting (in bed or EOB) 4. Standing Activity levels: - Passive ROM: 28 (61%) - IMS ≥2 (active exercises in bed): 18 (39%) - IMS ≥4 (actively sitting at bedside): 8 (17%)	1. ICU mortality - 30% overall (18/61) - 22% among those who received physiotherapy vs. 64% without physiotherapy (P=0.006)	No specific adverse events during rehabilitation
Wells et al. (2018) [53]	Retrospective cohort study	VV (n=98) VA (n=69)	Total ECMO: 254 - PT while on ECMO: 167 (intervention group) - PT after decannulation: 48 - No PT: 39	Total PT sessions: 607	1. Therapeutic exercises (268 sessions) 2. Bed mobility (170 sessions) 3. EOB activities (100 sessions) 4. Sit-to-stand transfers (106 sessions) 5. Stand pivot transfers (39 sessions) 6. Standing (98 sessions) 7. Ambulation (37 sessions)	1. Overall survival to discharge: 109/167 (65.3%). 2. Mode-specific survival - VA: 41/69 (59.4%) - VV: 68/98 (69.4%)	1. Minor events: 2 episodes of NSVT and 1 episode of hypotension 2. Major events: none
Pasrija et al. (2019) [61]	Retrospective case series	VA (n=15)	Total n=104 - Ambulated with femoral cannulas: 15 (7 with decompensated heart failure, 8 with massive PE)	1. Median time from cannulation to first out-of-bed mobilization: 3 days (range, 0–26). 2. Median time from cannulation to ambulation: 4 days (range, 1–42). 3. Median ambulation distance (first walk): 300 ft (IQR, 160–300).	1. Bed-to-chair transfer. 2. Marching in place. 3. Walking (goal: ≥300 ft)	1. In-hospital survival: 100% 2. 1-year survival: 100%	1. No major adverse events (decannulation, limb ischemia, or major bleeding). 2. Minor bleeding events: 3 patients (20%) had oozing around cannula site, managed by adding sutures.
Braune et al. (2020) [62]	Prospective observational study	VV (n=12) VA (n=17) VV-ECCO$_2$R (n=7) AV-ECCO$_2$R (n=3) RVAD (n=4)	Total n=115 on ECLS - Mobilized patients (IMS ≥3): 43 (37.4%) - Non-mobilized (IMS <3): 72 (62.6%)	1. Total active mobilizations (IMS ≥3): 332 during 1,242 ECLS day (26.7%). 2. Median duration per mobilization session: 130 min (IQR, 44–215).	1. Functional strengthening 2. Breathing exercises 3. Active upper and lower limb training 4. Endurance exercises 5. Standing, chair transfer, walking	Active mobilization (IMS ≥3) of ECLS patients undertaken by an experienced multi-professional team was feasible	1. Major events in mobilized group: - 3: major bleedings from femoral cannulation sites (6.9%) - 1: accidental venous cannula displacement (2.3%) 2. Minor events not detailed

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Table 3. Continued

Study	Study design	ECMO configuration	Patient	Frequency and duration	Rehabilitation modality	Outcome	Adverse event
Hayes et al. (2021) [73]	Pilot RCT (phase II)	VV (n=5) VA (n=10)	Total = 15 - Intensive PT: 7 - Standard PT: 8	Mean exercise time: 28.7 min/session (intensive PT) vs. 4.2 min/session (standard PT)	1. Intensive PT group - Passive/active ROM - Resistance training - Sitting, standing, and ambulation 2. Standard PT group - Passive ROM	1. In-hospital mortality - 3/7 (42.9%, intensive) vs. 1/8 (12.5%, standard) 2. Time to first stand: 5.5 days (intensive) vs. 20.8 days (standard), P=0.03.	No specific adverse events during rehabilitation
Abrams et al. (2022) [17]	Retrospective cohort study	VV (1,076 sessions) VA (1,630 sessions)	Total = 511 - Active PT cohort: 177 (BTT 124, BTR 53)	Total PT sessions: 2,706 (median, 8 sessions per patient; IQR, 2–21).	1. Bed exercise 2. Sitting, standing 3. Transfer to chair 4. Marching in place and walking 5. Cycle ergometer	1. 108 (61%) patients ambulated at least once (95 BTT, 13 BTR). 2. Out-of-bed activity (IMS ≥4): 138 patients (78%), 2,298 sessions (85%). 3. Survival to hospital discharge: 107/177 (60%).	1. Total events: 59 across 2,706 sessions (2%). 2. Major events - 2: cerebrovascular accidents - 1: cardiac arrest during PT
Mayer et al. (2022) [74]	Retrospective study	VV (n=142) VA (n=153) Hybrid (n=20)	Total n=315 - PT during ECMO: 218 - PT after ECMO: 70 - No PT: 27	PT during ECMO: - Mean sessions: 7.4 (SD, 12.7) - Frequency: 0.41 sessions/day - Time to first PT session: 4.5 day after ECMO start	1. In-bed passive/active exercises 2. Sitting, standing, walking 3. Mobility milestones (median days from ECMO start): - Sitting at edge of bed (IMS, 3): 13.2 days - Standing (IMS, 4): 16.9 days - Walking >1.5 m (IMS, 7): 19.7 days - Walking >45 m: 18.7 days	Survival was significantly higher in patients achieving mobility milestones: sitting at EOB (47% vs. 13%) and walking >45 m (26% vs. 3.5%).	No specific adverse events during rehabilitation
Sheasby et al. (2022) [78]	Retrospective cohort study	VV (n=42)	Total n=42 - Non-mobilized: 16 - Mobilized: 26	Unknown	1. Bed side PT, upper/lower limb ROM 2. Sitting, standing, and marching in place 3. Ambulation	Mobilized group had improved survival (73.1% vs. 43.8%; P=0.004)	Occurrences of cannula repositioning: 16 events (mobilized) vs. 1 event (non-mobilized), P=0.03
Cerier et al. (2023) [18]	Retrospective study	VV (n=67)	Total n=67 - Early PT/OT(<7 days form cannulation): 30 - Delayed PT/OT: 37	Unknown	1. Verticalization 2. Dangling at the EOB 3. Standing 4. Ambulation 5. Strength and aerobic exercises	Functional outcome (ambulation, day of discharge): 163.5 ft (early PT/OR) vs. 59.5 ft (delayed PT/OT), P<0.001	No specific adverse events during rehabilitation
Rottmann et al. (2023) [79]	Retrospective cohort study	VV (n=343)	Total n=343 - IMS ≥2 (active mobilization): 62 (18%) - IMS <2 (passive or no mobilization): 281 (82%)	Unknown	1. In-bed activities 2. EOB sitting 3. Transfer to chair 4. Standing	1. 30-day survival: IMS ≥ 2: 71% vs. 48% in IMS <2 (P=0.0012) 2. Ventilator weaning: 61.3% (IMS ≥2) vs. 46.6% (IMS <2), P=0.0489	No specific adverse events during rehabilitation

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Table 3. Continued

Study	Study design	ECMO configuration	Patient	Frequency and duration	Rehabilitation modality	Outcome	Adverse event
Liu et al. (2024) [80]	Prospective cohort study	VV (n=45)	Total n=45 - Early rehabilitation: 23 - Conventional rehabilitation: 22	1. Conventional rehabilitation - Head elevation, turning every 2 hours, daily ~30 min session 2. Early rehabilitation - Passive exercises: 1–2 sessions/day, 10–30 min each, ≥20 min/day, ≥ 5 day/wk - Physical factor therapy: 2 sessions/day, 10–30 min each - Respiratory training: 1–2 sessions/day, 5–7 day/wk - Progressive resistance training: 1–2 sessions/day, 10–30 min each, ≥30 min/day, ≥ 5 day/wk - Out-of-bed activities: 1–2 sessions/day, 10–30 min each, ≥30 min/day, ≥ 5 day/wk	1. Passive exercises 2. Physical factor therapy: NMES, electrotherapy, phototherapy 3. Respiratory training: inspiratory muscle training, abdominal breathing, deep breathing 4. Progressive resistance training: upper and lower limb exercises, bed cycling, bedside sitting 5. Out-of-bed activities: standing with assistance, wheelchair pedaling, step training, and walking	1. Early rehabilitation group showed less variation in the breathing-related muscles and motor muscles than the control group 2. ECMO duration: Shorter in the early rehabilitation group (8.0 vs. 12.0 days, P=0.002)	No specific adverse events during rehabilitation

ECMO: extracorporeal membrane oxygenation; VV: venovenous; VA: venoarterial; PT: physical therapy; BTT: bridge to transplantation; BTR: bridge to recovery; IQR: interquartile range; EOB: edge of bed; MV: mechanical ventilation; MRC: medical research council; ROM: range of motion; NMES: neuromuscular electrical stimulation; HR: heart rate; RR: respiratory rate; ICU: intensive care unit; ARDS: acute respiratory distress syndrome; IMS: intensive care unit mobility scale; NSVT: non-sustained ventricular tachycardia; PE: pulmonary embolism; $ECCO_2R$: extracorporeal carbon dioxide removal; RVAD: right ventricular assist device; ECLS: extracorporeal life support; RCT: randomized controlled trial; OT: occupational therapy.

specialized equipment—including mobilization harnesses, tilt tables, and cycle ergometers—can further restrict the scope and intensity of rehabilitation. Staff training and familiarity with ECMO-specific rehabilitation protocols represent additional challenges. Without dedicated educational initiatives and simulation-based training, teams may lack confidence in safe mobilization practice, thereby perpetuating a conservative, bed-rest-oriented culture [93,94].

These workforce and resource limitations directly impede access to rehabilitation and contribute to increased variability in practice across centers. In the absence of dedicated ECMO or rehabilitation teams, care is often guided by individual clinicians rather than structured protocols, resulting in many patients receiving only passive or minimal activity despite physiological stability. These system-level constraints highlight the need for institutional commitment and national policy advocacy to ensure equitable provision of ECMO rehabilitation.

Protocol and Cultural Barriers

The lack of standardized evidence-based protocols hampers consistent implementation even in resource-rich settings. Considerable variability exists across institutions in terms of sedation management, eligibility screening, mobilization techniques, and predefined stop criteria [16,20]. In the absence of clear, unified guidance, decisions often fall to individual clinicians—resulting in inconsistent practices. To address these gaps, an international guideline recently provided expert recommendations on indications, safety considerations, and practical strategies to standardize care across diverse settings [15]. However, implementing these guidelines depends heavily on active local leadership and team engagement.

Cultural attitudes within ICU teams also affect how protocols are implemented. Concerns about safety, such as the risk of cannula dislodgement or hemodynamic instability, and entrenched practices that favor bed rest may discourage the adoption of early mobilization despite growing evidence of its feasibility and safety. Moreover, limited institutional support or a lack of clear leadership commitment can reduce motivation and hinder the integration of rehabilitation into routine ICU workflows. Broader structural issues within healthcare systems can also undermine the long-term success of rehabilitation programs. Without stable funding, adequate staffing, and the integration of quality metrics into administrative policies, well-trained teams may struggle to maintain consistent practice. Addressing these systemic barriers is essential for translating the conceptual benefits of ECMO rehabilitation into sustainable real-world practice.

Substantial variability exists across institutions and regions in the implementation of ECMO rehabilitation, reflecting disparities in clinical resources and differences in ICU culture. Facilities with established awake ECMO protocols and dedicated physiotherapists tend to initiate rehabilitation earlier and with greater intensity. In contrast, hospitals with limited staffing or deeper sedation practices often restrict activity, even when patients are physiologically stable. These disparities demonstrate the influence of cultural and system-level factors on ECMO rehabilitation delivery, emphasizing the demand for global consensus and equitable resource allocation.

FUTURE DIRECTIONS

Although observational data and preliminary studies have laid the foundation for ECMO rehabilitation, future research should move beyond feasibility to establish evidence-based standards. To facilitate this, we propose a four-domain agenda encompassing clinical efficacy, protocol standardization, implementation strategies, and health economic considerations.

Efficacy and Optimal Timing

Adequately powered RCTs are required to establish the causal benefits of ECMO rehabilitation. Future research should evaluate survival and patient-centered outcomes, including discharge mobility, long-term quality of life, and neurocognitive recovery. Comparative arms should evaluate the timing (early vs. delayed), intensity (active vs. passive), and specific subpopulations (VA vs. VV-ECMO, transplant vs. non-transplant candidates).

Standardization of Protocols and Safety Frameworks

Unified protocols are required for reproducibility across centers, including clear eligibility criteria, safety checklists, mobilization algorithms, and stop criteria. Existing consensus statements offer limited preliminary guidance; thus, systematic validation across different healthcare systems and ECMO configurations remains a priority [15].

Implementation and Quality Improvement

Translating evidence into routine practice requires a structured science approach. Key priorities include multidisciplinary education, simulation-based training, leadership engagement, and cultural transformation within the ICU. Establishing multicenter quality registries and benchmarking networks could help facilitate real-time monitoring, identify best practices, and reduce interinstitutional variability.

Health Economics and Policy Evaluation

An observational study on lung transplant candidates suggested that active rehabilitation during ECMO may lower healthcare costs compared with standard care [76]. However, broader cost-effectiveness analyses across the general population receiving ECMO are lacking. Accordingly, future research should quantify the trade-offs between costs and benefits, considering not only direct ICU expenditures but also long-term outcomes, such as reduced post-discharge disabilities, fewer readmissions, and improved return-to-work rates. Understanding these economic dimensions is essential for informed policy-making and equitable resource allocation.

CONCLUSIONS

Early rehabilitation during ECMO has evolved from a theoretical concept to an achievable clinical reality in experienced centers. Current evidence substantiates its feasibility and safety when implemented through structured protocols by trained multidisciplinary teams. Clinicians are encouraged to incorporate rehabilitation into ECMO management, beginning with passive and in-bed exercises and progressing to active mobilization as patient stability permits. Establishing standardized team-based protocols, routine safety monitoring, and early engagement with physiotherapy are considered best practices in ECMO management.

Although definitive efficacy data and long-term outcome evidence remain limited, early mobilization aligns with a broader paradigm shift toward functional and patient-centered critical care. Future multicenter trials and implementation-focused research are essential to further refine optimal timing, safety parameters, and cost-effectiveness. In the interim, centers should adopt a cautious but proactive approach that prioritizes individualized assessment, comprehensive staff training, and adherence to protocol-driven teamwork for safe integration of rehabilitation into the ECMO workflow. Integrating structured rehabilitation with ECMO care redefines the metrics of success in critical care, shifting the focus from mere survival to improved long-term recovery, independence, and overall quality of life.

CONFLICT OF INTEREST

Woo Hyun Cho is an editorial board member of the journal but was not involved in the peer reviewer selection, evaluation, or decision process of this article. No other potential conflicts of interest relevant to this article were reported.

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