

Ultrasound Assessment of Diaphragm Structure and Function in Dialysis-Dependent Chronic Kidney Disease: A Systematic Review

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Abstract

Background: Respiratory muscle dysfunction is common in dialysis-dependent chronic kidney disease (CKD), but the structural and functional status of the diaphragm and its responsiveness to rehabilitation have not been consistently characterised using ultrasound.

Objective: To synthesise evidence on ultrasound-derived diaphragm thickness, thickening fraction, excursion, and stiffness in adults receiving dialysis and to examine whether rehabilitation interventions are associated with changes in these imaging outcomes.

Methods: A systematic review was conducted in accordance with PRISMA 2020. MEDLINE, Embase, CENTRAL, CINAHL, Web of Science Core Collection, Scopus, and PEDro were searched from inception to the final search date, supplemented by trial registries, citation tracking, reference list screening, and grey literature searches. Eligible studies included adults with dialysis-dependent CKD or advanced CKD reporting ultrasound-derived diaphragmatic outcomes. Two reviewers independently screened studies and extracted data. Randomised trials were assessed using RoB 2, and observational studies using design-appropriate Joanna Briggs Institute appraisal tools. Because of substantial clinical and methodological heterogeneity, findings were synthesised narratively in accordance with SWiM principles, and certainty was assessed using GRADE.

Results: Four studies involving 478 participants were included. Three were observational, and one was a small randomised trial. Ultrasound-derived diaphragm thickness during deep inspiration was lower in haemodialysis populations than in healthy controls or preserved-function subgroups. The thickening fraction was also consistently lower in the two studies reporting it. Excursion and velocity were directionally reduced, although statistical significance was not consistent. One study using shear-wave elastography reported substantially lower diaphragmatic stiffness in haemodialysis patients than in healthy controls, with excellent diagnostic discrimination, but this finding has not been replicated. The only interventional study evaluated intradialytic cycle ergometry rather than targeted respiratory muscle training and found no significant change in diaphragm thickness after four weeks, despite reported improvements in respiratory muscle strength. Overall certainty was low to very low for the principal outcomes.

Conclusion: Ultrasound provides convergent descriptive evidence of impaired diaphragmatic structure and function in dialysis-dependent CKD. However, evidence that targeted respiratory muscle training reverses ultrasound-defined structural abnormalities is absent. Future multicentre studies should harmonise ultrasound acquisition, validate diagnostic thresholds, and evaluate targeted respiratory muscle training with serial imaging alongside functional and patient-reported outcomes.

Keywords: chronic kidney disease; haemodialysis; diaphragm; ultrasonography; respiratory muscle; diaphragm thickness; thickening fraction; shear-wave elastography; rehabilitation; systematic review.

1. Introduction

Chronic kidney disease (CKD) is a major and growing cause of morbidity, mortality, and healthcare utilisation worldwide. The burden is particularly substantial among people who progress to kidney failure and require renal replacement therapy. Haemodialysis (HD), the most widely used renal replacement modality, is associated with systemic complications that extend beyond renal function, including reduced physical capacity, skeletal muscle wasting, respiratory muscle weakness, and exercise intolerance[1].

Several mechanisms may contribute to respiratory muscle impairment in dialysis-dependent CKD, including uraemic myopathy, chronic inflammation, metabolic acidosis, anaemia, oxidative stress, protein-energy wasting, and coexisting cardiovascular and metabolic disease. These processes may compromise diaphragm mass, contractile performance, and ventilatory reserve. [2]The resulting phenotype may manifest clinically as dyspnoea, fatigue, reduced exercise tolerance, and impaired health-related quality of life.[3]

Diaphragm ultrasonography provides a non-invasive method for evaluating respiratory muscle morphology and movement. Commonly reported parameters include diaphragm thickness during expiration and inspiration, thickening fraction, excursion, movement velocity, and, more recently, tissue stiffness assessed by shear-wave elastography. [4]These measures may provide complementary information on diaphragm structure and function; however, acquisition protocols, breathing manoeuvres, measurement sites, and analytic approaches vary considerably between studies.[5] Given the inherent limitations of conventional assessments such as fluoroscopy or trans-diaphragmatic pressure

measurement—including ionizing radiation exposure and procedural invasiveness—ultrasound has emerged as a preferred tool for real-time monitoring [6].

Respiratory muscle training (RMT), particularly inspiratory muscle training, has been investigated in dialysis populations and has demonstrated improvements in functional measures, including maximal inspiratory pressure and pulmonary function. [7] Exercise-based and technology-assisted rehabilitation, including virtual reality, has also been explored as a strategy to improve adherence and physical function. Nevertheless, improvements in functional outcomes do not necessarily demonstrate structural remodelling of the diaphragm. [8] Although exercise improves respiratory muscle strength, the underlying physiological impact on the diaphragm's contractile proteins and structural morphology in patients with end-stage renal disease remains largely unelucidated [9,10]. This gap in understanding is particularly notable given that diaphragmatic stiffness, as quantified by shear-wave elastography, exhibits marked reductions in dialysis patients compared to healthy controls [11].

The present review was therefore undertaken to determine what is currently known about ultrasound-derived diaphragmatic structure and function in adults with dialysis-dependent CKD, and to assess whether rehabilitation interventions have been shown to modify these imaging outcomes. [12] A secondary objective was to identify methodological gaps that must be addressed before diaphragm ultrasound can be used as a validated biomarker for rehabilitation response. [13]

2. Methods

2.1 Protocol and reporting

This systematic review was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement. The review protocol was prospectively registered in PROSPERO [CRD420261365280]. The Synthesis Without Meta-analysis (SWiM) reporting framework was used to guide the narrative synthesis. Because the review synthesised previously published evidence, institutional ethical approval was not required.

2.2 Eligibility criteria

Eligibility was defined using Population, Intervention, Comparator, and Outcome concepts. Adults (≥ 18 years) receiving maintenance HD, home HD, peritoneal dialysis, or with CKD stages 3–5 not yet receiving dialysis were eligible. Studies involving acute kidney injury in intensive care, mechanical ventilation, or neurological or neuromuscular conditions known to independently impair diaphragm function were excluded [11].

Eligible interventions included RMT, breathing exercises, combined aerobic and respiratory training, diaphragmatic or pursed-lip breathing, yoga-based breathing, biofeedback respiratory training, virtual-reality-assisted respiratory training, and mixed rehabilitation programmes containing a respiratory component. Eligible comparators included usual care, no intervention, sham or attention control, active respiratory-training comparators, and non-respiratory exercise. [14] Outcome measures focused on diaphragmatic morphology, including end-expiratory and end-inspiratory thickness and the calculated thickening fraction, alongside functional metrics derived from ultrasound. [15]

The primary outcomes were ultrasound-derived diaphragm thickness at end expiration and peak inspiration, diaphragm thickening fraction, and sonographic stiffness measures including shear-wave elastography. Secondary outcomes included maximal inspiratory and expiratory pressure, spirometric indices, six-minute walk distance, dyspnoea, respiratory muscle endurance, health-related quality of life, and adverse events. Randomised controlled trials were prioritised; quasi-randomised, non-randomised, prospective interventional, and cross-sectional studies were eligible when they reported relevant ultrasound-derived diaphragmatic outcomes. [16]

2.3 Information sources and search strategy

MEDLINE via PubMed, Embase, the Cochrane Central Register of Controlled Trials, CINAHL, Web of Science Core Collection, Scopus, and PEDro were searched from database inception to the final search date. ClinicalTrials.gov, the WHO International Clinical Trials Registry Platform, the EU Clinical Trials Information System, the Clinical Trials Registry–India, and PROSPERO were searched for ongoing or unpublished evidence. Reference lists of included studies and relevant reviews were screened; forward citation tracking was performed using Web of Science and Scopus; and grey literature was sought through ProQuest Dissertations and Theses, OpenGrey, the Grey Literature Report, and relevant nephrology society websites.

2.4 Study selection

Records were exported to a reference-management system, deduplicated, and screened in Covidence. Two reviewers independently screened titles and abstracts, followed by full texts. Disagreements were resolved through discussion and, where necessary, consultation with a third reviewer. Multiple reports of the same study were linked and counted

as a single study. Reasons for exclusion at full-text screening were recorded and should be presented in the PRISMA 2020 flow diagram.[17]

2.5 Data extraction

A pilot-tested extraction form was used by two independent reviewers. Extracted information included study design, country, sample size, participant characteristics, dialysis modality and duration, intervention and comparator characteristics, ultrasound equipment and acquisition protocol, respiratory outcomes, functional outcomes, patient-reported outcomes, adverse events, funding, conflicts of interest, and numerical results. Where data were available only in graphical form, values were digitised and checked against the original reports. The final supplementary extraction table should accompany the submitted manuscript.[18]

2.6 Risk of bias and methodological quality

The methodological quality of the included randomised clinical trial was additionally assessed using the PEDro scale. The trial received a PEDro score of 5/10 based on the item-level assessment presented in Supplementary Table S4. Criterion 1 (eligibility criteria specified) was not included in the total score, consistent with the PEDro scoring system.[19]

The included randomised trial was assessed using the Cochrane Risk of Bias 2 tool. Observational studies were assessed with design-appropriate Joanna Briggs Institute appraisal checklists. Two reviewers independently completed assessments, with disagreements resolved through discussion or arbitration by a third reviewer. Risk-of-bias judgements were incorporated into the interpretation of the narrative synthesis and certainty assessment.[20]

2.7 Data synthesis and certainty of evidence

Quantitative pooling was not undertaken because the included studies differed substantially in population, comparison framework, ultrasound modality, measurement site, breathing manoeuvre, outcome definitions, and intervention characteristics. Findings were therefore synthesised narratively, grouped by outcome and study design. Effect estimates, confidence intervals where available, direction of effect, statistical significance, and methodological limitations were considered together. Certainty of evidence was assessed using GRADE, considering risk of bias, inconsistency, indirectness, imprecision, and publication bias.[21]

3. Results

3.1 Study selection

Four studies met the eligibility criteria and were included in the qualitative synthesis. The included evidence comprised two cross-sectional studies, one prospective cohort study, and one randomised clinical trial. The four studies enrolled a combined 478 participants. The exact numbers of records identified, duplicates removed, records screened, full texts assessed, and reasons for exclusion should be inserted directly from the final PRISMA flow diagram before submission.[22]

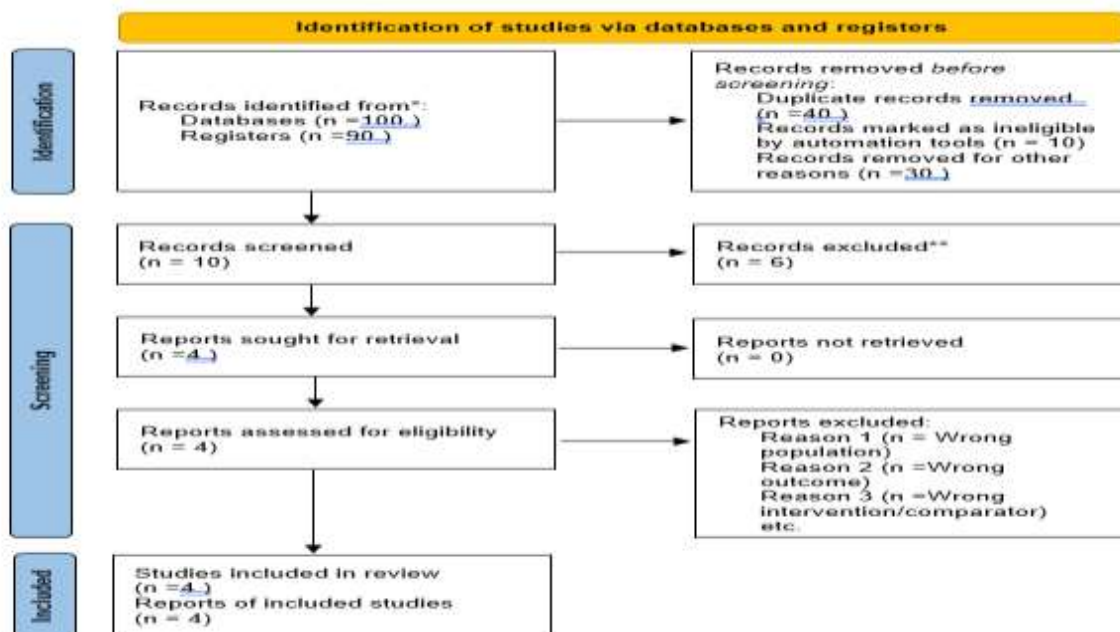


Figure 1. PRISMA 2020 flow diagram of study identification, screening, eligibility assessment, and inclusion.

3.2 Characteristics of included studies

The included studies were conducted in China, Türkiye, and Brazil. Three studies focused principally on maintenance HD, while one included both HD and peritoneal dialysis. Sample sizes ranged from 40 participants in the randomised trial to 206 participants in the largest cross-sectional study. The observational studies compared dialysis populations with healthy controls or stratified HD participants according to ultrasound-defined diaphragmatic dysfunction; the randomised trial compared intradialytic cycle ergometry with no exercise

Study	Design	Sample	Population	Ultrasound	Main purpose	PEDro score
Wang et al., 2019	Cross-sectional	206 (103 HD; 103 controls)	Maintenance HD and matched healthy controls	B-mode; right hemidiaphragm; thickness, TF, excursion/velocity	Structural and functional diaphragm comparison	—
Zheng et al., 2022	Prospective cohort	103 recruited; 98 analysed	Maintenance HD	B-mode; right hemidiaphragm; thickness, TF, excursion/velocity	Diaphragm dysfunction and 36-month prognosis	—
Dağ et al., 2025	Prospective cross-sectional	129 (69 dialysis; 60 controls); HD subgroup n=37	HD and PD with healthy controls	Grey-scale US + SWE	Thickness, stiffness, diagnostic discrimination	—
Armando Filho Gonçalves da Silva et al., 2025	Randomised clinical trial	40 (20 exercise; 20 control)	Maintenance HD	B-mode/B-M mode; right hemidiaphragm	Effect of intradialytic cycle ergometry on diaphragm morphology	5/10

3.3 Diaphragm thickness

Ultrasound-derived diaphragm thickness was reported in all four studies. During deep inspiration, Wang et al. reported lower thickness in HD patients than in matched healthy controls (0.386 ± 0.144 cm vs 0.439 ± 0.134 cm; $p=0.007$). Zheng et al. reported substantially lower maximal inspiratory thickness in participants classified as having ultrasound-defined diaphragmatic dysfunction than in those with preserved function ($p<0.001$). Dağ et al. also reported lower inspiratory thickness in HD than in healthy controls (2.24 ± 0.25 mm vs 2.86 ± 0.29 mm; $p<0.001$). In contrast, the Armando trial found no significant change in diaphragm thickness following four weeks of intradialytic cycle ergometry: contracted-phase MD -0.08 cm (95% CI -1.61 to 1.46 ; $p=0.99$) and relaxed-phase MD -1.21 cm (95% CI -2.60 to 0.19 ; $p=0.10$). [23]

3.4 Thickening fraction, excursion and velocity

Thickening fraction was reported by Wang et al. and Zheng et al., and was directionally lower in HD or ultrasound-defined diaphragmatic dysfunction. Wang et al. reported a lower thickening fraction in HD than in healthy controls (0.838 ± 0.618 vs 1.127 ± 0.757 ; $p=0.003$). Excursion and movement velocity were also reduced in the Wang cohort, whereas the Zheng cohort showed a similar effect direction without statistically significant differences in excursion ($p=0.095$) or velocity ($p=0.173$). These findings suggest convergent impairment of the diaphragm's contractile response, although statistical consistency is incomplete. [24]

3.5 Shear-wave elastography

Dağ et al. provided the only evidence using shear-wave elastography. Inspiratory stiffness was 25.61 ± 6.15 kPa in HD patients compared with 47.68 ± 6.67 kPa in healthy controls, while expiratory stiffness was 19.46 ± 4.37 kPa versus 33.26 ± 4.62 kPa, respectively. Diagnostic discrimination was excellent, with reported AUCs of 0.980 during inspiration and 0.987 during expiration. Because these estimates originate from a single study, they should be considered preliminary and require external validation. [25]

3.6 Interventional evidence

Only one included study was interventional. The randomised Brazilian trial evaluated progressive intradialytic lower-limb cycle ergometry three times per week for four weeks. No significant change in diaphragm thickness was observed

despite reported improvements in maximal inspiratory and expiratory pressures. Importantly, this was a peripheral aerobic intervention rather than targeted RMT. Therefore, the current review provides no direct randomised evidence that IMT, diaphragmatic breathing, or technology-assisted respiratory training produces ultrasound-detectable diaphragm remodelling in dialysis-dependent CKD.[26]

3.7 Prognostic evidence

The Zheng prospective cohort provided the only longitudinal prognostic evidence. Participants with ultrasound-defined diaphragmatic dysfunction had worse 36-month clinical outcomes than those with preserved function. Of 103 recruited participants, 98 were analysed, and 81 completed the full 36-month follow-up. Attrition included loss to contact, transplantation, and change to peritoneal dialysis. The prognostic findings, therefore, remain promising but require replication in larger, multicentre cohorts.[27]

3.8 Secondary outcomes

Maximal inspiratory and expiratory pressures were reported only in the interventional study. Six-minute walk distance, health-related quality of life, spirometric indices, and adverse events were not reported as outcomes in the included ultrasound studies. Symptom associations, including dyspnoea, fatigue, and hiccups, were reported descriptively in Wang et al., but quantitative intervention effects were not reported.[28] While evidence for specific respiratory muscle training remains limited in this context, previous research suggests that targeted inspiratory muscle training may yield measurable improvements in dyspnea, forced vital capacity, and maximal inspiratory pressure for hemodialysis patients [29]. However, establishing a definitive link between structural ultrasound markers of diaphragmatic atrophy and long-term improvements in functional capacity requires further investigation through standardized, high-intensity respiratory muscle training protocols [30,31].

The included randomised clinical trial received a PEDro score of 5/10. The score reflected positive ratings for random allocation, baseline comparability, adequate outcome availability, between-group statistical comparisons, and reporting of point estimates with variability; allocation concealment, participant and therapist blinding, assessor blinding, and intention-to-treat/retention criteria were not awarded points based on the supplied assessment. These limitations highlight the current lack of high-quality, blinded randomized controlled trials, leaving the clinical utility of ultrasonography as a primary diagnostic tool for respiratory sarcopenia in dialysis patients subject to future larger-scale validation.[32]

3.9 Risk of bias

The sole randomised trial was judged to have some concerns overall using the RoB 2 tool. The principal concerns related to insufficient reporting of allocation concealment and randomisation procedures, assessor blinding, completeness of outcome data, ultrasound measurement reliability, and a prespecified analysis plan. The three observational studies were assessed using design-appropriate appraisal tools, which raised concerns about selection bias, single-centre recruitment, attrition, limited generalisability, and incomplete integration of ultrasound with conventional respiratory function measures.

The domain-level and overall risk-of-bias judgements are summarised graphically below. The first figure presents study-level judgements across the RoB 2 domains, while the second figure presents the distribution of judgements across domains.[33]

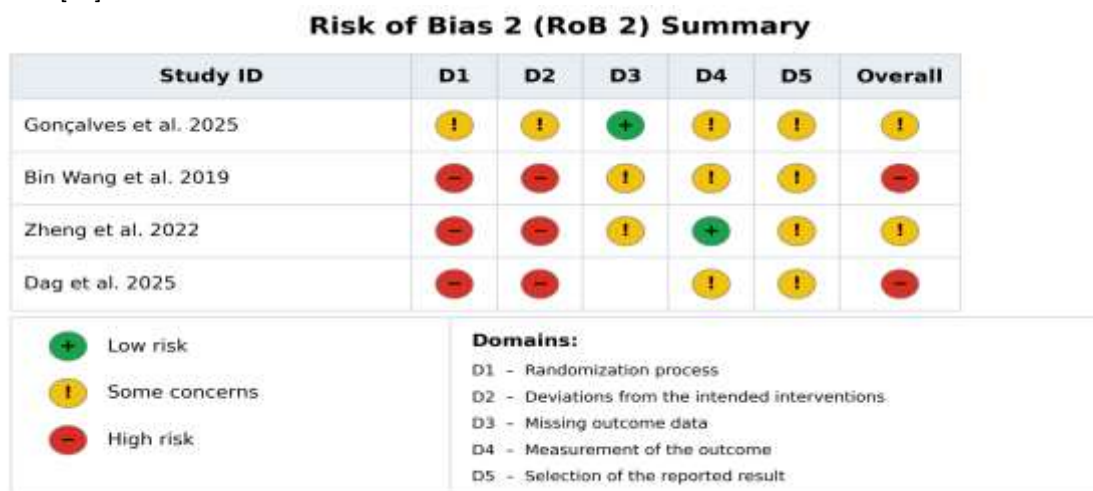


Figure 2. Risk of bias 2 (RoB 2) summary across the included studies

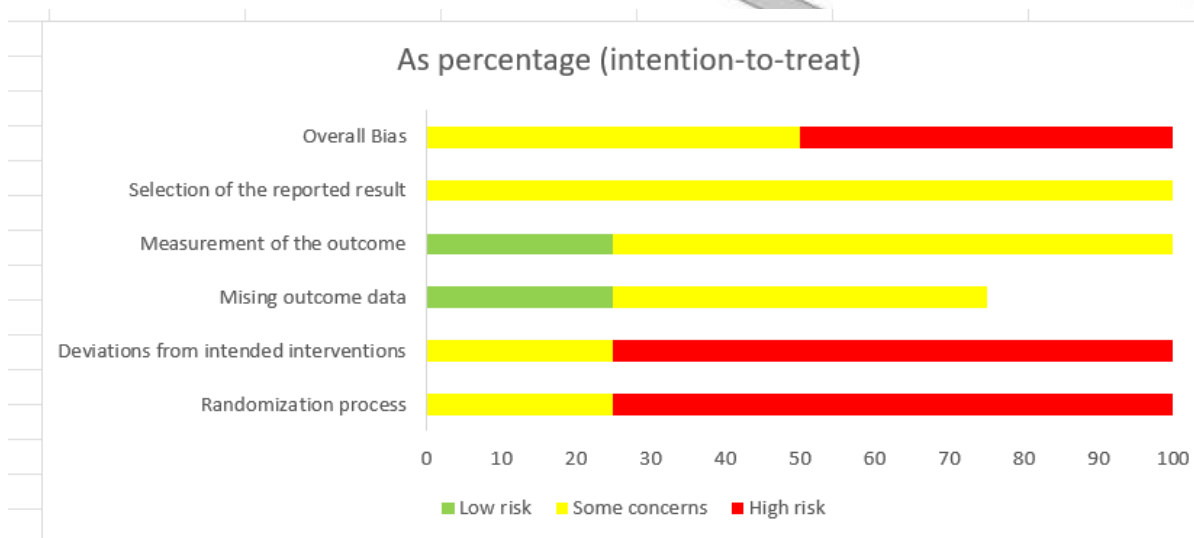


Figure 3. Distribution of risk-of-bias judgements across RoB 2 domains.

3.10 Certainty of evidence

Certainty was low for inspiratory diaphragm thickness and thickening fraction, very low for end-expiratory thickness and shear-wave elastography, and very low for single-study secondary outcomes. Downgrading was principally attributable to the small evidence base, predominance of observational designs, methodological heterogeneity, imprecision, and risk of bias in the only randomised trial. No outcome was upgraded because the evidence base was insufficient to support robust large-effect or dose-response judgements.[34]

4. Discussion

4.1 Principal findings

Four studies involving 478 participants met the inclusion criteria. Overall, the evidence indicates that dialysis-dependent CKD is associated with measurable abnormalities in diaphragm morphology and function on ultrasound. Inspiratory thickness and thickening fraction were consistently reduced, while excursion and velocity generally showed the same direction of impairment. Shear-wave elastography provided promising but single-study evidence of reduced diaphragm stiffness. In contrast, interventional evidence was extremely limited: the only randomised study evaluated peripheral cycle ergometry and did not demonstrate any structural change in the diaphragm.[35]

4.2 Interpretation of ultrasound findings

The convergence of reduced inspiratory thickness and thickening fraction across studies suggests that ultrasound can detect clinically relevant diaphragmatic impairment in dialysis populations. However, differences in acquisition protocols limit direct comparison. The divergence in end-expiratory thickness between Wang and Dağ is an example of how measurement zone, breathing manoeuvre, equipment, and participant characteristics may influence absolute values. Consequently, ultrasound thresholds derived from a single cohort should not yet be treated as universal diagnostic reference values.[36]

4.3 Structure versus function

The available evidence suggests that functional impairment may not map directly onto structural thickness. The randomised cycle-ergometry study reported improvements in respiratory muscle strength without a corresponding increase in ultrasound-derived thickness. This may indicate that short-term functional adaptation can occur without measurable hypertrophy, although the small sample size, short intervention period, and risk-of-bias concerns preclude a definitive conclusion. Future studies should measure structural, functional, and clinical endpoints concurrently.[37]

4.4 Prognostic significance

The 36-month Zheng cohort suggests that ultrasound-defined diaphragmatic dysfunction may have prognostic relevance. However, this evidence is observational and derived from a single centre. In addition, attrition occurred during follow-up, and some reasons for loss were clinically related to transplantation or modality change. Therefore, the association should be interpreted as hypothesis-generating rather than as evidence that ultrasound-defined dysfunction independently causes adverse outcomes.[38]

4.5 Implications for respiratory muscle training

The broader dialysis rehabilitation literature supports functional benefits from respiratory muscle training, but the present ultrasound-focused review demonstrates an important mechanistic evidence gap. None of the included studies evaluated targeted RMT with serial ultrasound assessment of diaphragm thickness or thickening fraction. Thus, it remains uncertain whether functional improvements produced by IMT or breathing interventions are accompanied by structural remodelling. This distinction is important because ultrasound should not yet be used to prescribe or titrate RMT dose on the assumption that thickness changes represent treatment response.[39]

4.6 Clinical implications

Diaphragm ultrasound is attractive because it is non-invasive, repeatable, and potentially feasible during dialysis. Nevertheless, current evidence supports its use primarily as an adjunctive research or assessment tool rather than as a validated standalone clinical decision-making biomarker. Functional measures such as MIP, MEP, spirometry, exercise capacity, symptoms, and quality of life remain necessary for comprehensive rehabilitation assessment.[40]

4.7 Strengths

Strengths of this review include a broad database search, supplementary registry and citation searching, independent study selection and extraction, design-appropriate risk-of-bias appraisal, and explicit assessment of certainty. The narrative synthesis was selected a priori because of substantial clinical and methodological heterogeneity.[41]

4.8 Limitations

The principal limitation is the small evidence base: only four studies met the inclusion criteria, and only one was randomised. All included studies were single-centre investigations, limiting external validity. Ultrasound acquisition protocols differed in measurement site, breathing manoeuvre, imaging modality, and reporting. Most studies used observational designs and therefore cannot establish causality. The only intervention study lasted four weeks and tested peripheral aerobic exercise rather than targeted RMT. Furthermore, simultaneous pulmonary function testing and ultrasound were not consistently performed, and gold-standard measures of diaphragm contractile strength were absent. These limitations reduce certainty and preclude quantitative pooling.[42]

4.9 Research priorities

Future studies should be multicentre and adequately powered; use harmonised ultrasound acquisition and reporting protocols; validate diagnostic thresholds against established measures of diaphragm function; and evaluate targeted RMT with serial ultrasound. Trials should measure diaphragm thickness, thickening fraction, excursion, MIP, MEP, spirometry, exercise capacity, symptoms, quality of life, and adverse events in the same participants. Longitudinal prognostic studies should also evaluate whether ultrasound-derived abnormalities independently predict hospitalisation, cardiovascular events, infection-related admissions, or other clinically meaningful outcomes.[43] Ultimately, establishing a robust evidence base requires integrating these imaging parameters within the broader context of multi-organ assessments to better delineate the complex pathophysiology of respiratory decline in patients with end-stage kidney disease.[44]

5. Conclusion

Current evidence indicates that dialysis-dependent CKD is associated with reduced ultrasound-derived diaphragm thickness during inspiration, reduced thickening fraction, and impaired excursion or movement velocity. Shear-wave elastography also shows promise for identifying diaphragmatic abnormalities, although evidence is currently limited to a single study. The prognostic significance of ultrasound-defined dysfunction is suggested by a single prospective cohort study but remains insufficiently validated. Most importantly, there is no direct randomised evidence demonstrating that targeted respiratory muscle training reverses ultrasound-defined diaphragmatic structural abnormalities in dialysis-dependent CKD. Ultrasound should therefore be considered a promising adjunctive biomarker that requires validation, rather than an established tool for monitoring or titrating respiratory rehabilitation.

References

- [1] Bernier-Jean A, Beruni NA, Bondonno NP, Williams G, Teixeira-Pinto A, Craig JC, Wong G. Exercise training for adults undergoing maintenance dialysis. *Cochrane Database of Systematic Reviews* 2022;2022. <https://doi.org/10.1002/14651858.cd014653>.
- [2] Mukai H, Pei M, Lindholm B, Heimbürger O, Bárány P, Anderstam B, Stenvinkel P, Qureshi AR. Restrictive lung disorder is common in patients with kidney failure and associates with protein-energy wasting, inflammation and cardiovascular disease. *PLoS ONE* 2018;13. <https://doi.org/10.1371/journal.pone.0195585>.

- [3] Man WD, Donaldson, Maddocks M, Martolini, Polkey M. Muscle function in COPD: a complex interplay. *International Journal of COPD* 2012;7:523. <https://doi.org/10.2147/copd.s28247>.
- [4] Mercurio G, D'Arrigo S, Moroni R, Grieco DL, Menga LS, Romano AVC, Annetta MG, Bocci MG, Eleuteri D, Bello G, Montini L, Pennisi MA, Conti G, Antonelli M. Diaphragm thickening fraction predicts noninvasive ventilation outcome: a preliminary physiological study. *Critical Care* 2021;25:219. <https://doi.org/10.1186/s13054-021-03638-x>.
- [5] Gransee HM, Smith JR, Johnston J, Knoll KM, Lee H, Jiang L, Urban MW, Johnson BD, Mantilla CB. Comparison of shear-wave elastography to state-of-the-art respiratory function testing to measure the range of forces generated by the diaphragm muscle. *Physiology* 2023;38. <https://doi.org/10.1152/physiol.2023.38.s1.5731374>.
- [6] Wang B, Yin Q, Wang Y, Tu Y, Han Y, Gao M, Pan M, Yang Y, Xue Y, Zhang L, Zhang L, Liu H, Tang R, Zhang X, Xiao J, Wang XH, Liu B. Diaphragmatic dysfunction associates with dyspnoea, fatigue, and hiccup in haemodialysis patients: a cross-sectional study. *Scientific Reports* 2019;9:19382. <https://doi.org/10.1038/s41598-019-56035-4>.
- [7] Katayıfçı N, Hüzmei İ, İriş D, Turğut F. Effects of different inspiratory muscle training protocols on functional exercise capacity and respiratory and peripheral muscle strength in patients with chronic kidney disease: a randomized study. *BMC Nephrology* 2024;25:184. <https://doi.org/10.1186/s12882-024-03610-1>.
- [8] Palleschi A, Mattioni G, LoMauro A, Privitera E, Musso V, Morlacchi LC, Vergari M, Velardo D, Grasselli G. Diaphragm and Lung Transplantation. *Transplant International* 2024;37:12897. <https://doi.org/10.3389/ti.2024.12897>.
- [9] Katayıfçı N, Hüzmei İ, İriş D, Turğut F. Impairments of functional exercise capacity, muscle strength, balance and kinesiophobia in patients with chronic kidney disease: a cross-sectional study. *BMC Nephrology* 2024;25:19. <https://doi.org/10.1186/s12882-023-03448-z>.
- [10] Medeiros AIC de, Fuzari HKB, Rattesa C, Brandão DC, Marinho PÉ de M. Inspiratory muscle training improves respiratory muscle strength, functional capacity and quality of life in patients with chronic kidney disease: a systematic review. *Journal of Physiotherapy* 2017;63:76–83. <https://doi.org/10.1016/j.jphys.2017.02.016>.
- [11] Dağ N, Berktaş HB, Uslu AG, Burulday V. Sonoelastographic evaluation of diaphragmatic thickness and stiffness in dialysis patients. *BMC Medical Imaging* 2025;25:380. <https://doi.org/10.1186/s12880-025-01932-6>.
- [12] Ahmed LAN, Eltrawy HH, Elsadek AM, Ali WE, Abozeid HE, Qutb SF, Elsayed F, Enayet AAEM, Elshehawy AA. Diaphragmatic dysfunction in hemodialysis patients: risk factors and effect of incentive spirometry training. *Renal Replacement Therapy* 2023;9. <https://doi.org/10.1186/s41100-023-00516-w>.
- [13] Zhou EFM, Fu SN, Huang C, Huang XP, Wong AYL. Reliability and validity of ultrasonography in evaluating the thickness, excursion, stiffness, and strain rate of respiratory muscles in non-hospitalized individuals: a systematic review. *BMC Oral Health* 2023;23:959. <https://doi.org/10.1186/s12903-023-03558-y>.
- [14] Laurent H, Costes F, Richard R, Filaire M. Respiratory muscle endurance training among patients with chronic diseases: A systematic review of available evidence. *Experimental Physiology* 2025;111:2880–94. <https://doi.org/10.1113/ep092300>.
- [15] Zhang X, Zhang X, Yang D, Liu L, Huo X, Deng Z. Ultrasound monitoring respiratory muscle rehabilitation training can promote the recovery of diaphragmatic function in traumatic spinal cord injury (TSCI) patients. *European Journal of Medical Research* 2025;30:733. <https://doi.org/10.1186/s40001-025-03023-2>.
- [16] Amorim LKS, Silva N, Arandas WCPS, Silva BEP, Figueirêdo BB. Aspectos metodológicos da avaliação e medidas da espessura diafragmática com uso do ultrassom. *Revista Neurociências* 2023;31:1–25. <https://doi.org/10.34024/rnc.2023.v31.15422>.
- [17] Frampton GK, Livoreil B, Petrokofsky G. Eligibility screening in evidence synthesis of environmental management topics. *Environmental Evidence* 2017;6. <https://doi.org/10.1186/s13750-017-0102-2>.
- [18] Liberati A, Altman DG, Tetzlaff J, Mulrow CD, Gøtzsche PC, Ioannidis JPA, Clarke M, Devereaux PJ, Kleijnen J, Moher D. The PRISMA Statement for Reporting Systematic Reviews and Meta-Analyses of Studies That Evaluate Health Care Interventions: Explanation and Elaboration. *PLoS Medicine* 2009;6. <https://doi.org/10.1371/journal.pmed.1000100>.
- [19] Smith B, Littlewood C, May S. An update of stabilisation exercises for low back pain: a systematic review with meta-analysis. *BMC Musculoskeletal Disorders* 2014;15:416. <https://doi.org/10.1186/1471-2474-15-416>.
- [20] Boutemine L, El-Banna M, Atyeh R, Sami W, Rizvi MR. Effectiveness of Standardized Nurse-Led Triage Protocols in Improving Outcomes, Timeliness, and Accuracy in Road Traffic and Trauma Care in Low-Resource Settings: A Systematic Review. *Journal of Multidisciplinary Healthcare* 2026:1–15. <https://doi.org/10.2147/jmdh.s585877>.
- [21] Lansbury L, Rodrigo C, Leonardi-Bee J, Nguyen-Van-Tam JS, Lim WS. Corticosteroids as adjunctive therapy in the treatment of influenza. *Cochrane Database of Systematic Reviews* 2019;33:466–7. <https://doi.org/10.1002/14651858.cd010406.pub3>.

- [22] Firth J, Marx W, Dash S, Carney R, Teasdale S, Solmi M, Stubbs B, Schuch FB, Carvalho AF, Jacka FN, Sarris J. The Effects of Dietary Improvement on Symptoms of Depression and Anxiety: A Meta-Analysis of Randomized Controlled Trials. *Psychosomatic Medicine* 2019;81:265–80. <https://doi.org/10.1097/psy.0000000000000673>.
- [23] Neves RVP, Corrêa H de L, Reis AL, Andrade RV, Araújo TB de, Santos RL dos, Oliveira FFS, Araújo GEBM, Marra AVG, Baracho TA, Martins TO, Barbosa J, Garcia MN, Miller NMG, Deus LA, Rosa T dos S. Exercise Improves Respiratory Function, Body Fluid and Nitric Oxide in Hemodialysis Patients. *International Journal of Sports Medicine* 2024;45:994–1004. <https://doi.org/10.1055/a-2348-2684>.
- [24] Dong Z, Liu Y, Gai Y, Meng P, Lin H, Zhao Y, Xing J. Early rehabilitation relieves diaphragm dysfunction induced by prolonged mechanical ventilation: a randomised control study. *BMC Pulmonary Medicine* 2021;21:106. <https://doi.org/10.1186/s12890-021-01461-2>.
- [25] Huang J, Zhang W, Fu W, Le J, Qi Y, Hou X, Pan X, Li R, He B. Noninvasive evaluation of pulmonary hypertension using the second heart sound parameters collected by a mobile cardiac acoustic monitoring system. *Frontiers in Cardiovascular Medicine* 2023;10:1292647. <https://doi.org/10.3389/fcvm.2023.1292647>.
- [26] Medeiros AIC de, Brandão DC, Souza RJP de, Fuzari HKB, Barros CESR, Barbosa JBN, Leite JC, Cavalcanti FCB, Andrade AD de, Marinho PÉ de M. Effects of daily inspiratory muscle training on respiratory muscle strength and chest wall regional volumes in haemodialysis patients: a randomised clinical trial. *Disability and Rehabilitation* 2018;41:3173–80. <https://doi.org/10.1080/09638288.2018.1485181>.
- [27] Jansz TT, Özyilmaz A, Reekum FE van, Boereboom FTJ, Jong PA de, Verhaar MC, Jaarsveld BC van. Progression of coronary artery calcification in conventional hemodialysis, nocturnal hemodialysis, and kidney transplantation. University of Groningen Research Database (University of Groningen / Centre for Information Technology) 2020;15. <https://doi.org/10.1371/journal.pone.0244639>.
- [28] Criner GJ, Cordova F, Sternberg AL, Martínez FJ. The National Emphysema Treatment Trial (NETT): Part II: Lessons Learned about Lung Volume Reduction Surgery. *American Journal of Respiratory and Critical Care Medicine* 2011;184:881–93. <https://doi.org/10.1164/rccm.201103-0455ci>.
- [29] Silva JR da, Policarpo JH, Dantas D de S, Marinho PÉ de M. Effects of inspiratory muscle training on dyspnea and lung capacity in patients with chronic kidney disease on hemodialysis: a systematic review and meta-analysis. *Physiotherapy Theory and Practice* 2025;41:2202–10. <https://doi.org/10.1080/09593985.2025.2495129>.
- [30] Moraes T, Oliveira MS de, Cunha BLM, Silva JS, Marinho PÉ de M. Impact of chronic kidney disease on respiratory muscle strength, lung capacity, peripheral muscle strength, and functional capacity in dialysis patients: a systematic review. *Physiotherapy Theory and Practice* 2026;1–10. <https://doi.org/10.1080/09593985.2026.2624514>.
- [31] Teixeira M de S, Ferrari F, Dipp T, Carvalho GU, Bitencourt E da S, Saffi MAL, Stein R. Effects of intradialytic inspiratory muscle training at different intensities on diaphragm thickness and functional capacity: clinical trial protocol in patients undergoing haemodialysis. *BMJ Open* 2023;13. <https://doi.org/10.1136/bmjopen-2022-066778>.
- [32] Zheng J, Yin Q, Wang S, Wang Y, Xiao J, Tang T, Ni W, Ren L, Liu H, Zhang X, Liu B, Wang B. Ultrasound-assessed diaphragm dysfunction predicts clinical outcomes in hemodialysis patients. *Scientific Reports* 2022;12:16550. <https://doi.org/10.1038/s41598-022-20450-x>.
- [33] Fortescue R, Kew KM, Mathioudakis AG. Interventions to improve inhaler technique for people with asthma. *Cochrane Database of Systematic Reviews* 2017;2022. <https://doi.org/10.1002/14651858.cd012286.pub2>.
- [34] Abdelhamid A, Brown T, Brainard J, Biswas P, Thorpe G, Moore H, Deane K, AlAbdulghafoor FK, Summerbell C, Worthington HV, Song F, Hooper L. Omega-3 fatty acids for the primary and secondary prevention of cardiovascular disease. *Research Explorer (The University of Manchester)* 2018;3. <https://doi.org/10.1002/14651858.cd003177.pub3>.
- [35] O'Halloran KD. Diaphragm ultrasonography: A picture is worth a thousand words. *Experimental Physiology* 2024;110:358–9. <https://doi.org/10.1113/ep092452>.
- [36] Laghi F, Saad M, Shaikh H. Ultrasound and non-ultrasound imaging techniques in the assessment of diaphragmatic dysfunction. *BMC Pulmonary Medicine* 2021;21:85. <https://doi.org/10.1186/s12890-021-01441-6>.
- [37] Kambič T, Novakovic M, Tomažin K, Strojnik V, Jug B. Blood Flow Restriction Resistance Exercise Improves Muscle Strength and Hemodynamics, but Not Vascular Function in Coronary Artery Disease Patients: A Pilot Randomized Controlled Trial. *Frontiers in Physiology* 2019;10:656. <https://doi.org/10.3389/fphys.2019.00656>.
- [38] Mahdavi SS, Yared K, Wu G, Omar B, Savundra D, Nagai G, Hockmann E, Svendrovski A, Bellasi A, Tam P, Sikaneta T. Associations between echocardiographic findings and prospective changes in residual renal function in patients new to peritoneal dialysis. *Scientific Reports* 2019;9:18434. <https://doi.org/10.1038/s41598-019-54851-2>.
- [39] Shei R, Dekerlegand RL, Mackintosh KA, Lowman J, McNarry MA. Inspiration for the Future: The Role of Inspiratory Muscle Training in Cystic Fibrosis. *Sports Medicine - Open* 2019;5:36. <https://doi.org/10.1186/s40798-019-0210-3>.

- [40] Silva RN, Goulart C da L, Oliveira CR de, Mendes RG, Arena R, Myers JA, Borghi-Silva A. Respiratory muscle strength can improve the prognostic assessment in COPD. *Scientific Reports* 2024;14:12360. <https://doi.org/10.1038/s41598-024-54264-w>.
- [41] Marconi S, Gilberti G, Zanini B, Marullo M, Montani G, Risi B, Padovani A, Castellano M, Filosto M. Diet and nutrition in patients with neuromuscular disorders, as lifestyle factors affecting clinical parameters and quality of life: a narrative systematic review. *Nutrition Research Reviews* 2026;39:1–41. <https://doi.org/10.1017/s0954422426100420>.
- [42] Boon AJ, Sekiguchi H, Harper CJ, Strommen JA, Ghahfarokhi LS, Watson JC, Sorenson EJ. Sensitivity and specificity of diagnostic ultrasound in the diagnosis of phrenic neuropathy. *Neurology* 2014;83:1264–70. <https://doi.org/10.1212/wnl.0000000000000841>.
- [43] Pellicori P, Platz E, Dauw J, Maaten JM ter, Martens P, Pivetta E, Cleland JGF, McMurray JJV, Müllens W, Solomon SD, Zannad F, Gargani L, Girerd N. Ultrasound imaging of congestion in heart failure: examinations beyond the heart. *European Journal of Heart Failure* 2020;23:703–12. <https://doi.org/10.1002/ejhf.2032>.
- [44] Das A, Naranje P, Bhalla AS, Das CJ. Imaging of Pulmonary Manifestations in Chronic Kidney Disease: A Review. *Indographics* 2023;2:95–108. <https://doi.org/10.1055/s-0043-1774757>.