

# OCCUPATIONAL RESPIRATORY LOAD AND FUNCTIONAL SAFETY: A CRITICAL REVIEW OF INSPIRATORY MUSCLE TRAINING

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## ABSTRACT

**Background:** Sustained high respiratory load is recognised as a functional-safety issue in high-demand environments, yet remains underrepresented in occupational health. Constrained breathing, high inspiratory work and limited recovery may accelerate inspiratory muscle fatigue, increase perceptual strain and impair task execution. Inspiratory muscle training (IMT) has been proposed as a preventive strategy, but its effectiveness appears to depend on dose governance. **Objectives:** To critically appraise randomised controlled trials (RCTs) of IMT in competitive swimmers as a high-demand model, focusing on inspiratory muscle strength, functional capacity under respiratory load, pulmonary function and perceived exertion, and examine how dose governance influences safety-relevant outcomes. **Methodology:** A critical review of RCTs used a PICOT framework. Methodological quality was assessed using Oxford Levels of Evidence, the Physiotherapy Evidence Database (PEDro) scale and the Cochrane Risk of Bias 2.0 (RoB 2.0) tool. **Results:** Three RCTs were included (Oxford level 1b; PEDro 6–8/10; RoB 2.0: some concerns). Supervised IMT with progressive loading and documented adherence produced consistent improvements in inspiratory strength and functional-capacity markers, whereas weak dose verification was associated with absent or equivocal effects despite longer programme duration. **Conclusions:** IMT may support respiratory-load regulation and functional safety only under explicit and verifiable dose-governance conditions; duration alone is insufficient.

**Keywords:** Ventilatory Constraint, Dose Governance, Comparator Credibility, Adherence Monitoring, Perceptual Strain.

## 1. INTRODUCTION

Occupational health frameworks increasingly treat sustained exposure to high physiological load as a determinant of functional safety and long-term health. However, respiratory load, defined as the combination of ventilatory constraint, high inspiratory work, and limited recovery, remains underrepresented as a safety-relevant exposure relative to musculoskeletal and cardiovascular demands (Jurić *et al.*, 2019). Comparable respiratory-load profiles may also emerge in safety-critical, high-demand contexts in which breathing is constrained, inspiratory work is elevated, and recovery is curtailed across repeated bouts (McConnell, 2011). Accordingly, competitive swimming is used here as a controlled exposure model to examine dose-governed strategies for

respiratory-load management and safety-relevant functional capacity, rather than as a performance outcome in itself (Kilding *et al.*, 2010). In high-demand settings, constrained breathing and repeated high-intensity efforts can precipitate inspiratory muscle fatigue and altered ventilatory control, increasing perceived effort and reducing functional capacity with potential consequences for task execution and safety (Pyne & Sharp, 2014; Barbosa *et al.*, 2008).

A key mechanistic pathway is the respiratory metaboreflex, whereby inspiratory muscle fatigue promotes a redistribution of blood flow towards ventilatory muscles at the expense of locomotor musculature, increasing cardiovascular strain and reducing motor efficiency (McConnell, 2011). Under repeated or prolonged loading, this response is associated with higher perceptual strain and reduced exercise tolerance, supporting its relevance to safety-relevant functional limitation in contexts characterised by recurrent ventilatory stress (McConnell, 2011; HajGhanbari *et al.*, 2013).

Inspiratory muscle training (IMT) has been proposed as a targeted strategy to improve inspiratory muscle capacity and delay fatigue during sustained respiratory loading (Fernández-Lázaro *et al.*, 2021; HajGhanbari *et al.*, 2013). By applying an external resistive stimulus, IMT aims to increase inspiratory muscle strength and endurance, reduce the relative cost of breathing, and potentially attenuate metaboreflex-related strain. Evidence suggests improvements in inspiratory muscle function and selected ventilatory outcomes, but effects appear contingent on dose governance (relative intensity, progression, supervision, and adherence) (McConnell, 2011; HajGhanbari *et al.*, 2013; Fernández-Lázaro *et al.*, 2021).

Within this framework, swimming provides a high-demand exposure analogue in which respiratory load is systematically imposed through rhythmically constrained breathing, high inspiratory work during intense bouts, and limited recovery across training cycles (Fernández-Lázaro *et al.*, 2021). This exposure profile provides a biologically plausible and empirically testable context to examine how IMT may contribute to respiratory load governance and safety-relevant functional capacity, while also highlighting how methodological heterogeneity (notably, inadequate reporting of delivered dose and comparator credibility) limits translation into preventive practice (Pyne & Sharp, 2014; Barbosa *et al.*, 2008; Fernández-Lázaro *et al.*, 2021). Therefore, this review critically examines evidence from randomised controlled trials (RCTs) of IMT in competitive swimmers, synthesising its effects on inspiratory muscle strength, functional capacity under respiratory load, pulmonary function, and perceived exertion, while evaluating key dose-governance features (intensity, progression, supervision/adherence, and comparator credibility) in order to inform preventive respiratory-load management and functional safety in high-demand environments.

## 2. MATERIALS AND METHODS

This study presents a critical literature review of RCTs investigating IMT in competitive swimmers, with a primary focus on physiological markers of respiratory load, functional capacity, and safety-relevant outcomes within an occupational health framework.

To ensure conceptual consistency between the review question, eligibility criteria, and outcome interpretation, the clinical question was structured using the PICOT framework (Table 1).

**Table 1:** PICOT framework for structuring the clinical question.

| PICOT                   | Detailed description                                                                                                                                                                                |
|-------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>P (Population)</b>   | Competitive swimmers ( $\geq 14$ years), federated and regularly engaged in regional, national, or international competitions.                                                                      |
| <b>I (Intervention)</b> | Structured inspiratory muscle training (IMT) programmes using adjustable linear resistance devices (e.g., adjustable threshold-loading devices)                                                     |
| <b>C (Comparison)</b>   | Comparison with control conditions, including sham training or usual training without specific inspiratory muscle training.                                                                         |
| <b>O (Outcomes)</b>     | Inspiratory muscle strength and respiratory load control<br>Functional capacity under respiratory load<br>Pulmonary function under respiratory constraint<br>Perceived exertion and perceptual load |
| <b>T (Time)</b>         | Intervention durations ranging from 4 to 12 weeks, with follow-up assessments when available.                                                                                                       |

## 2.1. SEARCH STRATEGY

A structured literature search was conducted in PubMed and Scopus to identify RCTs examining the effects of IMT in competitive swimmers. Search terms were organised into three concept blocks and combined using Boolean operators as follows: (“inspiratory muscle training” OR “respiratory muscle training”) AND (“swimming” OR “swimmers”) AND (“performance” OR “pulmonary function” OR “perceived exertion”). Records retrieved from this search were then screened according to the predefined eligibility criteria. Population relevance was further confirmed through manual screening of titles, abstracts, and full texts, retaining only studies involving competitive swimmers with regular and structured training exposure. Search filters were applied to include articles published in English, limited to RCTs, and restricted to the last 10 years to ensure contemporary relevance of the evidence.

## 2.2. ELIGIBILITY CRITERIA

Eligibility criteria were predefined using the PICOT framework (Table 1) to ensure conceptual consistency between the research question, study selection, and outcome interpretation. Randomised controlled trials were eligible if they examined structured IMT interventions in competitive swimmers and reported outcomes relevant to respiratory load and functional capacity. Studies were required to include an appropriate comparator condition (sham training or usual training) and to be published in English within the specified time frame. Trials were excluded if they did not focus on competitive swimming populations, included participants with clinically diagnosed respiratory, cardiovascular, or neuromuscular conditions, combined IMT with other interventions precluding isolation of its effects, or failed to report outcomes relevant to respiratory load or functional capacity.

## 2.3. STUDY SELECTION AND DATA EXTRACTION

Study selection was conducted in two sequential stages in accordance with the predefined eligibility criteria. First, titles and abstracts retrieved from the database search were screened to identify potentially relevant records. Full-text articles were then assessed for final eligibility, with inclusion decisions based on alignment with the predefined population, study-design, and outcome criteria described above. Following structured database retrieval and sequential

screening of titles, abstracts, and full texts, three RCTs met the predefined eligibility criteria and were included in the final review.

Data extraction was undertaken using a structured approach to ensure consistency across the included studies. Extracted information comprised study design, participant characteristics, intervention features (including training load, duration, frequency, and progression), comparator conditions, outcome measures, and principal findings. Particular attention was given to variables related to dose delivery and monitoring, given their relevance to respiratory-load regulation, functional capacity, and safety under sustained ventilatory demand.

## 2.4. METHODOLOGICAL QUALITY AND RISK OF BIAS ASSESSMENT

Methodological quality was assessed using the Oxford Levels of Evidence, the Physiotherapy Evidence Database (PEDro) scale, and the Cochrane Risk of Bias 2.0 (RoB 2.0) tool. The appraisal focused on key domains of internal validity, including randomisation, allocation concealment, blinding, completeness of outcome data, and reporting transparency. Particular attention was paid to aspects especially relevant to inspiratory muscle training research, namely the clarity and consistency of intervention protocols, the appropriateness of comparator conditions, and the validity of outcomes related to respiratory load and functional capacity.

## 3. RESULTS

### 3.1. INCLUDED STUDIES

Three RCTs met the eligibility criteria and were included in the review (Cunha *et al.*, 2019; Yañez-Sepúlveda *et al.*, 2021; Tan *et al.*, 2023). All studies examined structured IMT in competitive swimmers and reported at least one outcome related to inspiratory muscle strength, functional capacity under respiratory load, pulmonary function, or perceived exertion (Table 2).

### 3.2. STUDY CHARACTERISTICS AND INTERVENTION FEATURES

The included trials differed in intervention duration, intensity prescription, progression procedures, supervision, and comparator design. Two studies used sham-controlled comparators (Cunha *et al.*, 2019; Yañez-Sepúlveda *et al.*, 2021), whereas one used usual training without sham (Tan *et al.*, 2023). Intervention duration ranged from 4 to 12 weeks. Inspiratory strength outcomes were reported using different measures across studies, including maximal inspiratory pressure (P<sub>I</sub>max) and the dynamic inspiratory strength index (S-Index). A comparative overview of study design, IMT dose characteristics, and outcome-level effects is presented in Table 2.

### 3.3. OUTCOME-SPECIFIC FINDINGS

**Inspiratory muscle strength:** Tan *et al.* (2023) and Yañez-Sepúlveda *et al.* (2021) reported improvements in inspiratory strength indices following IMT. Cunha *et al.* (2019) reported increases in inspiratory measures in both intervention and sham groups, with no clear between-group difference (Table 2).

**Functional capacity under respiratory load:** Tan *et al.* (2023) reported improvements in breathing-related task markers, including breathing frequency and distance to first breath, alongside task-performance outcomes. Yañez-Sepúlveda *et al.* (2021) reported improvements in time-trial performance across 50–200 m distances. Cunha *et al.* (2019) reported no clear between-group difference in swimming-performance proxies (Table 2).

**Pulmonary function under respiratory constraint:** Tan *et al.* (2023) reported increases in vital capacity, and Yañez-Sepúlveda *et al.* (2021) reported improvements in selected spirometric and ventilatory parameters. Cunha *et al.* (2019) did not report consistent between-group spirometric changes (Table 2).

**Perceived exertion and perceptual load:** Only Cunha *et al.* (2019) directly assessed perceived exertion using the Borg scale and reported no clear between-group difference. The remaining studies did not report direct perceptual measures (Table 2).

**Table 2:** Summary of included RCTs by PICOT domains, reporting IMT dose governance (intensity, progression, adherence/monitoring), comparator conditions, and outcome-specific effects.

| Study                                                                                                                                                                                                                                                                                                                                                             | Design / sample                                       | IMT prescription (dose control)                                                                                           | Comparator                                                         | Key effects (between-group, where available)                                                                                                                                                                                                            |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Cunha <i>et al.</i> , 2019                                                                                                                                                                                                                                                                                                                                        | RCT; swimmers; n=32 (IMT17/SHAM15); attrition in SHAM | 50% $PI_{max}$ ; adjustments to maintain 30 breaths; progression not clearly operationalised; self-logged adherence       | Sham IMT (15% $PI_{max}$ ), limited adherence/technique monitoring | IM strength: no clear between-group advantage; both groups $\uparrow PI_{max}$ ; Pulmonary: small $\uparrow FVC$ within IMT; no consistent between-group spirometry; Functional capacity: no clear between-group difference in swim performance proxies |
| Yañez-Sepúlveda <i>et al.</i> , 2021                                                                                                                                                                                                                                                                                                                              | RCT; swimmers; n=15 (EG9/SHAM6)                       | POWERbreathe; 2 sessions/day, 4 wk; 50% S-Index; progression reported; high adherence threshold                           | Sham IMT (15% S-Index), equivalent structure                       | IM strength: large effects ( $\uparrow S$ -Index/ $\uparrow MIF$ ); Pulmonary: variable; precision limited; Functional capacity: large improvements in time-trial tasks (50–200 m)                                                                      |
| Tan <i>et al.</i> , 2023                                                                                                                                                                                                                                                                                                                                          | RCT; swimmers; n=43 (EG: 20 / CON23)                  | Power Breather Plus; 3×30 inhalations/day (15–20 min), 6 wk; intensity/progression not clearly quantified as % $PI_{max}$ | Usual training (no sham)                                           | IM strength: $\uparrow PI_{max}$ , $\uparrow MIF$ , $\uparrow MIC$ ; Pulmonary: $\uparrow VC$ ; Functional capacity: $\downarrow$ breathing frequency, $\uparrow$ distance to first breath; improved sprint task outcomes                               |
| <b>Abbreviations:</b> CON: control; EG: experimental group; IM: inspiratory muscle; IMT: inspiratory muscle training; MIF: maximal inspiratory flow; MIC: maximal inspiratory capacity; $PI_{max}$ : maximal inspiratory pressure; RCT: randomised controlled trial; S-Index: dynamic inspiratory strength index; VC: vital capacity; wk: weeks; d/wk, days/week. |                                                       |                                                                                                                           |                                                                    |                                                                                                                                                                                                                                                         |

### 3.4. CRITICAL APPRAISAL OF METHODOLOGICAL QUALITY

The methodological quality and risk-of-bias profile of the included studies are summarised in Table 3, which presents the Oxford level of evidence, PEDro score, overall RoB 2.0 judgement, and the main sources of methodological bias.

**Table 3:** Methodological quality assessment of included studies based on the PEDro scale, Oxford Levels of Evidence, and the Cochrane Risk of Bias 2.0 (RoB 2.0) tool.

| Study (Year)                         | Oxford level | PEDro (/10) | RoB 2.0 overall judgement | Main sources of bias                                                       |
|--------------------------------------|--------------|-------------|---------------------------|----------------------------------------------------------------------------|
| Cunha <i>et al.</i> , 2019           | 1b           | 8           | Some concerns             | Low adherence; limited supervision; unclear equivalence of sham monitoring |
| Yañez-Sepúlveda <i>et al.</i> , 2021 | 1b           | 7           | Some concerns             | Small sample; incomplete blinding                                          |
| Tan <i>et al.</i> , 2023             | 1b           | 6           | Some concerns             | No sham comparator; limited blinding                                       |

**Abbreviations:** Oxford level according to the Oxford Centre for Evidence-Based Medicine. PEDro scores reflect methodological quality. RoB 2.0 overall judgement based on randomisation, deviations from intended intervention, missing outcome data, outcome measurement, and selective reporting.

### 3.5 INTERPRETATION OF METHODOLOGICAL QUALITY

All included studies were classified as level 1b evidence according to the Oxford Centre for Evidence-Based Medicine, corresponding to individual randomised controlled trials. PEDro scores ranged from 6 to 8, indicating overall moderate-to-good methodological quality, with variability primarily related to blinding procedures and control condition design (Burns *et al.*, 2011; de Morton, 2009).

Across studies, the most consistent sources of potential bias were the absence of participant and assessor blinding and, in one case, the lack of a sham comparator. These factors resulted in RoB 2.0 ratings of “some concerns” for all trials. Nevertheless, all studies employed randomised designs, objective outcome measures, and predefined protocols, supporting the internal validity of the primary findings.

The inclusion of a sham-controlled design in one trial provided stronger control of expectancy and placebo effects, whereas reduced adherence and incomplete reporting of intervention dose in other studies limited inference regarding dose–response relationships and respiratory load governance.

## 4. DISCUSSION

### 4.1. INSPIRATORY MUSCLE STRENGTH AND RESPIRATORY LOAD CONTROL

Inspiratory muscle strength is a key determinant of ventilatory efficiency and stability under constrained breathing, making it directly relevant to occupational respiratory load and functional safety in competitive swimming (Graham *et al.*, 2019; HajGhanbari *et al.*, 2013). Across the included RCTs, strength gains were most consistent when IMT was delivered with progressive relative loading and supervision, suggesting that respiratory load modulation is dose-dependent rather than time-dependent.

Supervised protocols over 4–6 weeks produced clear improvements in inspiratory strength in two trials (Tan *et al.*, 2023; Yañez-Sepúlveda *et al.*, 2021), despite differences in measurement (PI<sub>max</sub> vs S-Index). Mechanistically, these changes align with known adaptations—enhanced neuromuscular recruitment, local fatigue resistance, and diaphragmatic remodelling—supporting a lower relative cost of breathing under repeated high ventilatory demand (McConnell, 2011; Fernández-Lázaro *et al.*, 2021; Antonelli *et al.*, 2020; Kilding *et al.*, 2010).

In contrast, Cunha *et al.* (2019) reported no meaningful improvement after 12 weeks, a finding best explained by poor exposure fidelity: very low adherence (<30%), limited progression, and high baseline PI<sub>max</sub> (>130 cmH<sub>2</sub>O), consistent with reduced remaining adaptive reserve (Wylegala

*et al.*, 2006). From a functional safety standpoint, this trial is informative: without load governance (progression + monitoring), longer duration does not translate into risk-relevant capacity gains.

Overall, improvements in inspiratory strength and, by extension, respiratory load tolerance, appear contingent on individualised relative intensity, structured progression, and supervision, with the greatest margin for change in developing swimmers (Tier 2) (Tan *et al.*, 2023; Yañez-Sepúlveda *et al.*, 2021; McKay *et al.*, 2022).

#### 4.2. FUNCTIONAL CAPACITY UNDER RESPIRATORY LOAD

When the primary aim is preventive, swimming-related outcomes are more appropriately interpreted as indicators of functional capacity under respiratory constraint than as sport performance *per se*. Two RCTs showed improvements in task-relevant indicators after supervised, progressive IMT (Tan *et al.*, 2023; Yañez-Sepúlveda *et al.*, 2021). These improvements (e.g., faster completion of standardised tasks, increased distance to first breath, reduced breathing frequency) are best understood as markers of greater tolerance to ventilatory constraint and more stable task execution under high respiratory load.

The increase in distance to first breath is particularly informative in constrained-breathing contexts, as it may reflect improved inspiratory reserve and ventilatory control with less disruption to stroke mechanics, supporting sustained task efficiency and reduced functional strain (Pyne & Sharp, 2014; Barbosa *et al.*, 2008). Physiologically, this pattern is compatible with reduced inspiratory fatigue and delayed metaboreflex activation, which may preserve locomotor perfusion and attenuate systemic strain under repeated high-intensity bouts (Griffiths & McConnell, 2012; Jurić *et al.*, 2019; McConnell, 2011; Wells *et al.*, 2005).

Cunha *et al.* (2019) did not show clear functional gains, again reinforcing that functional benefits depend on delivered dose, not nominal programme length. In occupational terms, this suggests that IMT supports functional safety only when it reduces respiratory load for a given external task, which in turn requires verified exposure.

#### 4.3. PULMONARY FUNCTION UNDER RESPIRATORY CONSTRAINT

Pulmonary function outcomes are better understood as indicators of ventilatory reserve than as primary endpoints for safety-oriented IMT. Two RCTs reported improvements in selected indices after supervised IMT (Tan *et al.*, 2023; Yañez-Sepúlveda *et al.*, 2021), including variables linked to ventilatory capacity. In constrained environments such as swimming—where hydrostatic pressure and breathing rhythm impose mechanical load—incremental gains may be functionally relevant by increasing ventilatory reserve and reducing the relative strain of repeated workloads (Barbosa *et al.*, 2008; Bougault & Boulet, 2012; HajGhanbary *et al.*, 2013; McConnell, 2011).

However, findings were not consistent across all studies, and null effects in Cunha *et al.* (2019) suggest that pulmonary changes may be secondary to inspiratory strength gains and sensitive to adherence and baseline ceilings. From a safety-oriented perspective, the key message is that pulmonary function improvements matter insofar as they contribute to reserve under high respiratory demand, rather than as isolated spirometric changes (Wells *et al.*, 2005; Graham *et al.*, 2019).

#### 4.4. PERCEIVED EXERTION AND PERCEPTUAL LOAD

Perceived exertion is a safety-relevant mediator because perceptual strain can limit tolerance, degrade technique, and increase error risk under repeated exposure (Griffiths & McConnell,

2012; Pyne & Sharp, 2014). Evidence remains limited: only Cunha *et al.* (2019) assessed perceived exertion using the Borg scale and found no clear effect, which is unsurprising given low adherence and lack of progressive overload. The other trials did not measure perceptual outcomes, limiting inference.

Nonetheless, indirect indicators (e.g., reduced breathing frequency and increased distance to first breath) are compatible with reduced perceptual respiratory load through lower inspiratory fatigue and altered afferent feedback, but this remains hypothesis-generating rather than confirmatory (HajGhanbari *et al.*, 2013; McConnell, 2011). Within a preventive framework, standardised perceptual outcomes should be regarded as essential rather than optional. This is consistent with occupational-health research, in which validated instruments such as the Swedish Occupational Fatigue Inventory (SOFI) have been used to characterise perceived fatigue as a safety-relevant construct and to support the preventive assessment of work-related strain (Santos *et al.*, 2017).

#### 4.5. DOSE GOVERNANCE AND METHODOLOGICAL CONSTRAINTS FOR SAFETY INFERENCE

Across RCTs, outcome patterns align more consistently with delivered dose than with nominal programme duration. Supervised delivery, progressive relative loading, and documented adherence coincided with the clearest gains in inspiratory strength and functional capacity under ventilatory constraint (Tan *et al.*, 2023; Yañez-Sepúlveda *et al.*, 2021), whereas weaker dose verification and low adherence coincided with null or equivocal effects despite longer exposure (Cunha *et al.*, 2019). Comparator credibility (sham vs usual training) and limited reporting/control of concurrent training load further constrained safety-relevant inference (Eldridge *et al.*, 2021; Fernández-Lázaro *et al.*, 2021). Overall, IMT appears most defensible as a preventive tool when dose governance is explicit and verifiable. In this context, competitive swimming provides a controlled model for examining how respiratory-load exposure and dose-governed interventions may shape functional responses under repeated high-demand conditions (Jurić *et al.*, 2019; McConnell, 2011).

#### 4.6. LIMITATIONS

This review is limited by the small number of available RCTs and the modest sample sizes of the included studies, which predominantly involved adolescent competitive swimmers and therefore restrict generalisability across age groups and performance levels. Substantial heterogeneity in IMT prescription, progression, supervision, and adherence reporting limits dose-response inference and cross-study comparability. Although all studies were randomised, incomplete blinding, variable comparator credibility, and inconsistent monitoring of delivered dose introduce moderate risk of bias. Finally, the absence of follow-up assessments and inconsistent evaluation of perceptual safety outcomes constrain conclusions regarding the durability of adaptations and perceptual load modulation under sustained respiratory constraint.

### 5. CONCLUSIONS

Evidence from randomised trials indicates that inspiratory muscle training can support respiratory load regulation and functional safety in competitive swimmers only when delivered under controlled dose conditions, including supervised execution, progressive relative loading, and documented adherence. In the absence of effective dose governance, programme duration alone

does not appear sufficient to meaningfully reduce respiratory load or improve safety-relevant functional capacity.

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