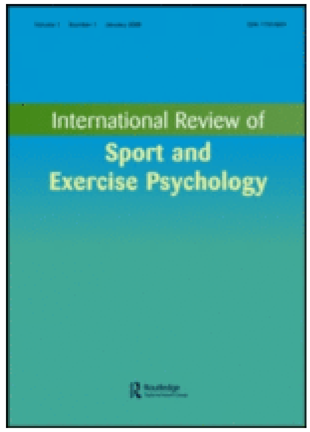

The Influence of Breathing Techniques on Physical Sport Performance: A Systematic Review and Meta-analysis

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Abstract

Breathing techniques are predicted to affect specific physical and psychological states, such as relaxation or activation, that might benefit physical sport performance (PSP). Techniques include slow-paced breathing (SPB), fast-paced breathing (FBP), voluntary hyperventilation (VH), breath-holding (BH), and alternate- and uni-nostril breathing. A systematic literature search of six electronic databases was conducted in April 2022. Participants included were athletes and exercisers. In total, 37 studies were eligible for inclusion in the systematic review, and 36 were included in the five meta-analyses. Random effects meta-analyses for each breathing technique were computed separately for short-term and longer-term interventions. Results showed that SPB and BH were related to improved PSP, with large and small effect sizes for longer-term interventions, respectively. In short-term interventions, SPB, BH, and VH were unrelated to PSP. There was some evidence of publication bias for SPB and BH longer-term interventions, and 41% of the studies were coded as having a high risk of bias. Due to an insufficient number of studies, meta-analyses were not computed for other breathing techniques. Based on the heterogeneity observed in the findings, further research is required to investigate potential moderators and develop standardised breathing technique protocols that might help optimise PSP outcomes.

Keywords: respiration; inhalation; exhalation; autonomic nervous system; athletes

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Introduction

The act of breathing occurs automatically and, to a certain degree, unconsciously. However, certain parameters such as breathing frequency (number of cycles per minute [cpm]) can be voluntarily controlled and used purposefully to achieve beneficial physiological and psychological states (Russo, Santarelli, & O'Rourke, 2017). The practice of modifying breathing parameters originates from practices such as yoga and meditation, which were first introduced to Western culture in the late 1800s (Gerritsen & Band, 2018; Jerath, Edry, Barnes, & Jerath, 2006; Russo et al., 2017). A diverse range of breathing techniques exist, such as slow-breathing – usually to induce relaxation (Gerritsen & Band, 2018; Russo et al., 2017) – or voluntary hyperventilation – usually to achieve psychophysiological activation (Kox et al., 2014). Due to the proposed benefits and inexpensive equipment required for these techniques, their application has gained popularity in diverse fields such as public health, clinical settings, and school and work environments (Gerritsen & Band, 2018; Russo et al., 2017). In the sport context, previous reviews and meta-analyses have explored the influence of one breathing technique (slow-paced breathing [SPB]) during longer-term interventions implemented with biofeedback (Jimenez Morgan & Molina Mora, 2017; Pagaduan, Chen, Fell, & Xuan Wu, 2020; Pagaduan, Chen, Fell, & Xuan Wu, 2021). These reviews support the potential of SPB to improve sport performance. However, we are unaware of any research syntheses exploring breathing techniques beyond SPB. The aim of this paper is to provide a systematic review and meta-analysis of all breathing techniques on sport performance.

For the purpose of this research, sport performance is operationalised as physical outcomes related to sport performance, such as speed and strength outcomes (see Toth, McNeill, Hayes, Moran, & Campbell, 2020). These outcomes may be of interest beyond the sport domain for other contexts involving aspects of physical performance, such as education, firefighting, medicine, military, music, police, and other organisational settings. The focus of this review is on breathing techniques that can be completed without additional devices directly influencing lung functioning, such as aided inspiration (Garver, Scheadler, Smith, Taylor, & Harbach, 2018) or gas concentration during breathing (Koelwyn, Wong, Kennedy, & Eves, 2013). This is to ensure that the breathing techniques reviewed can be easily accessed and used by athletes in the field. However, techniques involving biofeedback devices are included, as biofeedback does not directly change breathing conditions but is rather used for monitoring purposes, such as giving visual feedback on tidal volume to reduce partial pressure of end-tidal carbon dioxide ($PETCO_2$) during hyperventilation (Fujii et al., 2015). In protocols implementing SPB with biofeedback, participants are shown their beat-to-beat heart rate data to be able to determine the most suitable breathing frequency (Lehrer & Gevirtz, 2014) and/or to ensure that they follow the correct breathing pattern (Laborde, Allen, et al., 2021). Overall, these monitoring systems can aid in fine-tuning breathing techniques. However, they are not compulsory for completing the breathing techniques. In addition, breathing techniques using biofeedback can be performed by athletes in the field, in contrast to techniques involving changing respiratory load and gas concentration, where such devices constitute the main training medium.

Breathing techniques are classified into five main categories: SPB, fast-paced breathing (FPB), voluntary hyperventilation, breath-holding, and alternate- and uni-nostril breathing. A brief outline of each breathing technique is provided below, detailing how such breathing techniques might influence physical sport performance through physiological and/or psychological mechanisms.

Slow-paced breathing (SPB)

SPB aims to decrease respiratory frequency to under 10 cpm (Russo et al., 2017; Zaccaro et al., 2018). The benefits of SPB at the physiological level are based on its effects on respiratory sinus arrhythmia, the baroreflex, pulmonary afferents, the vagus nerve, and the strengthening of brain network dynamics (Bernardi, Gabutti, Porta, & Spicuzza, 2001; Gerritsen & Band, 2018; Laborde, Allen, et al., 2022; Laborde, Allen, et al., 2021; Noble & Hochman, 2019; Sevoz-Couche & Laborde, 2022; Shaffer & Meehan, 2020). Respiratory sinus arrhythmia reflects the increase in heart rate during inhalation and its decrease during exhalation (Berntson et al., 1997; Eckberg & Eckberg, 1982). Through SPB, the amplitude of respiratory sinus arrhythmia increases, stimulating the baroreflex (Bernardi et al., 2001), which represents the homeostatic system regulating blood pressure. Moreover, through the prolonged exhalation implemented in SPB, the vagus nerve activity regulating cardiac functioning (termed cardiac vagal activity [CVA]) increases, which in turn stimulates parasympathetic effects on the heart, creating relaxation effects (Bae, Matthews, Chen, & Mah, 2021; Gerritsen & Band, 2018; Laborde, Allen, et al., 2021; You, Laborde, Salvotti, et al., 2021; You, Laborde, Zammit, Iskra, Borges, & Dosseville, 2021; You, Laborde, Zammit, Iskra, Borges, Dosseville, et al., 2021; Zaccaro et al., 2018).

The increased activity of the vagus nerve on the heart is measured through heart rate variability (HRV). HRV is defined as the change in the time intervals between successive R peaks (Malik, 1996), and is considered a central measure of neurocardiac function, as it indexes the activity of the parasympathetic nervous system in regulating cardiac functioning through the vagus nerve (Berntson et al., 1997; Laborde, Mosley, & Thayer, 2017). Higher CVA relates positively to a large range of beneficial psychophysiological outcomes (Forte, Favieri, & Casagrande, 2019; Forte, Morelli, Grässler, & Casagrande, 2022; Holzman & Bridgett, 2017; Laborde, Mosley, Bellenger, & Thayer, 2022; Mosley & Laborde, 2022; Thayer, Ahs, Fredrikson, Sollers, & Wager, 2012), specifically regarding adaptability, resilience, and well-being, as it enables optimal interaction of neurocardiac processes to meet the physiological and psychological demands of the organism (Smith, Thayer, Khalsa, & Lane, 2017; Thayer, Hansen, Saus-Rose, & Johnsen, 2009). The increase in CVA during slow and deep breathing is thought to contribute to the neural induction of physiological relaxation. Studies implementing SPB have shown immunological improvements and reductions in stress-related psychopathology (Gerritsen & Band, 2018; Lehrer, Vaschillo, & Vidali, 2020; Russo et al., 2017; Zaccaro et al., 2018). Most research on athletes has focused on SPB with biofeedback (Jimenez Morgan & Molina Mora, 2017; Pagaduan et al., 2020; Pagaduan et al., 2021). However, several studies implementing SPB without biofeedback have also found positive effects on the physiological and psychological variables commonly associated with benefits after implementing SPB protocols (Hoffmann, Jendreizik, Ettinger, & Laborde, 2019). A frequency of ~6 cpm is thought to trigger the largest increases in baroreflex stimulation, resonance effects and increases in CVA (Laborde, Allen, et al., 2022; Lehrer & Gevirtz, 2014; Sevoz-Couche & Laborde, 2022). Importantly, no differences have been observed in physiological outcomes after implementing SPB with or without biofeedback (Laborde, Allen, et al., 2021; Wells, Outhred, Heathers, Quintana, & Kemp, 2012). Due to the proposed psychophysiological regulatory effects of SPB, this breathing technique represents a viable intervention for enhancing physical sport performance (Jimenez Morgan & Molina Mora, 2017; Pagaduan et al., 2020; Pagaduan et al., 2021).

Fast-paced breathing (FPB)

FPB is defined as a breathing technique with a respiratory frequency of more than 20 cpm (Tortora & Derrickson, 2014). Similar to SPB, FPB can also be found as part of yoga practices (Peng et al., 2004). However, less evidence is available regarding the psychological and physiological effects of FPB compared to SPB. During FPB, heart rate, oxygen (O_2) uptake, carbon dioxide (CO_2) elimination, systolic and diastolic blood pressure increase and

CVA decreases (Peng et al., 2004; Singh Bal, 2015; Upadhyay-Dhungel, Yadav, Prakash, & Nayak, 2016; Van De Borne et al., 2000). These patterns of physiological changes suggest an activation of the sympathetic nervous system and a decrease in the activation of the parasympathetic nervous system. However, these immediate changes seem transitory, given blood pressure values appear to return to baseline values after FPB has ceased (Upadhyay-Dhungel et al., 2016). Similarly, no long-term cardiovascular changes have been found in response to FPB (Pal, Velkumary, & Madanmohan, 2004; Sharma et al., 2013). Based on findings from short-term interventions, FPB can be expected to have an activating effect on the body that would benefit sport performance in circumstances that require a higher level of activation.

Voluntary Hyperventilation

Voluntary hyperventilation refers to voluntary pulmonary ventilation that is deeper and usually faster than normal respiration, exceeding the O_2 uptake and CO_2 removal ratio that the metabolism requires (McArdle, Katch, & Katch, 2015). It should be noted that hyperventilation refers to voluntary deep breathing at either a normal or fast breathing frequency (McArdle et al., 2015) and not to an exercise-induced physiological consequence of reaching the second ventilatory threshold (McArdle et al., 2015; Powers & Beadle, 1985). Voluntary hyperventilation is primarily characterized by a fall in blood $PETCO_2$ and a rise in blood pH, corresponding to a respiratory alkalosis (Hornsveld & Garssen, 1997). This respiratory alkalosis decreases the arterial CO_2 pressure, temporarily reducing the urge to breathe and consequently prolonging the breath-holding duration until the arterial CO_2 pressure rises again and triggers the urge to breathe (Schagatay, Andersson, Hallen, & Palsson, 2001).

Regarding sport performance, increases in acidity in muscles during high-intensity exercise are related to performance decreases due to compromises in energy supply and excitation-contraction (Sakamoto, Naito, & Chow, 2014). Strategies that can combat this increase in acidity might be useful for sustaining sport performance, as well as potentially aiding in recovery after intense exercise bouts (Sakamoto et al., 2014; Sakamoto, Naito, & Chow, 2020). During voluntary hyperventilation, blood O_2 levels increase, and CO_2 levels decrease. Therefore, it has been suggested that the increase in blood pH resulting from the decrease in CO_2 levels can delay the rapid decrease in blood pH induced by intense exercise, delaying fatigue (Jacob et al., 2015; Sakamoto et al., 2020). The physiological mechanisms underlying voluntary hyperventilation provide a rationale for its use as a pre-exercise routine to improve short-duration sport performance, such as swimming, diving, or sprinting (Jacob et al., 2015). In addition, voluntary hyperventilation is predicted to improve performance in short-duration high-intensity exercise via enhanced anaerobic energy supply, enabled by the maintenance of favourable cell conditions (Forbes, Kowalchuk, Thompson, & Marsh, 2007; McMahon & Jenkins, 2002) and improved muscle function (Green, 1997). Given these physiological effects, voluntary hyperventilation might be expected to benefit high-intensity sport performance.

Breath-holding

Breath-holding, also referred to as apnoea, is defined as the voluntary cessation of breathing (Alpher, Nelson, & Blanton, 1986). Voluntary apnoea consists of two phases; 1) the initial phase (i.e., easy-going), which persists until the physiological breaking point, and 2) the struggle phase, which is characterised by an increasing urge to breathe and progressive involuntary breathing movements (Dujic et al., 2009). Overall, prolonged breath-holding triggers a range of compensatory mechanisms involving an increase in blood pressure, redistribution of blood flow, and bradycardia (Eichhorn et al., 2017). Specifically, an increase in systemic norepinephrine is observed, contributing to blood shift from peripheral tissues to the central nervous system, which helps to preserve O_2 saturation in cerebral tissues for a longer period (Eichhorn et al., 2017). Breath-holding has been primarily studied in the diving response

(Foster & Sheel, 2005), where it is necessary to distinguish the effects of apnoea in air, with water immersion, and with the contact with water itself. Breath-hold diving elicits a specific physiological response, characterised by bradycardia, caused by an increase in CVA (Andersson, Liner, Runow, & Schagatay, 2002; Ferretti & Costa, 2003; Gooden, 1994), peripheral vasoconstriction (Leuenberger, Hardy, Herr, Gray, & Sinoway, 2001), and elevated mean arterial blood pressure (Guaraldi et al., 2009; Willie et al., 2015) in order to maintain sufficient O_2 supply to the brain (Eichhorn et al., 2017; Lindholm & Lundgren, 2009). This reaction is linked to sympathetic and parasympathetic activation that takes place during full-body immersed apnoea (Fagius & Sundlof, 1986; Ferretti & Costa, 2003; Foster & Sheel, 2005).

Breath-holding could affect sport performance through multiple mechanisms: the pronounced bradycardia can help to decrease overall activation levels (Eichhorn et al., 2017), and performing breath-holding during exercise can help simulate hypoxic conditions and hence trigger hypoxic training adaptations that are useful for competition (Brocherie, Cantamessi, Millet, & Woorons, 2022; Fornasier-Santos, Millet, & Woorons, 2018; Woorons et al., 2011; Woorons, Millet, & Mucci, 2019). Hypoventilation training is also classified as breath-holding in this systematic review. Hypoventilation is implemented by exhaling to residual volume, performing the exercises without breathing, and exhaling again afterwards (Fornasier-Santos et al., 2018). Mirroring hypoxic conditions, longer-term interventions involving hypoventilation at low pulmonary volumes trigger physiological adaptations via a delayed metabolic acidosis, indicating an improved buffer capacity (Brocherie et al., 2022; Fornasier-Santos et al., 2018; Woorons et al., 2008). Interventions coined as hypoventilation by their authors but which involved reduced breathing frequency at around 6 cpm are classified as SPB in this paper.

Alternate-nostril and Uni-nostril Breathing

Alternate- and uni-nostril breathing techniques rely on the use and manipulation of the nasal cycle, such as breathing only through one nostril while blocking the airflow through the other, aiming to achieve specific effects on the autonomic nervous system (Telles, Verma, Sharma, Gupta, & Balkrishna, 2017). Previous studies have reported activation effects of right-nostril breathing on the autonomic nervous system, increasing heart rate, blood pressure, and O_2 uptake (Sohal & Upadhyay-Dhungel, 2013; Telles, Nagarathna, & Nagendra, 1994; Telles et al., 2017). Right-nostril breathing has been suggested to activate the sympathetic nervous system, while left-nostril breathing has been proposed to activate the parasympathetic nervous system (Telles et al., 2019). The physiological background of this breathing technique has been proposed to rely on mechanical receptors in the nasal mucosa, which registers the unilateral flow of air across the nasal membranes and transmit these signals to the hypothalamus, which represents the higher centre for autonomic regulation (Shannahoff-Khalsa, Boyle, & Buebel, 1991; Telles et al., 2019; Telles et al., 2017). This influence on the autonomic nervous system indicates the potential effects of nostril breathing on sport performance. It is suggested that due to the effects of right-nostril breathing on increasing sympathetic nervous activity and the effects of left-nostril breathing on decreasing sympathetic nervous activity, the balancing of the autonomic nervous system is achieved through alternate-nostril breathing (Raghuraj & Telles, 2008). Alternate- and uni-nostril breathing could therefore impact sport performance through their activating and deactivating effects.

Psychological effects of Breathing Techniques

Breathing techniques might also impact physical sport performance through psychological mechanisms. The link between respiration and brain activation is established through various sensory pathways, as breathing contributes to the ongoing modulation of cortical neuronal activity, in turn affecting not only motor and sensory processes but also cognitive and emotional ones (Heck et al., 2017).

Regarding SPB, one of its key physiological outcomes is to trigger an increase in CVA (Laborde, Allen, et al., 2021; Lehrer & Gevirtz, 2014; Sevoz-Couche & Laborde, 2022). A theoretical model that attempts to explain the connection between SPB and psychological mechanisms is the *neurovisceral integration model* (Smith et al., 2017; Thayer et al., 2009), which makes predictions regarding the psychophysiological states associated with CVA. The neurovisceral integration model is based on the functioning of the central autonomic network (Benarroch, 1997) and assumes that a higher CVA is associated with enhanced executive functioning, emotion regulation, and overall self-regulation. Given the importance of executive function (Kalen et al., 2021; Scharfen & Memmert, 2019), emotion regulation (Beatty & Janelle, 2019; Ruiz & Robazza, 2021), and self-regulation (e.g., McCormick, Meijen, Anstiss, & Jones, 2018) to sport performance, these psychological adaptations might also contribute somewhat to changes in physical sport performance.

FPB has been identified as a beneficial strategy for improving information processing and eliciting faster responses to environmental changes (Boyadzhieva & Kayhan, 2021). The predominantly positive effects on attention are suggested to be driven by increased sympathetic activation, marked by elevated norepinephrine secretion. This mechanism is proposed to be involved in the regulation of the frontoparietal attention network (Sara & Bouret, 2012), suggesting that the neural basis of the effects which FPB exert on the attention-related brain regions resembles that of moderate-intensity exercise (Radel, Tempest, & Brisswalter, 2018).

At the psychological level, (involuntary) hyperventilation has been primarily linked to anxiety and panic attacks, based on the Pavlovian conditioning paradigm (Ley, 1994, 1999). Nevertheless, it has been suggested that combining hyperventilation with positive associations might decrease its negative conditioning (Salkovskis & Clark, 1990). Used in combination with other techniques, voluntary hyperventilation has been found to contribute to enhanced psychophysiological activation (Citherlet, Crettaz von Roten, Kayser, & Guex, 2021; Kox et al., 2014). Future research is still needed to clarify the specific psychological effects of voluntary hyperventilation.

Regarding alternate-nostril breathing, little is known about its potential psychological effects. On a more general account, inhaling through the nose, in comparison to inhaling through the mouth, is suggested to synchronise activity in the olfactory cortex as well as in limbic-related brain areas, including the amygdala and hippocampus, triggering optimised cognitive processing and behavioural adaptation (Noble & Hochman, 2019; Zelano et al., 2016). In summary, breathing techniques could impact sport performance through several psychological mechanisms, but a more comprehensive understanding of these connections is needed and requires further research.

The Current Study

There is considerable evidence that breathing techniques have diverse physical and physiological effects that could benefit sport performance. However, as far as we are aware, no previous systematic review has been conducted that attempted to synthesise research on breathing techniques and sport performance. Previous reviews (Jimenez Morgan & Molina Mora, 2017; Pagaduan et al., 2020; Pagaduan et al., 2021) have tended to focus on one breathing technique (SPB) and have not taken into consideration other breathing techniques. Moreover, they have only included studies implementing SPB using HRV biofeedback and excluded studies implementing SPB without biofeedback. Additionally, they include studies such as case reports, experimental studies without a control group, or SPB combined with other techniques, somewhat limiting understanding of the efficacy of SPB as a standalone intervention. Previous reviews have also not separated effects identified in single-session (short-term) from longer-term interventions. In light of this, we elected to conduct a new systematic review to provide a comprehensive overview of the field, following the definition of Lasserson, Thomas, and Higgins (2019, p.3) “a systematic review attempts to collate all the empirical evidence that fits pre-specified eligibility criteria in order to answer a specific research question. It uses explicit, systematic methods that are selected with a view to minimizing bias, thus providing more reliable findings from which conclusions can be drawn and decisions made". The aim of this systematic review was to synthesise all research on breathing techniques as they relate to physical sport performance, using meta-analyses where possible to compute average effect sizes across studies to help quantify the effectiveness of short-term and longer-term interventions.

Method

The systematic review was pre-registered in PROSPERO (CRD42020200784) and is reported using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher, Liberati, Tetzlaff, Altman, & Group, 2009; Page et al., 2021). Details (including the PRISMA checklist) can be found in the Supplementary Material.

Literature Search

The database search was first conducted in July 2020 and updated in April 2022. The search included six databases: PubMed, Web of Science, ProQuest, PsycINFO, Scopus, and SPORTDiscus. The search terms and restriction criteria are detailed in Table 1. All studies identified through the initial search were imported into Zotero, where duplicates were removed.

Insert Table 1 here

Eligibility Criteria

Eligibility criteria are described in line with the PICOS criteria (Methley, Campbell, Chew-Graham, McNally, & Cheraghi-Sohi, 2014).

Participants

Participants were required to be active sport participants of any expertise level and engage in a regular sport regimen. The criterion for their engagement in regular sport and exercise was met if participants followed a sport or exercise training protocol during the time course of the study. Consequently, participants were either athletes taking part in training and sport competitions, or exercisers actively engaged in a regular exercise regimen for reasons other than competitive ones. All participants were included, regardless of their health status. No specific criteria were set for sport discipline, age, or gender. Studies not reporting participants' sport or exercise engagement were excluded if it could not be established whether they engaged in regular sport and/or exercise training.

Interventions

Interventions considered were any breathing techniques performed in the absence of concomitant stimuli which explicitly aimed to actively influence breathing. The breathing interventions considered were categorised into SPB, FPB, voluntary hyperventilation, breath-holding, and alternate-/uni-nostril breathing. Techniques implementing a breathing frequency lower than 10 cpm are defined as SPB (Russo et al., 2017; Zaccaro et al., 2018). Of note, spontaneous breathing normally occurs between 12 and 20 cpm (Tortora & Derrickson, 2014). FPB is defined as a respiratory frequency of more than 20 cpm. Voluntary hyperventilation can be achieved by either manipulating breathing frequency and/or breathing depth, using a breathing frequency above a normal breathing rate and/or by breathing deeper than usual (McArdle et al., 2015). In both cases, the goal of voluntary hyperventilation is to reduce $PETCO_2$. Techniques involving the cessation of breathing for long periods are referred to as breath-holding (Alpher et al., 1986). The techniques mentioned above focus either on a pattern of nasal inhalation and oral exhalation or only oral breathing. However, some techniques also focus solely on nasal inhalation and exhalation. These techniques can be performed either through one nostril (a uni-nostril technique) or through the right and left nostril alternatively (alternate-nostril breathing).

Other types of breathing techniques, such as yogic and diaphragmatic breathing, were also included if they were able to fit the inclusion criteria of at least one of the five main categories. Breathing techniques implemented simultaneously with other interventions, such as visualisation or watching motivational videos, were excluded. This was done to ensure a clear investigation of the effects of the breathing technique on physical sport performance variables. Moreover, breathing interventions performed with devices altering the gaseous composition or introducing an inspiratory or expiratory load were also excluded. However, biofeedback or devices measuring physiological indexes (such as $PETCO_2$ or blood pH) were included as they are used to ensure the correct completion of the breathing technique or to determine breathing frequency. Breathing techniques implemented during exercise were included if they also implemented a control condition with the same exercise protocol without the breathing intervention.

Control

Only studies with a placebo and/or control group or condition as a comparison (in which spontaneous breathing was not modified) were included.

Outcomes

Studies were included if they measured outcomes capturing objective measures of physical sport performance. These include time, speed, strength, or specific sport performance indexes such as stroke rate in swimming or soccer agility (based on Harris, Allen, Vine, & Wilson, 2021; Murdoch et al., 2021; Noetel, Ciarrochi, Van Zanden, & Lonsdale, 2017; Rupprecht, Tran, & Gröpel, 2021; Toth et al., 2020). These outcomes could be combined, such that a decrease in performance time, and in increase in strength or speed, represent better sport performance. Given that the scientific investigation of physical sport performance often requires breaking down its components to tease out mechanisms and specify effects, our classification of physical sport performance includes not only objective performance markers similar to those obtained as outcomes of sport competitions, but also any physical outcome linked to sport performance, such as power measured during a cycling ergometer test, or bench/leg press performance (similar to Harris et al., 2021; Murdoch et al., 2021; Noetel et al., 2017; Rupprecht et al., 2021; Toth et al., 2020). Studies investigating short-term and/or longer-term breathing interventions were eligible for inclusion. Short-term (acute) interventions were defined as studies which implemented the breathing intervention only once. If the study implemented different breathing techniques on different days, this study was still deemed as short-term if each technique was implemented only once. In contrast, longer-term (chronic) interventions were defined as studies involving multiple sessions (over several days, weeks, or months) with the same breathing technique intervention. This classification was based on a preliminary appraisal of the literature, where it appeared that studies were either implementing breathing techniques on a single occasion (e.g., Sakamoto et al., 2020; You, Laborde, Zammit, Iskra, Borges, & Dosseville, 2021), or implementing breathing interventions that lasted several sessions (e.g., Fornasier-Santos et al., 2018; Jimenez Morgan & Molina Mora, 2017; Pagaduan et al., 2020; Pagaduan et al., 2021). While previous systematic reviews and meta-analyses focused solely on long-term interventions (Jimenez Morgan & Molina Mora, 2017; Pagaduan et al., 2020; Pagaduan et al., 2021), we felt that it was also important to consider studies involving short-term interventions (a single session). As such short-term interventions could provide an opportunity for athletes/exercisers to use in the field with little time investment and training, both the effects of short-term and longer-term interventions are considered in separate meta-analyses.

Study designs

Study designs eligible for inclusion were randomised-control studies and studies using within- and/or between-subjects designs.

Study Selection

Studies exported from the search of the electronic databases were independently reviewed by two researchers (MI and NZ). Studies were first reviewed by title. If the study was deemed relevant or the relevance was unclear, then the study progressed to abstract review. Again, if the study was deemed relevant or the relevancy was unclear, then the study progressed to a full-text search. After the initial review of papers at full-text level, a citation network analysis of these papers was performed, manually evaluating the reference list of all full texts screened, as well as the reference list of potentially relevant existing review articles. New articles citing the included articles were also explored for potential relevance using the dedicated function in Web of Science and Google Scholar. A third reviewer with experience in systematic reviews (SL) supervised the full-text final decision process. There were no discrepancies noted between MI and NZ. To ensure quality in the selection and screening process, the two reviewers (MI and NZ) were trained prior to the selection processes, and interrater reliability was calculated. In addition, several pilot data extractions were performed with the third reviewer (SL) prior to commencing data extraction for this paper in order to clarify any doubts regarding the criteria related to the selection and screening process. Any further uncertainty of the first two reviewers (MI and NZ) during the selection and screening process was directly clarified with the third reviewer (SL).

Data Extraction

Two researchers (MI, NZ) independently conducted the data extraction. Extracted information included: breathing technique, short-term or longer-term intervention, the number of sessions (for longer-term effects), participant characteristics (age, gender, sport discipline, healthy/clinical), type of sport, outcomes measured, type of outcome measured, the study design (within vs between-subject design), publication year, breathing rate (in cpm), inhalation/exhalation ratio, nose or mouth breathing, deep or shallow breathing, breathing pacers used, body position (e.g., lying down or standing), and whether biofeedback was used. A third researcher (SL) supervised the data extraction process. No discrepancies were observed between the researchers. In the case of missing data, authors were contacted, and the missing data were requested. If no reply was received, the study was included in the systematic review but excluded from the meta-analysis if sufficient information on effect sizes was not available. Authors were also contacted and asked for any unpublished data potentially relevant to the research synthesis (no additional unpublished studies were identified).

Risk of Bias

The risk of bias was assessed using the Risk of Bias 2 framework (Sterne et al., 2019). Studies were assessed on five criteria, each of which received a rating of either low risk, some concerns, or high risk of bias. The five domains were: 1) risk of bias from the randomisation process, 2) risk of bias due to deviations from the intended intervention, 3) risk of bias due to missing outcome data, 4) risk of bias in measurement of the outcome, and 5) risk of bias in selection of the reported result. Each study received an overall risk of bias score. If a study received a high risk of bias rating in one domain, the overall study was deemed at high risk of bias. A study received an overall judgement of some concerns, if some concerns were given in at least one domain, or if the domains receiving some concerns did not substantially influence confidence in study results. A low-risk rating was given if the study received low-risk ratings in all domains. Two researchers (MI and NZ) reviewed each study independently. Thereafter, the inter-rater reliability was conducted and revealed two discrepancies between the reviewers, showing a 99.1% agreement in total. One discrepancy was in the domain related to deviations from intended interventions, and the second was in the domain related to selecting the reported result. However, no discrepancies arose in the overall risk of bias judgement. A third reviewer (SL) reviewed the inter-rater risk of bias judgments as well as discrepancies arising between the two researchers and made the final decision.

Effect Sizes

Hedges' *g* effect size was used to estimate the pooled mean effect as this is generally considered the best estimate for meta-analyses of studies with small sample sizes (Durlak, 2009; Lakens, 2013). The computation tables (including all formulae references [page and formula reference number] - based on Borenstein, Hedges, Higgins, & Rothstein, 2009) used to compute the effect sizes for the different study designs are provided on the Open Science Framework. A positive effect size represents a beneficial effect of breathing interventions on physical sport performance. In cases where a higher value was indicative of worse performance (e.g., time in swimming), the effect size direction was reversed such that a positive effect size represented better performance for the breathing intervention condition. Data were pooled in interventions when several control groups were used, when several time points were measured during the same intervention, and when control/experimental groups were split according to nostril dominance (Higgins & Thomas, 2019). In cases where data were pooled, the sample size (*N)* of participants was adjusted for the effect size calculation. In cases of multiple effects per intervention group, the sample size was adjusted (*N/number of reported effect sizes*) for the effect sizes calculation. Based on contemporary guidelines for effect size interpretation, an effect size g = 0.20 was considered *small* at the level of single events (but potentially more consequential in the long-term), an effect-size g = 0.41 was considered *medium* and of some explanatory and practical use even in the short-term, and an effect-size g = 0.63 was considered *large* and potentially powerful in both the short and long-term (Funder & Ozer, 2019).

Statistical Analysis

All analyses were conducted using R Studio (Version 1.2.1093), using the packages *meta*, *metafor,* and *metaviz* (Viechtbauer, 2010). The full R script is available on the Open Science Framework, as well as all csv files used for analyses (including the ones of the sensitivity analysis)[1]. Effect sizes across studies were pooled using a random-effect model (Higgins & Thomas, 2019). Separate meta-analyses were run for each breathing technique, distinguishing further between short-term and longer-term interventions. According to

[1] 10.17605/OSF.IO/XK59D

Viechtbauer and Cheung (2010), outliers were estimated using studentized deleted residuals. In within-subject designs or between-subject designs with change scores, the Hedges' g (SMD = MD/SDpooled) and its standard error were computed according to recommendations from Borenstein et al. (2009; 4.15 – page 24) and the Cochrane Handbook (Higgins et al., 2022; chapter 23, section 23.2.7.2). The standard error was computed using the imputation of a correlation coefficient at 0.6 between the performances of pre-breathing intervention and post-breathing intervention. To assess the reliability of this coefficient, sensitivity analyses were run up to the averaged coefficients of correlation ±0.20 per 0.05 interval (between 0.4 and 0.8). No differences in the relationships between effect sizes, significance tests, and outlier detection were identified, underlying the reliability of our results.

Heterogeneity

The between-study heterogeneity was measured using Tau^2 (variance of true effects, using Hedges' estimator (Hedges & Olkin, 1985)), and further assessed using the I^2 statistic, which measures the percentage of the observed variance reflecting the variance of the true effects rather than sampling error (Borenstein, 2019; Higgins, Thompson, Deeks, & Altman, 2003). Moderator analyses were planned in case $I^2 > 50\%$, with intervention length, type of sport, type of outcome, pre-/during/post-exercise intervention, nose/mouth breathing, deep/shallow breathing, and risk of bias estimated as potential moderators. The prediction interval was also computed to consider the potential effect of breathing techniques when it is applied within an individual study setting, as this may be different from the average effect (Riley, Higgins, & Deeks, 2011). The prediction interval can be defined as the interval within which the effect size of a new study would fall if this study was selected randomly from the same population of the studies already included in the meta-analysis (Ades, Lu, & Higgins, 2005; Spineli & Pandis, 2020). In other words, it tells us how the true effect varies across populations, and it does it on the same scale as the computed effect sizes, allowing us to directly evaluate the utility of an intervention. The Hartung and Knapp method was used to adjust confidence intervals and test statistics (Hartung & Knapp, 2001a, 2001b; IntHout, Ioannidis, & Borm, 2014).

Small study effects

Small study effects (an indicator of potential publication bias) were first assessed by visual inspection of funnel plots and followed up using Egger's regression asymmetry test. If evidence for asymmetry was found ($p < 0.100$, one-tailed), the trim and fill procedure was used to estimate the number of potential missing effects and provide an adjusted Hedges' *g* estimate (pseudo Hedges' *g*) (Duval & Tweedie, 2000; Egger, Davey Smith, Schneider, & Minder, 1997; Viechtbauer & Cheung, 2010).

Results

Study Search

The initial database search resulted in 14,860 identified records. An additional 6,479 records were identified through the citation network analysis. After removing duplicates, 18,598 records were included for screening. In total, 461 studies were reviewed at the full-text level, with 424 studies excluded according to the inclusion criteria for the systematic review. The complete selection process is presented in Figure 1.

Insert Figure 1 here

From the total of 37 studies [74 effect sizes] included, 13 implemented SPB (five for short-term effects [five effect sizes], eight for longer-term effects [13 effect sizes]), 13 implemented breath-holding (six for short-term effects [10 effect sizes], seven for longer-term effects [20 effect sizes]), ten implemented hyperventilation (all for short-term effects [21 effect sizes]) and one implemented FPB (short-term effect [5 effect sizes]). One study investigated the effects of both breath-holding and voluntary hyperventilation (Malakhov, Makarenkova, & Melnikov, 2014). No studies were identified that tested the effects of alternate- and uni-nostril breathing. Sample sizes ranged from 7 to 67, and participants' age ranged from 15.4 ± 1.4 to

38.6 ± 5.9 years, with a grand-mean age of 22.6 ± 5.6 years. Participants were all in good health and engaged in a regular exercise/sport regimen or were competitive athletes in sports including swimming, rugby, dance, cycling, triathlon, running, basketball, Jiu-Jitsu, yoga, soccer, athletics, volleyball, hockey, and power-training.

Included studies investigated the effect of breathing interventions on physical markers of sports performance including swimming (speed, k = 3; stroke rate, k = 4; time, k = 11; coordination index, k = 1; number of sprints, k = 1), cycling (power output, k = 13; speed, k = 1; time, k = 2), running (speed, k = 5; time, k = 13; number of sprints, k = 1; Yo-Yo Intermittent Recovery Level 1 test performance, k = 1), balancing (k = 2), dance (points, k = 1), basketball (shooting, k = 1; passing, k = 1; dribbling, k = 1), shooting (accuracy, k = 1), finger and arm-tapping speed (k = 2) and strength exercises (burpees, k = 1; bench press, k = 1; grip strength, k = 2; leg and back strength, k =1; knee extensions, k = 1, leg press, k = 1; counter movement jump, k = 1, and squat jump, k = 1). In total, 22 studies [41 effect sizes] were short-term breathing interventions, and 15 studies [33 effect sizes] were longer-term interventions. Regarding the timing of the breathing technique, nine studies implemented breathing techniques before performing sport activities, 18 performed breathing techniques during sport, and six applied breathing techniques as a recovery method between sport exercise sets. Other studies did not specify the timing of the breathing intervention. Measured outcomes fell into four main categories of time, strength, speed, and idiosyncratic sport-specific performance measures. Time was measured as a performance outcome in 18 studies, 14 studies reported strength outcomes, nine studies reported speed outcomes, and 12 studies reported specific performance outcome measures. Overall, 20 studies used a within-subject design and 17 studies used a between-group design. Details on included studies are reported in Table 2, the full reference of each study is presented in Table 3, and a comparative overview is presented in Table 4.

Insert Table 2 here

Insert Table 3 here

Insert Table 4 here

Risk of Bias

The risk of bias evaluation revealed that 22 studies (59%) were coded as having some risk of bias, while 15 (41%) studies were coded as having a high risk of bias. The main domains receiving some concerns were the risk of bias in the measurement of the outcome and the risk of bias in the selection of the reported result. The large number of studies receiving a high-risk rating was due to the studies not being pre-registered. The results of the risk of bias assessment are presented in Table 5.

Insert Table 5 here

Meta-analyses

Meta-analyses were run for three breathing techniques: SPB (short-term and longer-term interventions), breath-holding (short-term and longer-term interventions), and hyperventilation (short-term interventions), with separate analyses run for short-term and longer-term interventions.

Slow-paced breathing

For short-term interventions, there was no significant difference (p = .232) in physical sport performance between SPB and control conditions, $k = 5$, $g = 0.08$ (95% CI: -0.07 to 0.23), with small to moderate heterogeneity (prediction interval [-0.20 to 0.35]) entirely due to sampling error ($I^2 = 0\%$; Tau² = 0; see Figure 2). The prediction interval indicates that the true effect sizes in 95% of comparable populations will fall somewhere in between small negative to small positive effects. Studentized residuals showed no obvious outliers. Egger's test for funnel plot asymmetry was not computed due to the low number of effect sizes. A visual inspection did not suggest any asymmetry (Figure 3).

Insert Figure 2 here

Insert Figure 3 here

For longer-term interventions, there was a large difference ($p < .001$) in physical sport performance between SPB and control conditions, $k = 13$, $g = 0.64$ (95% CI: 0.31 to 0.98), demonstrating that those in the SPB conditions performed better than those in control conditions. There was a large heterogeneity in the results (prediction interval [0 to 1.29]) but entirely due to sampling error ($I^2 = 0\%$; Tau² = 0; Figure 4). The prediction interval indicates that the true effect sizes in 95% of comparable populations will fall somewhere in between null to large positive effects. Studentized residuals indicated no outliers. Egger's test for funnel plot asymmetry showed some evidence of a small-study effect ($p = .020$) and, potentially, publication bias. A trim-and-fill analysis showed three missing studies on the left side (see Figure 5). With these three missing effects imputed, the effect size was reduced from large to moderate but remained significant ($p < .050$) in favour of SPB over control conditions, $k = 16$, $g = 0.48$ (95% CI: 0.06 to 0.89).

Insert Figure 4 here

Insert Figure 5 here

Breath-holding

For short-term interventions, there was no significant difference ($p = .098$) in physical sport performance between breath-holding and control conditions, $k = 10$, $g = -0.40$ (95% CI: -0.89 to 0.09). There was a very large heterogeneity in the results (prediction interval [-1.95 to 1.15]) with 83% of the variance in the observed effect reflecting variance in the true effect ($I^2 = 83.4\%$; Tau² = 0.40; Figure 6). The prediction interval indicates that the true effect sizes in 95% of comparable populations will fall somewhere in between large negative to large positive effects. Studentized residuals indicated two potential outliers. These two studies (Guimard et al., 2014; Malakhov et al., 2014) had very large negative effect sizes (respectively $g = -1.89$,

576 SE_g= 0.38; and g = - 1.52, SE_g= 0.21). Yet, no moderator analysis was run due to the
577 asymmetrical distribution of effect sizes (k = 2 vs. k = 8) and given no clear moderator emerged
578 from the two studies showing the large negative effect sizes. Analyses were re-run with these
579 studies excluded, with a non-significant effect size observed, k = 8, g = -0.09 (95% CI: -0.20
580 to 0.02). There was still moderate to large heterogeneity in the results (prediction interval [-
581 0.34 to 0.16]) but entirely due to sampling error this time (I^2 = 0%; Tau^2 = 0). Thus, one – or
582 several - moderators between these two groups of studies explained all the variance in the true
583 effect. Egger's test for funnel plot asymmetry was not computed due to the low number of
584 effect sizes. However, a visual inspection of the data suggested a small amount of asymmetry
585 (Figure 7).

586 Insert Figure 6 here

587 Insert Figure 7 here

588 For longer-term interventions, there was a significant difference (p < .001) in physical
589 sport performance between breath-holding and control conditions, k = 20, g = 0.44 (95% CI:
590 0.23 to 0.66) with moderate heterogeneity in the results (prediction interval [0.16 to 0.73])
591 entirely due to sampling error (I^2 = 0%; Tau^2 = 0; Figure 8). The prediction interval indicates
592 that the true effect sizes in 95% of comparable populations will fall somewhere in between
593 small to large positive effects. Studentized residuals indicated no outliers. A visual inspection
594 of the data suggested a small asymmetry (Figure 9) that was confirmed by the Egger's test
595 showing evidence of a small-study effect (p = .088) and, potentially, publication bias. The trim-
596 and-fill analysis showed three missing studies on the left side, with a significant effect (p <
597 .010) observed for the adjusted Hedges' g, k = 23, g = 0.34 (95% CI: 0.09 to 0.58).

598 Insert Figure 8 here

599 Insert Figure 9 here

600 ***Voluntary Hyperventilation***

For short-term interventions, there was no significant difference (p = .140) in physical sport performance between voluntary hyperventilation and control conditions, k = 20, g = 0.06 (95% CI: -0.02 to 0.14). There was a small heterogeneity in the results (prediction interval [g = -0.05 to 0.16]) entirely due to sampling error (I^2 = 0%; Tau^2 = 0; Figure 10). The prediction interval indicates that the true effect sizes in 95% of comparable populations will fall somewhere in between null to small positive effects. Studentized residuals indicated no outliers. A visual inspection of the data suggested a potential asymmetry (Figure 11) that was not confirmed by the Egger's test (p = .131).

Insert Figure 10 here

Insert Figure 11 here

Discussion

The aim of this review was to synthesise all previous research on breathing techniques and physical sport performance. The breathing techniques tested in studies included SPB, FPB, hyperventilation, and breath-holding. Results showed that SPB and breath-holding were related to improved physical sport performance, with large and small effect sizes for longer-term interventions, respectively. In short-term interventions, SPB, breath-holding, and voluntary hyperventilation were unrelated to physical sport performance. There was some evidence of publication bias for SPB and breath-holding longer-term interventions, and a high percentage of studies (41%) were coded as having a high risk of bias. Due to an insufficient number of studies, meta-analyses were not computed for other breathing techniques. There was little evidence of heterogeneity in meta-analyses, but the large confidence intervals observed for pooled mean effects (owing to the small sample sizes within studies) indicate that the true effect sizes remain largely unknown.

Slow-paced breathing

Concerning SPB, the meta-analyses showed that short-term SPB interventions had no impact on physical sport performance, while longer-term SPB interventions have been effective in improving physical sport performance. For short-term SPB interventions, the small heterogeneity is entirely due to sampling error (see I^2 and Tau^2). This means that the overall effect is relatively accurate, but that the variance of the true effect tends to be even smaller. Yet, this is largely influenced by one study (Laborde 2019), which has a larger sample size than the other studies considered. Thus, future studies will need to be more highly powered.

The absence of significant effects for SPB short-term interventions (Conlon, Arnold, Preatoni, & Moore, 2022; Laborde, Lentes, et al., 2019; Lim, Kim, Marsh, & Belfry, 2018a, 2018b; Pelka et al., 2017; Perez-Gaido, Lalanza, Parrado, & Capdevila, 2021) may stem from various reasons. First, a single SPB session may be insufficient to trigger meaningful changes. Second, there were few effect sizes included. Third, the large heterogeneity of methodologies concerning the implementation of the short-term SPB interventions may partly explain this finding. Only one study (Perez-Gaido et al., 2021) followed a standardised protocol (Lehrer et al., 2013; Lehrer, Vaschillo, & Vaschillo, 2000). Fourth, the lack of effects for short-term interventions may also be due to the cessation of the stimulation of the vagus nerve after performing SPB, with CVA returning to baseline values as soon as the participant stops SPB (You, Laborde, Salvotti, et al., 2021; You, Laborde, Zammit, Iskra, Borges, & Dosseville, 2021). Following this line of reasoning, the question of the dose-response may also be explored in future research, even if the dose (i.e. duration) of SPB does not seem to influence CVA during or after SPB, longer SPB doses appear to trigger lower spontaneous respiratory frequencies after ceasing SPB (You, Laborde, Zammit, Iskra, Borges, & Dosseville, 2021).

Regarding SPB longer-term interventions, the large heterogeneity is almost entirely due to sampling error (see I^2 and Tau^2). It means that the overall effect is relatively inaccurate and thus may hide the variance of the true effect, which probably has more narrow boundaries. The variances per study are somehow comparable, thus, it is possible that the assessment methods were not accurate, had very high inter-individual variability, or used too small sample sizes. The correction for multi-effect has also largely increased the confidence interval of Paul and Garg (2012) (k=3), Vickery (2007) (k=3), and Stavrou, Voutselas, Karetsi, and Gourgoulianis (2017) (k=2). According to Funder and Ozer (2019) interpretation guidelines, the impact of SPB longer-term studies could range from negligible to potentially large and powerful.

SPB longer-term interventions findings confirm previous summary works (Jimenez Morgan & Molina Mora, 2017; Pagaduan et al., 2020; Pagaduan et al., 2021), while stricter inclusion criteria were adopted in the current paper (e.g., no case report, requirement of a control group, no combination between SPB and other techniques), allowing us to draw clearer conclusions regarding the specific effects of SPB. The benefits of SPB longer-term interventions might be explained by overall improved self-regulation abilities following the neurovisceral integration model (Smith et al., 2017; Thayer et al., 2009). One of the main outcomes of SPB is the stimulation of the vagus nerve, reflected in the increase of CVA (Kromenacker, Sanova, Marcus, Allen, & Lane, 2018; Sevoz-Couche & Laborde, 2022). Following the neurovisceral integration model, this increase in CVA is likely to be associated with enhanced executive functioning, emotion regulation, and overall self-regulation, which have been linked to improved sport performance (Beatty & Janelle, 2019; Kalen et al., 2021; McCormick et al., 2018; Ruiz & Robazza, 2021; Scharfen & Memmert, 2019). These links are supported by the findings of a meta-analysis across domains (Lehrer, Kaur, et al., 2020), showing that longer-term SPB interventions coupled with biofeedback enhance emotional and physical health as well as athletic, cognitive, and artistic performance. Additionally, it is suggested that longer-term physiological adaptations may also be mediated by improved cardiovascular recovery (Perez-Gaido et al., 2021). Indeed, if during exercise there is a parasympathetic deactivation, a shift to parasympathetic reactivation occurs as soon as exercise stops (Michael, Graham, & Davis, 2017; Stanley, Peake, & Buchheit, 2013). Stimulating the vagus nerve after exercise to enhance this reactivation and optimize recovery has therefore been suggested as a relevant strategy (Pecanha, de Paula-Ribeiro, Nasario-Junior, & de Lima, 2013; Pecanha, Forjaz, & Low, 2017; Pecanha, Silva, & Forjaz, 2014), which can be achieved via SPB (Perez-Gaido et al., 2021; Sevoz-Couche & Laborde, 2022).

Interestingly, among the studies reporting improvements in sport performance after implementing longer-term SPB interventions, some (Choudhary, Trivedi, & Choudhary, 2016; Paul & Garg, 2012; Raymond, Sajid, Parkinson, & Gruzelier, 2005) followed the standardised protocol of Lehrer and colleagues (Lehrer et al., 2013; Lehrer et al., 2000), while others did not (Burtch et al., 2017; Stavrou, Toubekis, & Karetsi, 2015; Vickery, 2007; Woorons, Mucci, Richalet, & Pichon, 2016) This standardised protocol aims to determine the individual breathing frequency at which the largest physiological benefits occur, while also closely guiding the SPB practice and adjusting the breathing frequency in case of discomfort (for an update of this protocol, see as well Shaffer & Meehan, 2020). This protocol ensures a gradual adaptation to SPB and the correct execution of this breathing technique. Specifically, it involves both the determination of the individual resonance frequency (Lehrer et al., 2013; Lehrer et al., 2000) and the training / adjustment of this resonance frequency over several sessions. Consequently, the short-term SPB interventions (Conlon et al., 2022; Laborde, Lentes, et al., 2019; Lim et al., 2018a, 2018b; Pelka et al., 2017) did not follow this protocol, to the exception of Perez-Gaido et al. (2021) for the initial session related to determining the individual resonance frequency. As discomfort and stress may be experienced when starting practising SPB (Allen & Friedman, 2012; You, Laborde, Zammit, Iskra, Borges, Dosseville, et al., 2021), the use of a standardised protocol which closely monitors the execution of this technique and aims to enhance the experience of the participant may support the positive outcomes achieved with SPB. In particular, parameters such as the exact breathing frequency, the presence of a respiratory pause, and the inhalation/exhalation ratio can be individually adjusted to optimise the individual psychophysiological effects (Bae et al., 2021; Laborde, Iskra, et al., 2021; Song & Lehrer, 2003; Van Diest et al., 2014).

At the psychological level, the mechanisms through which SPB influences physical sport performance could differ between short-term and longer-term interventions. For SPB short-term interventions, previous work outside sport showed that they might positively impact psychological variables relevant to physical sport performance, such as stress management (Laborde, Allen, Gohring, & Dosseville, 2017), decision making (De Couck et al., 2019), and inhibition (Hoffmann et al., 2019). Consequently, considering the limitations mentioned above, short-term SPB interventions might play a role in psychological factors influencing physical sport performance. Regarding SPB longer-term interventions, the psychological adaptations might be associated with the physiological adaptations occurring over time. More specifically, the repeated implementation of SPB during longer-term interventions could lead to chronic increases in CVA (Laborde, Hosang, Mosley, & Dosseville, 2019; Sevoz-Couche & Laborde, 2022), which could improve self-regulation as suggested by the neurovisceral integration model (Smith et al., 2017; Thayer et al., 2009).

To summarise, longer-term interventions may be more effective in creating lasting long-term changes in terms of improved self-regulation mechanisms, in particular linked to CVA, which would translate to increased sport performance. Short-term interventions remain to be investigated for their effectiveness, potentially involving larger sample sizes, a longer familiarisation protocol, and individualising the respiratory parameters so as to better adapt to each athlete and exerciser (Shaffer & Meehan, 2020).

Breath-holding

The meta-analysis for breath-holding interventions on physical sport performance showed no effect for short-term interventions, but a positive medium effect for longer-term interventions. Regarding short-term interventions, most studies showed no effects (Bouten et al., 2020; Malakhov et al., 2014; Robertson et al., 2020; Stavrou et al., 2017; Woorons, Dupuy, Mucci, Millet, & Pichon, 2019; Woorons, Mucci, Aucouturier, Anthierens, & Millet, 2017), and two studies showed large negative effects on physical sport performance (Guimard et al., 2014; Malakhov et al., 2014). The first analysis (k = 10) resulted in a large heterogeneity (see I^2 and Tau^2) but when the outliers are removed, with k = 8 results show a moderate heterogeneity almost entirely due to sampling error (see I^2 and Tau^2). The difference between the two groups (k = 2 vs. k = 8) was responsible for the large initial heterogeneity. The fact that the I^2 and Tau^2 dropped to 0 when k = 8 suggests that the two groups probably have different true effects. One or several moderators might explain this difference.

One of the main explanations put forward to explain the lack of effects of short-term breath-holding interventions is that as muscular and cerebral oxygenation is reduced during breath-holding, performing this technique before or during exercise could hinder muscle and cerebral functioning (Guimard et al., 2014; Woorons, Dupuy, et al., 2019; Woorons et al., 2017). Other disadvantages of breath-holding short-term interventions are related to decreased heart rate, peripheral vasoconstriction, and discomfort (Bouten et al., 2020). In summary, breath-holding hypoxia-induced state was found to have either no effect or to negatively affect immediate acute physical sport performance. However, given breath-holding training mirrors to some extent the conditions of altitude hypoxia-induced states (Brocherie, Girard, Faiss, & Millet, 2017; Girard, Brocherie, & Millet, 2017), the adaptations could simply take time to occur, suggesting possible benefits of long-term interventions.

Regarding longer-term breath-holding interventions, studies reported null to moderate positive effects on physical sport performance (Brocherie et al., 2022; Fornasier-Santos et al., 2018; Lapointe, Paradis-Deschenes, Woorons, Lemaitre, & Billaut, 2020; Trincat, Woorons, & Millet, 2017; Tyutyukov, Safonova, & Shakirova, 2015; Woorons, Billaut, & Vandewalle, 2020; Woorons, Millet, et al., 2019). The results indicate moderate heterogeneity, almost entirely due to sampling error (see $I^2 = 0\%$; $Tau^2 = 0$). This large sampling error (or at least its proportion over the variance of the true effect) is due to the correction for multiple effects: Brocherie et al. (2022) (k=3), Fornasier-Santos et al. (2018) (k=2), Lapointe et al. (2020) (k=3), Trincat et al. (2017) (k=3), Tyutyukov et al. (2015) (k=2), Woorons, Millet, et al. (2019) (k=2), and Woorons et al. (2020) (k=5). According to Funder and Ozer (2019) interpretation guidelines, based on the prediction intervals, the impact of breath-holding longer-term interventions could range from negligible to medium effects that could have explanatory and practical uses.

The effectiveness of breath-holding in longer-term interventions seems to depend on whether the duration of the intervention was long enough to promote physiological adaptations. It is further suggested to be specific to the nature and intensity of the physical sport performance considered, and to be as well muscle type-dependent (Fornasier-Santos et al., 2018; Trincat et al., 2017). Specifically, fast-twitch fibres required in sprinting exercises could benefit from breath-holding in longer-term interventions (Trincat et al., 2017) due to improved blood perfusion and anaerobic energy supplies to the muscles caused by breath-holding (Fornasier-Santos et al., 2018).

The main focus of longer-term breath-holding interventions was repeated-sprint ability training realized with breath-holding at low lung volume, also referred to as hypoventilation at low lung volume (Brocherie et al., 2022; Fornasier-Santos et al., 2018; Lapointe et al., 2020; Trincat et al., 2017; Woorons et al., 2020; Woorons, Millet, et al., 2019). Repeated-sprint ability was chosen as the main focus given that short-duration sprints (< 10s), interspersed with brief recoveries (<60 seconds), are common in many individual (e.g., racket sports) and team sports, and consequently, the ability to recover and to reproduce performance in subsequent sprints is an important factor influencing physical sport performance (Bishop, Girard, &

Mendez-Villanueva, 2011; Girard, Mendez-Villanueva, & Bishop, 2011). For the practical methodological implementation, the question arises about the difference between holding the breath at high vs. low lung volume (i.e., after maximal inhalation or exhalation). Although breath-holding at high lung volume may help to simulate, to some extent, hypoxic conditions (Guimard et al., 2018; Joulia et al., 2003), only breath-holding at low lung volume creates fast physiological changes (i.e., a fast drop in arterial oxygen saturation) best mirroring hypoxic conditions to perform repeated sprints in hypoxia (Lapointe et al., 2020; Trincat et al., 2017; Woorons et al., 2010; Woorons, Millet, et al., 2019; Woorons et al., 2007; Woorons et al., 2017). Training repeated-sprint ability in hypoxia was found to provide better performance improvements in comparison to normoxic conditions (Brocherie et al., 2017). The physiological adaptations might not be like those of training in systemic hypoxia, given that the hypoxic stimulus is not continuous with voluntary hyperventilation. However, it can still stress the organism to provide greater training adaptation effects than training in normoxic conditions (i.e., using unrestricted breathing) (Brocherie et al., 2022).

Overall, repeated-sprint training in hypoxia was found to be effective in improving factors limiting repeated-sprint ability performance, simulating to some extent the effects of altitude and hypoxic devices (Brocherie et al., 2022; Fornasier-Santos et al., 2018; Lapointe et al., 2020; Trincat et al., 2017; Woorons et al., 2020; Woorons, Millet, et al., 2019). The positive benefits were mostly found in the ability to repeat sprints, likely due to the improved buffer capacity within the blood and muscle tissues, leading to better pH regulation (Woorons et al., 2008), while the maximum velocity was not affected. Despite variable results, findings indicate that longer-term breath-holding interventions should therefore be implemented when hypoxic conditions are sought to be achieved, without travelling to high-altitude areas for training and without using hypoxic devices (Brocherie et al., 2022; Brocherie et al., 2017).

In general, breath-holding interventions require a standardisation of procedures prior to the act of breath-holding. Some studies conducted breath-holding after maximal inhalation (e.g., Malakhov et al., 2014), while some performed breath-holding after maximal exhalation (hypoventilation at low lung volume; Brocherie et al., 2022; Fornasier-Santos et al., 2018; Lapointe et al., 2020; Trincat et al., 2017; Woorons et al., 2020; Woorons, Millet, et al., 2019; Woorons et al., 2017). Depending on the targeted outcomes, the most optimal procedure for applying breath-holding must be investigated.

At the psychological level, breath-holding, and specifically its duration, might be associated with emotional and cognitive processes that can impact physical sport performance (Kanthack, Guillot, Saboul, Debarnot, & Di Rienzo, 2019; Krause, Benke, Hamm, & Pane-Farre, 2021; Sutterlin et al., 2013; Thompson-Lake, De La Garza, & Hajek, 2017; Van Hove et al., 2020). At the emotional level, breath-holding is usually associated with threat perceptions associated with potential damage to vital functions (Kanthack et al., 2019). This threat perception may be decreased by using motor imagery, the voluntary process of mentally representing an action without executing it (Decety, 1996). Using motor imagery visualising breathing during breath-holding has been found to increase breath-hold duration during breath-holding compared to visualising breath-holding (Kanthack et al., 2019). Consequently, motor imagery of breathing may help to increase breath-holding duration. Future research should investigate to which extent motor imagery of specific breathing patterns may be used to improve their effectiveness on physical sport performance. Regarding its impact on cognition, breath-holding has been found to be associated with, among other brain regions, the parietal and frontal cortices (McKay, Adams, Frackowiak, & Corfield, 2008), which are linked to cognitive functions such as inhibition (Watanabe et al., 2002), working memory (Funahashi, 2017), and flexibility (Kim, Johnson, Cilles, & Gold, 2011). Further, breath-holding duration has been suggested to be an index for self-control resources and enhanced executive functions, however, mixed findings were found in the literature (Sutterlin et al., 2013; Thompson-Lake et al., 2017; Van Hove et al., 2020), and this assumption should be further investigated. Finally, considering a bidirectional relationship between breath-holding and psychological aspects related to performance, it appears worth mentioning that breath-holding duration seems to be largely affected by motivation (Parkes, 2006).

To summarise, short-term breath-holding did not lead to changes in physical sport performance, likely due to decreased oxygenation. However, interventions triggering long-term physiological adaptations resulting from training in hypoxic conditions could lead to benefits for physical sport performance. Similarly, to other breathing techniques, the use of standardised familiarisation and training procedures seems a worthy area of further investigation.

Voluntary hyperventilation

For voluntary hyperventilation, the findings indicated that physical sport performance did not differ between voluntary hyperventilation and control conditions. The results showed a small heterogeneity (see prediction interval) entirely due to sampling error (see I^2 and Tau^2). Consequently, the overall effect is relatively accurate, and the variance of the true effect tends to be even smaller. It comes from the fact that most studies have the same effect (null), and the ones that deviate from this average effect have large variance and thus count lower weight in the calculation.

One of the main mechanisms put forward for the use of voluntary hyperventilation is respiratory alkalosis, with voluntary hyperventilation saturating the blood with oxygen and removing carbon dioxide, provoking an increase in blood pH, which is suggested to reduce part of the adversary effects of fatigue during intense efforts (Forbes et al., 2007; Morrow, Fell, & Gladden, 1988). The systematic review suggests that the effects of voluntary hyperventilation are likely to depend on factors such as the nature of the task and the duration of the voluntary hyperventilation (Dobashi, Fujii, Ichinose, Fujimoto, & Nishiyasu, 2021; Fujii et al., 2015; Gray, Pritchett, Pritchett, & Burnham, 2018; Jacob et al., 2015; Kaçoğlu & Işik, 2017; Malakhov et al., 2014; Sakamoto et al., 2014; Sakamoto, Naito, & Chow, 2015, 2018; Sakamoto et al., 2020). To illustrate this, Sakamoto and colleagues performed a series of studies (Sakamoto et al., 2014, 2015, 2018, 2020) testing the effects of voluntary hyperventilation used as a recovery strategy between repeated intense efforts and reported both significant performance improvements (Sakamoto et al., 2014, 2020) or an absence of effects (Sakamoto et al., 2015, 2018) depending on the physical sport performance outcome measured and the duration of hyperventilation. Specifically, it appears that voluntary hyperventilation durations that are either too short or too long (Sakamoto et al., 2014, 2018) fail to impact performance and that the amount of muscles groups involved also plays a role, with a larger amount being more likely to benefit from the respiratory alkalosis induced by voluntary hyperventilation (Sakamoto et al., 2015, 2020).

Beyond the effects related to respiratory alkalosis and muscle fatigue, some sport-specific effects may be targeted. In swimming for example, researchers (Gray et al., 2018; Jacob et al., 2015) suggested that voluntary hyperventilation would reduce the urge to breathe, and in this case, also help improving swimming technique with fewer breaths (Psycharakis & McCabe, 2011), providing the participants with a technical advantage, at least for race durations with a prevalence of anaerobic metabolism (Gray et al., 2018). On a different account, voluntary hyperventilation may hinder balance due to increased body sway stemming from the increased breathing amplitude (Malakhov et al., 2014).

At the psychological level, given the links between involuntary hyperventilation and panic, anxiety, and fear disorders (Carter, Marin, & Murrell, 1999; Ley, 1999; Meuret, Ritz, Wilhelm, & Roth, 2005), specific care should be taken when introducing voluntary hyperventilation to athletes and exercisers. Specifically, when involuntary hyperventilation occurs, it has been shown that visualising positive pictures provokes a more adaptive psychophysiological response (Allen & Friedman, 2012). At the cognitive level, the hypocapnia induced by involuntary hyperventilation was found to be related to cognitive deficits (Ley, 1999) and decreased cerebral blood flow velocity (Debreczeni, Amrein, Kamondi, & Szirmai, 2009). At the emotional level, hyperventilation is related to anger, anxiety, and fear, and these emotional responses may trigger hostile coping responses in hostile situations, and should therefore better be prevented (Philippot et al., 2002). Finally, given that voluntary hyperventilation may interfere with the neuronal activity-driven regulation of cerebral circulation (Debreczeni et al., 2009; Ley, 1999), future research must better understand its impact on the cognitive factors influencing the different kinds of physical sport performance. Designing a familiarisation protocol for voluntary hyperventilation (Carter et al., 1999; Ley, 1999; Meuret et al., 2005) to ensure a positive psychological response of the participant prior to its use in sporting settings could potentially help to influence its effect on physical sport performance positively.

In summary, while the data from this meta-analysis demonstrate no effect of short-term voluntary hyperventilation interventions on physical sport performance, further research is required in order to clearly understand the parameters of voluntary hyperventilation triggering physical sport performance increases and decreases, to lead to the development of standardised protocols according to the outcomes targeted. Similar to SPB and breath-holding, a large diversity of methodological procedures appears concerning due to the way voluntary hyperventilation was implemented. We can illustrate this observation with breathing frequencies ranging from 12cpm (Gray et al., 2018) to 60cpm (Sakamoto et al., 2018) and durations ranging from 15s (Sakamoto et al., 2018) to 20min (Dobashi et al., 2021). Furthermore, all included studies focused on short-term interventions, and potential long-term adaptations might have been overlooked. As physiological adaptations require time to provoke a reduction in fatigue which could support physical sport performance, investigating the effects of longer-term voluntary hyperventilation interventions is essential to better understand how this technique may influence physical sport performance (McArdle et al., 2015).

Fast-paced breathing

For FPB, only one study could be included based on the inclusion criteria (Telles, Sharma, & Balkrishna, 2014). This study reported beneficial effects on subsequent physical sport performance, pointing to a significant increase in right-hand grip strength, while left-hand grip, leg, and back strength showed no significant differences. Additionally, finger and arm tapping speed increased significantly. Results may be explained by the activation of the sympathetic nervous system, which triggers physiological adaptations such as increased heart rate (Peng et al., 2004; Upadhyay-Dhungel et al., 2016; Van De Borne et al., 2000).

At the psychological level, FPB may affect physical sport performance via improved information processing and by eliciting faster responses to environmental changes (Boyadzhieva & Kayhan, 2021). Its effects on attention may be driven by activation of the sympathetic nervous system and an elevated norepinephrine secretion, which is involved in the regulation of the frontoparietal attention network (Sara & Bouret, 2012). Additionally, FPB has been found to trigger increased cerebral oxygenation in brain areas responsible for executive functioning, in the right and left prefrontal cortices (Bellissimo, Leslie, Maestas, & Zuhl, 2020), and increases in concentration spans have also been reported after FPB practices (Upadhyay-Dhungel et al., 2016).

Most studies implementing this technique had to be excluded as FPB was practised together with yoga exercises. As FPB often requires forceful exhalation to maintain the high respiration frequency, it leads to the strengthening of the abdominal muscles, which are essential for postural and sport-specific purposes (Upadhyay-Dhungel et al., 2016). This may further contribute to potential benefits to physical sport performance. In addition, many studies did not include populations which were actively engaged in sports or exercise, and thus had to be excluded from this paper. In general, previous research indicates that FPB may provide a technique for increasing short-term, intense exercise requiring fast energy supplies. However, future studies are required to investigate this premise further. Based on the potential benefits of FPB on physical sport performance, we encourage further research on this breathing technique that specifically isolates the effects of FPB on physical sport performance.

Limitations

Strengths of this systematic review include the systematic approach to study identification, the focus on multiple breathing techniques, the separation of short- and longer-term interventions, and the use of meta-analysis to inform conclusions. However, there are also some important limitations that need to be considered. First, it was necessary to exclude several studies due to missing information (e.g., the sport/exercise regimen of the participants), along with no response received from authors when contacted for that information; due to the implementation of concomitant practices, such as meditation, yoga, or visualisation; as well as the lack of a control group performing an exercise or sport regimen similar to the experimental group. These missing studies might have contributed to more accurate estimations than those reported here. Second, we decided for some studies to include several outcomes, to best reflect the diversity of physical sport performance investigated. Consequently, this led to a statistical correction for multi-effect (i.e., dividing the sample size by the number of effect sizes extracted per study), which, together with the overall low sample size of the included studies, contributed to large confidence intervals and statistical heterogeneity, as reflected in the prediction interval obtained. Therefore, the variance of the true effects might differ considerably from the observed variances. Fourth, it was not possible to test potential moderating effects, due to the large sampling error overlapping the variance in the observed effect (low I^2 values). Effect sizes might differ according to the outcome measured (e.g., strength, speed, sport-specific measure) or the timing of the breathing intervention (i.e., before, during, or after sports competition), and future research can help to clarify whether some breathing techniques might be more or less effective for physical sport performance across these moderators. Fifth, it should be noted that the psychological benefits of the breathing techniques still need to be investigated further , and those reported in this paper are still largely speculative, or thought to be a consequence of the physiological effects of breathing techniques. Consequently, future research should urgently consider the potentially unique psychological effects of breathing techniques, in order to better understand their influence on sport performance. Sixth, as illustrated in Table 2, there was a large diversity of the control tasks used as comparators for the breathing interventions, ranging from watching videos to reading and in some cases no control task was provided. This diversity of control tasks may have influenced the interpretation of the findings, and future research should pay close attention to the control task chosen. The control task should be as similar as possible to the breathing technique investigated, and only differing on key breathing parameters being the focus of the investigation. Seventh, this study included physical sport performance outcomes beyond those which can be considered as direct outcomes of sport competitions. While this approach allowed for a more global understanding of the influence of breathing techniques on general physical sport performance, future research is warranted to focus specifically on the outcomes of sport competitions. Finally, it is important to note that one of the main limitations of breathing techniques studies is that given the participant needs to actively change his/her breathing pattern, studies cannot be conducted single- or double-blind, and hence researcher factors could also influence the outcomes, and should be systematically investigated in future research (Fornasiero et al., 2018).

Deviations from the PROSPERO protocol

Since the pre-registration of the study protocol in PROSPERO, it was necessary to make some amendments (revised version uploaded to PROSPERO on February 5th, 2021). The first relates to the intended broader focus of the systematic review. Originally, we planned to consider physical, psychological, and physiological outcomes related to sport performance. However, during the literature search, it became apparent that there was a large heterogeneity of outcomes related to all these areas. As such, we took the decision to focus solely on outcomes related to physical sport performance, given that physical performance is the primary criteria upon which athletes are judged. Second, upon collecting the final sample of studies, it became apparent that short-term and longer-term interventions needed to be explored separately in analyses. Third, we decided to include breathing interventions implemented during exercise provided they also included a control condition with the same exercise protocol. Finally, the original PROSPERO proposal only mentioned SPB, FPB, and breath-holding as breathing techniques. With further literature reviewed, we identified and added two additional categories of hyperventilation and alternate- and uni-nostril breathing. The definition of the five categories was added to the PROSPERO pre-registration protocol after noticing terminology discrepancies in the studies reviewed.

Recommendations for Future Research

The findings from this systematic review highlight several possibilities for future research. An overarching aim would be to develop general guidelines and standards for the use of breathing techniques for physical sport performance. To achieve this, more research investigating the timing of breathing interventions is required (before, during, and after sport) for both short-term and longer-term interventions. Future studies also need to consider a larger range of sport disciplines, as the main sports investigated were running (17.9%), swimming (35.7%), and cycling (21.4%). Moreover, all included studies sampled healthy participants, meaning the efficacy of various breathing techniques for clinical samples remains unknown. More research is also required for understudied breathing techniques such as FPB and alternate- and uni-nostril breathing. Further research on breath-holding would benefit from standardising procedures for breathing strategies performed before breath-holding. Longer-term hyperventilation interventions are also required to establish to which extent effects observed in short-term interventions transfer to longer-term interventions. Finally, various parameters such as breathing frequency, depth, and locus of breathing (thoracic/abdominal) differ across studies. Researchers should aim to establish how differences in these parameters (e.g., 6 cpm vs 5 cpm for SPB) might affect outcomes. Research into these differences will help to ultimately develop detailed guidelines for the use of breathing techniques to improve physical sport performance.

Conclusion

This study sought to collate research findings relating to whether physical sport performance is influenced by the use of various breathing techniques. The most convincing evidence indicated that longer-term SPB and breath-holding interventions can benefit physical sport performance. Short-term SPB, breath-holding, and hyperventilation interventions appear to have no beneficial effect on sport performance. However, these effects are likely to be context-dependent and more research is needed to establish important moderators of these effects. Our research synthesis advances previous systematic reviews and meta-analyses (Jimenez Morgan & Molina Mora, 2017; Pagaduan et al., 2020; Pagaduan et al., 2021), given they have focused so far only on SPB. Moreover, contrary to these previous summary works, our inclusion criteria excluded case reports, experimental studies not including a control group, or studies combining the breathing technique of interest with other techniques which might influence the physical sport performance outcomes. Finally, the distinction between short-term and longer-term effects was not included in previous works.

In comparison to other techniques targeting similar mechanisms, such as non-invasive brain stimulation to stimulate the vagus nerve (Schmaußer, Hoffmann, Raab, & Laborde, 2022; Vanderhasselt & Ottaviani, 2022), or simulating altitude environments to create hypoxic conditions in hypoxic chambers (Brocherie et al., 2017), breathing techniques may reach similar outcomes without using additional devices / modifying environment, respectively with SPB to stimulate the vagus nerve (Laborde, Allen, et al., 2022; Sevoz-Couche & Laborde, 2022; Vanderhasselt & Ottaviani, 2022) and breath-holding on low lung volume to create hypoxic conditions (e.g., Brocherie et al., 2022; Woorons et al., 2020). The findings of this review might be of interest to those working with high-level athletes. Coaches might consider introducing athletes to SPB and monitoring athlete performance over time to establish whether SPB can benefit athletic performance (as results suggest performance improvement is likely). If physical sport performance can benefit from training in hypoxic conditions, then coaches might consider using breath-holding at low lung volume as an alternative to (simulated) altitude training. Further research is needed into other breathing techniques before their widespread use can be recommended. We recommend further research into all breathing techniques to help develop specific guidelines for the implementation of breathing techniques among researchers, athletes, coaches, and sport professionals.

Conflicts of Interest

The authors declare no conflicts of interest.

Data availability statement

The R code, the computation tables, as well as all csv files are available at 10.17605/OSF.IO/XK59D.

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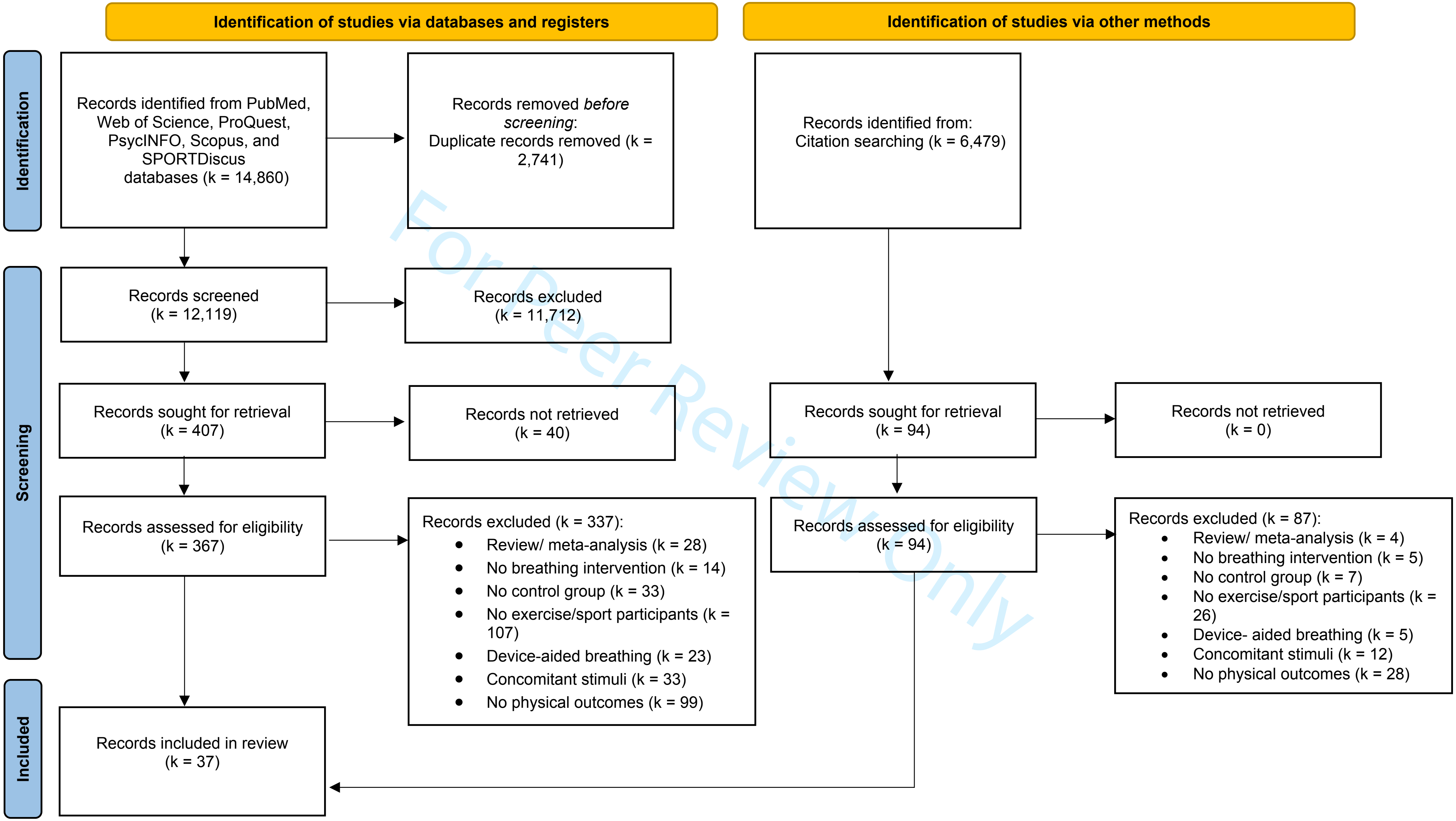
PRISMA 2020 flow diagram for new systematic reviews which included searches of databases, registers and other sources



From: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71. For more information, visit: http://www.prisma-statement.org/

Figure 2: Forest plot for slow-paced breathing – short-term effects

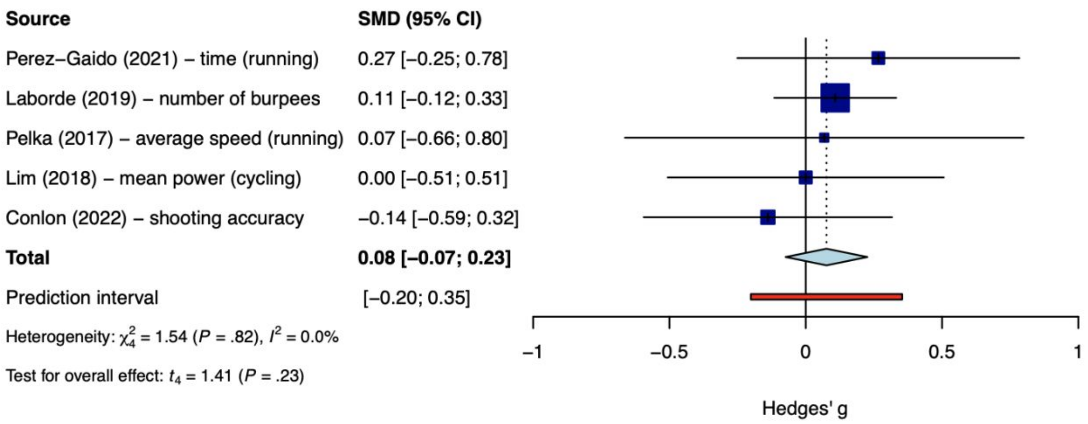


Figure 3: Funnel plot for slow-paced breathing – short-term effects

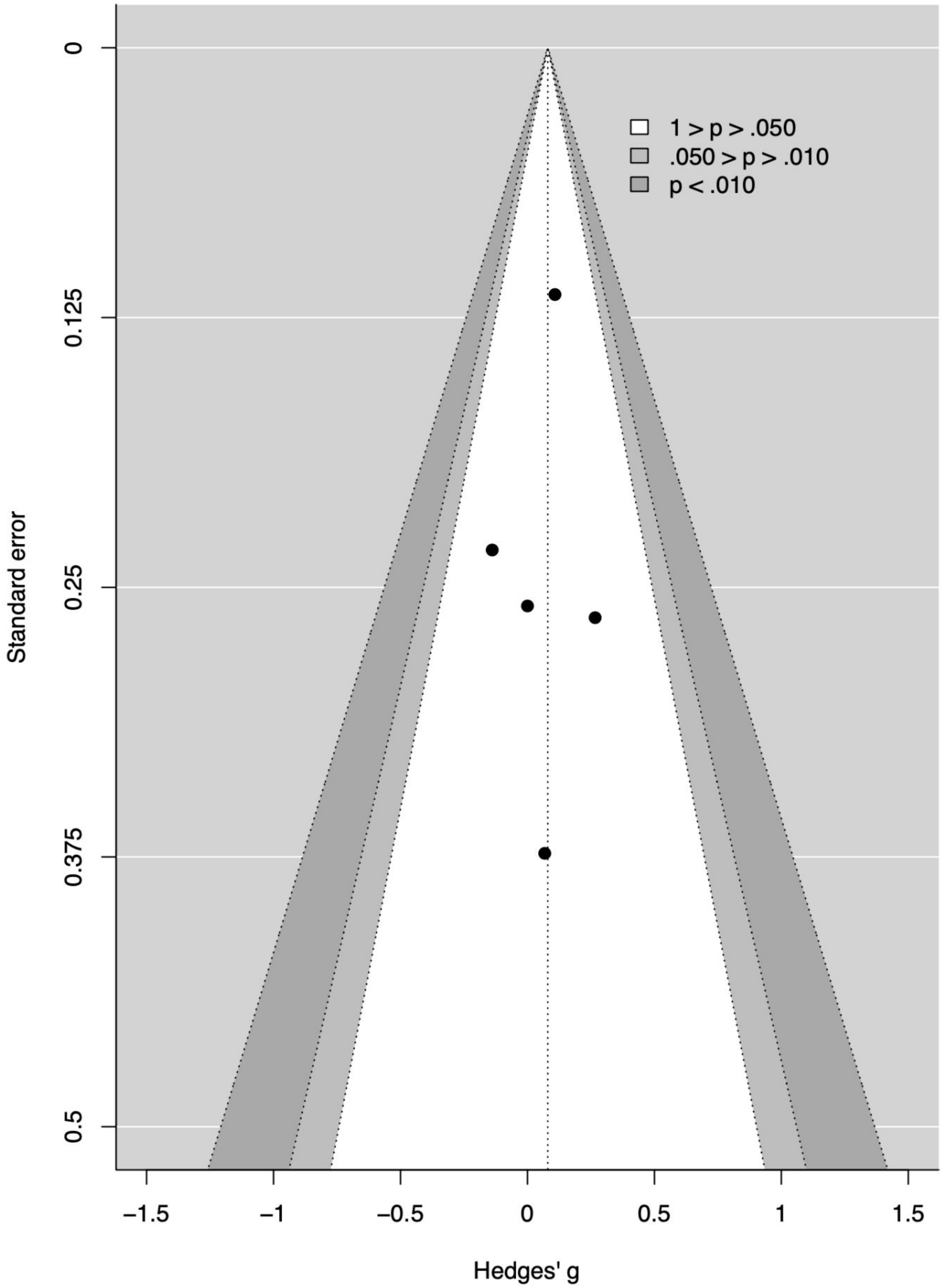


Figure 4: Forest plot for slow-paced breathing – long-term effects

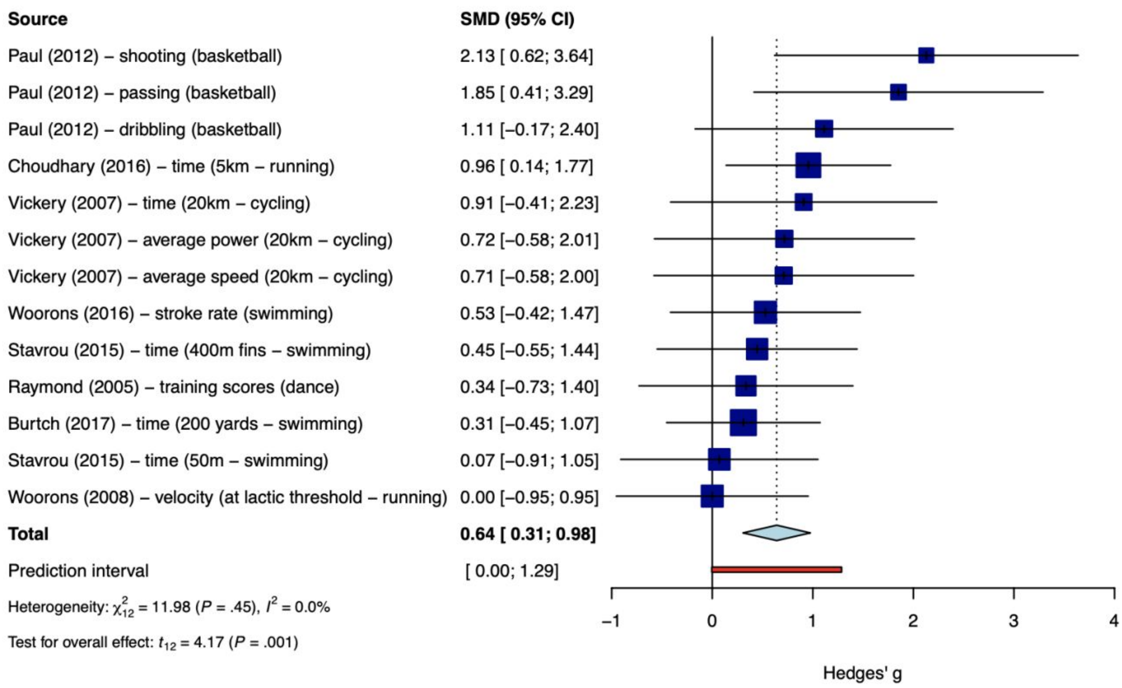


Figure 5: Funnel plot for slow-paced breathing – long-term effects (with trim-and-fill analysis)

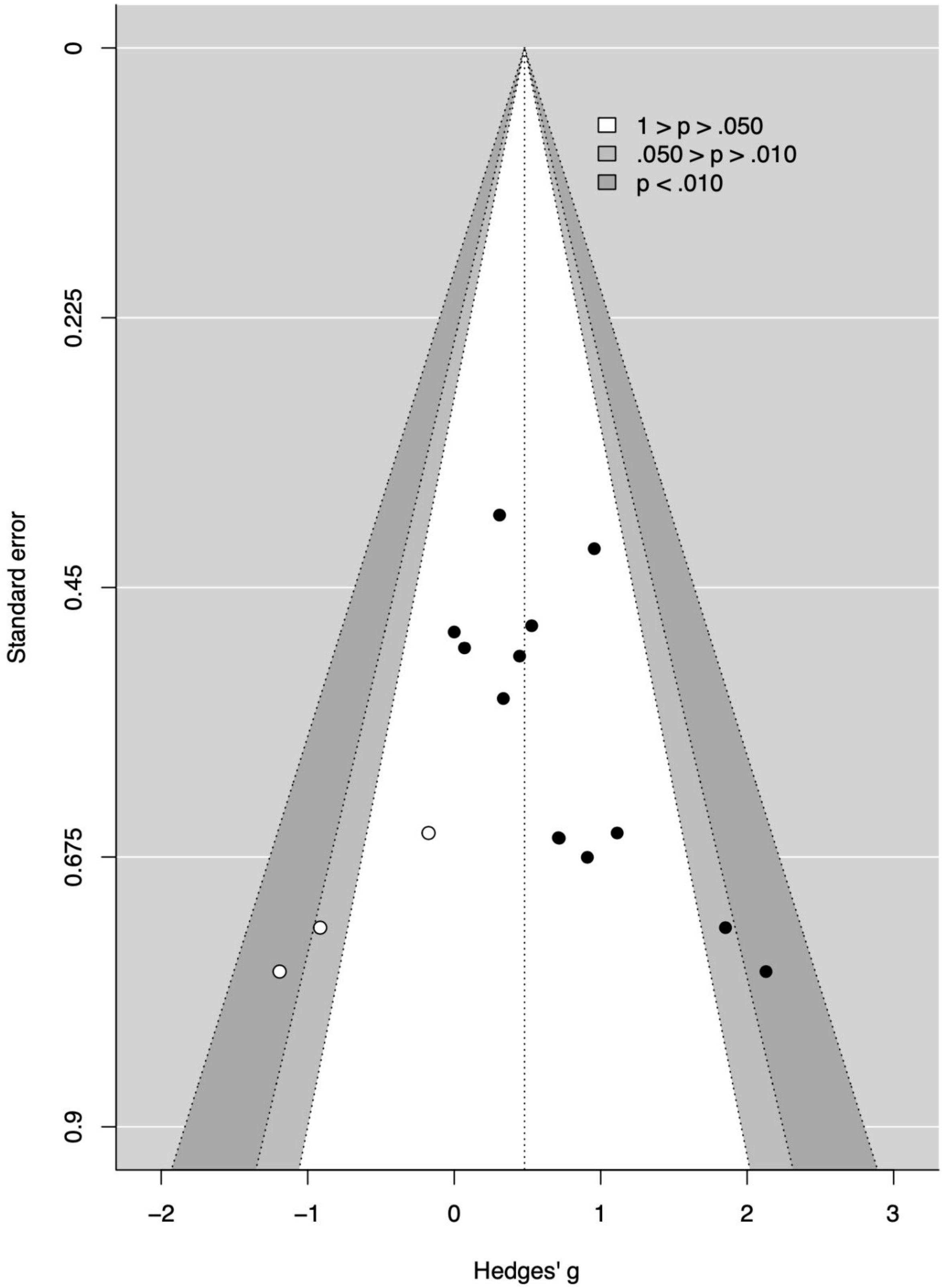


Figure 6: Forest plot for breath-holding – short-term effects

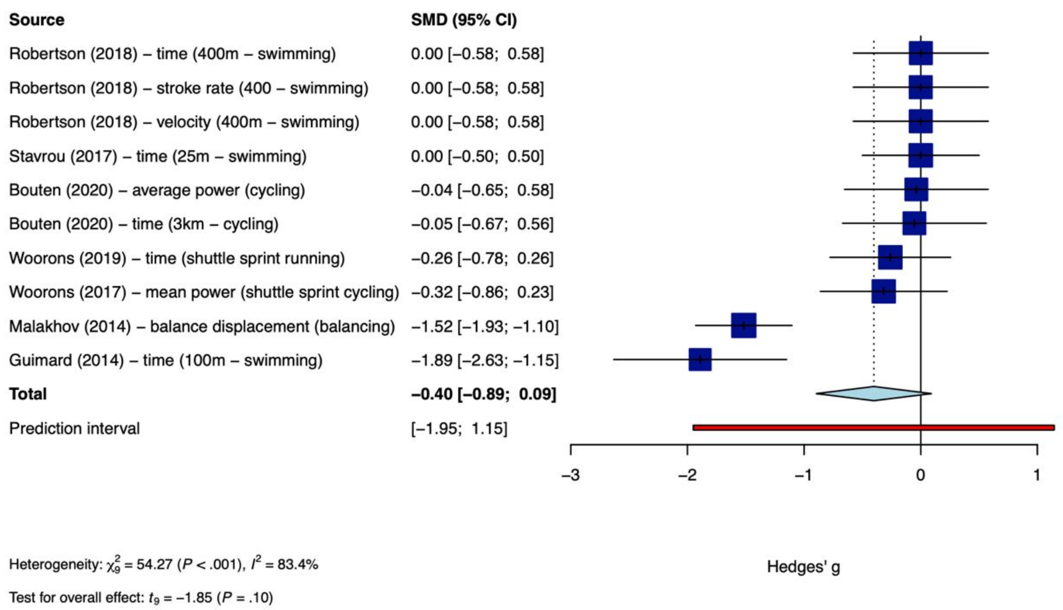


Figure 7: Funnel plot for breath-holding – short-term effects (after outliers removal)

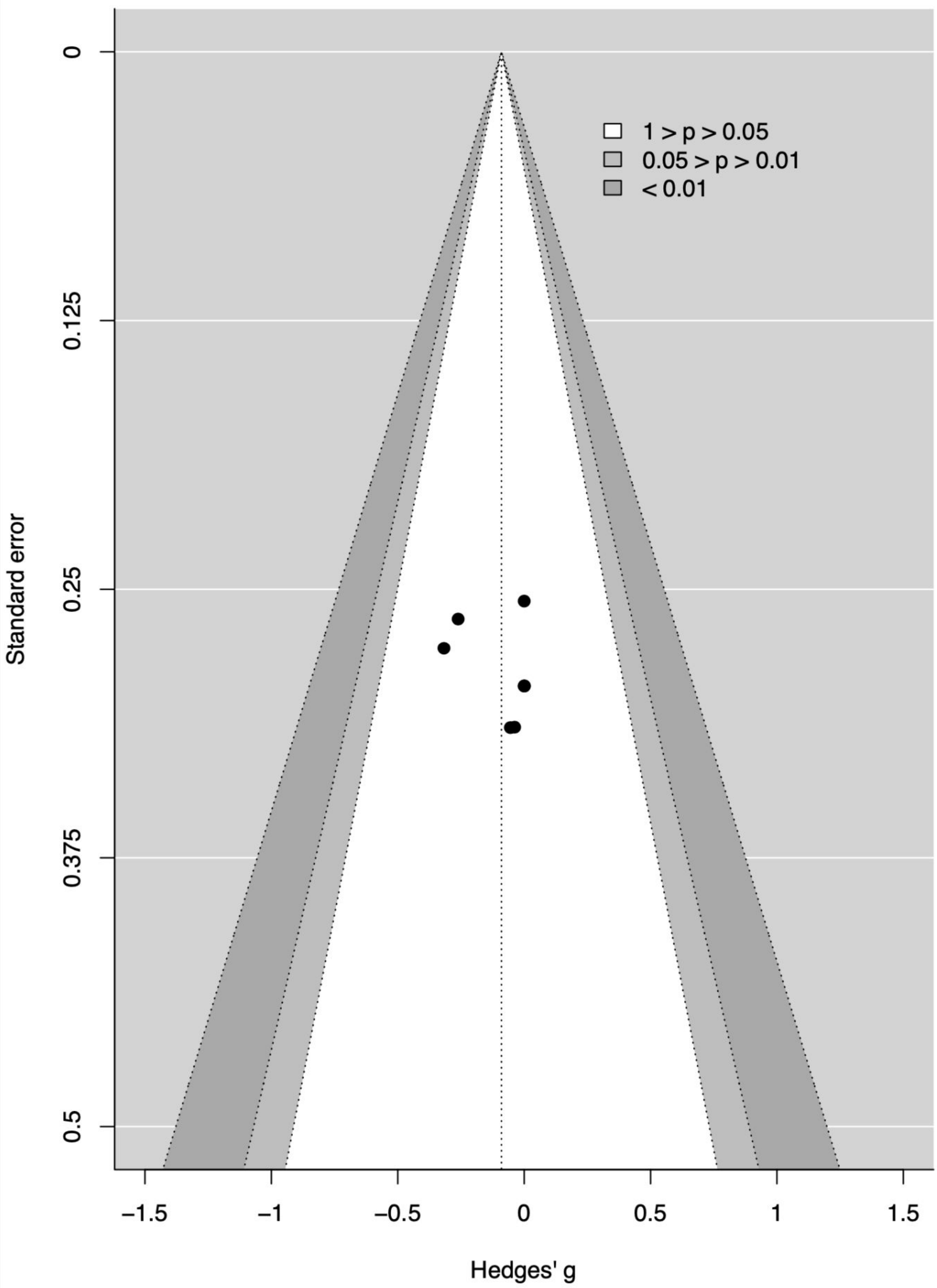


Figure 8: Forest plot for breath-holding – long-term effects

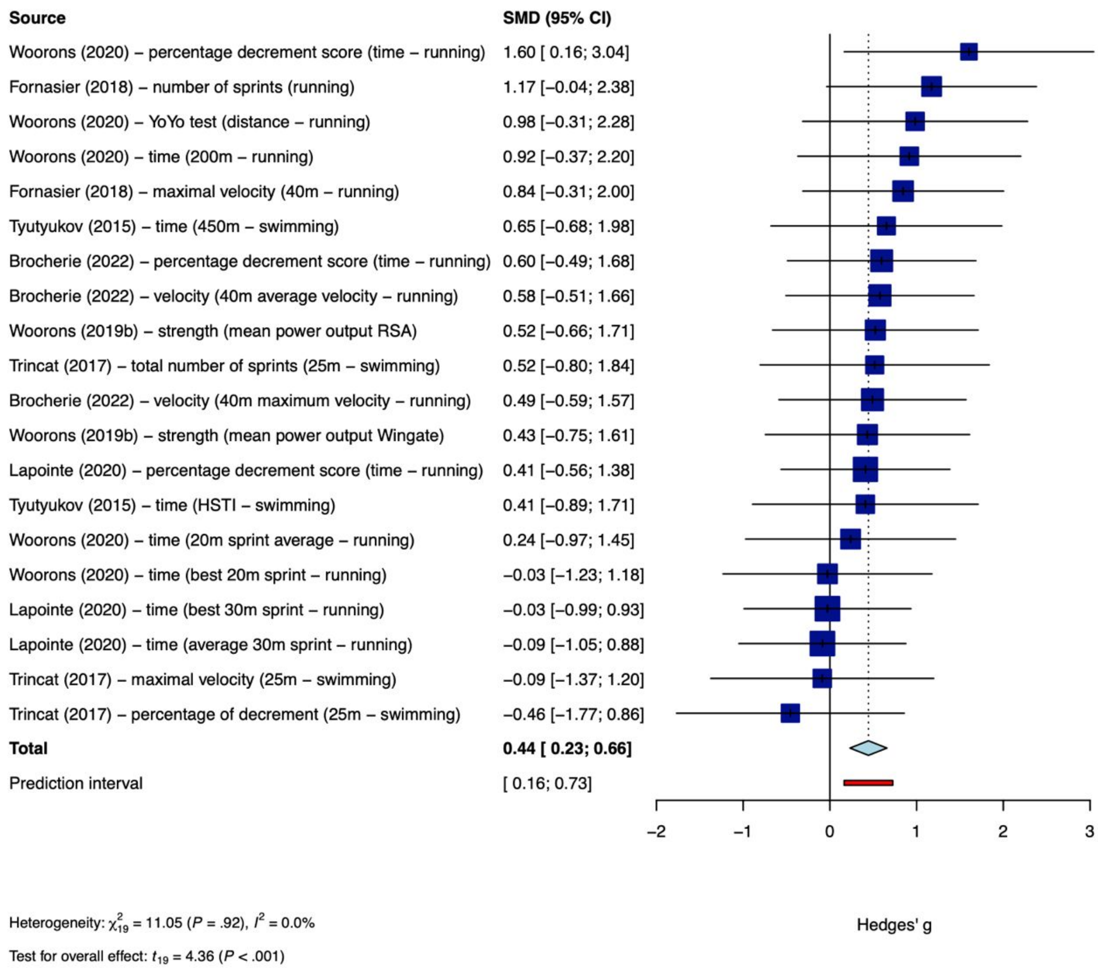


Figure 9: Funnel plot for breath-holding – long-term effects (with trim-and-fill analysis)

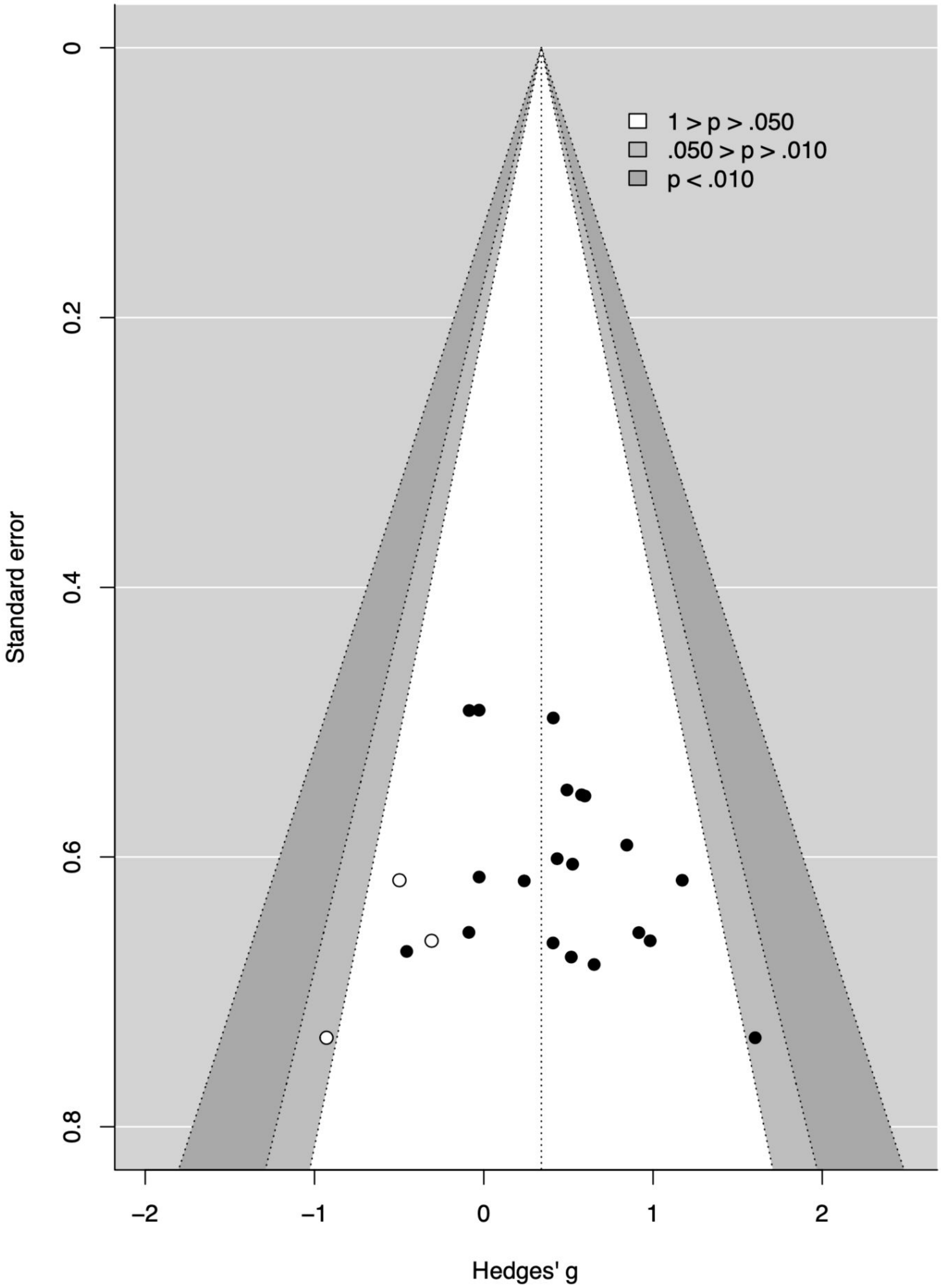


Figure 10: Forest plot for hyperventilation – short-term effects

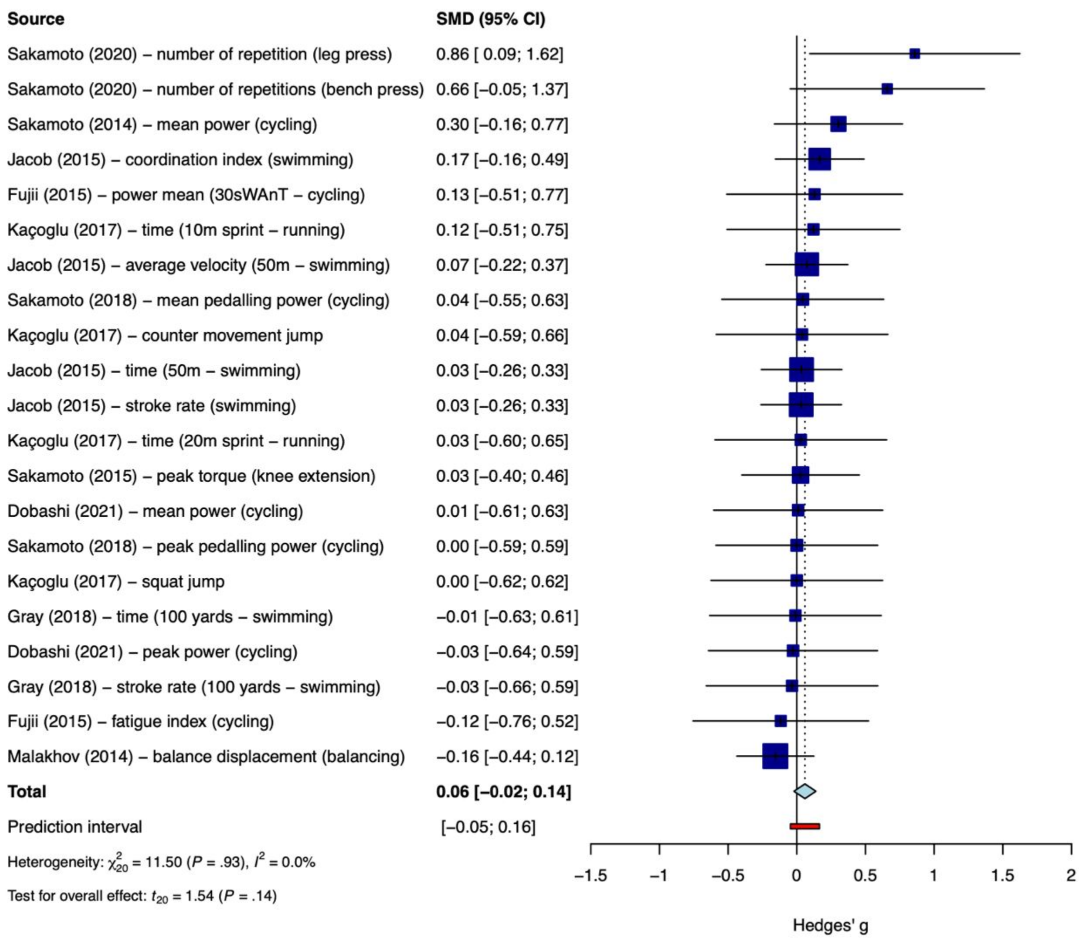


Figure 11: Funnel plot for hyperventilation – short-term effects

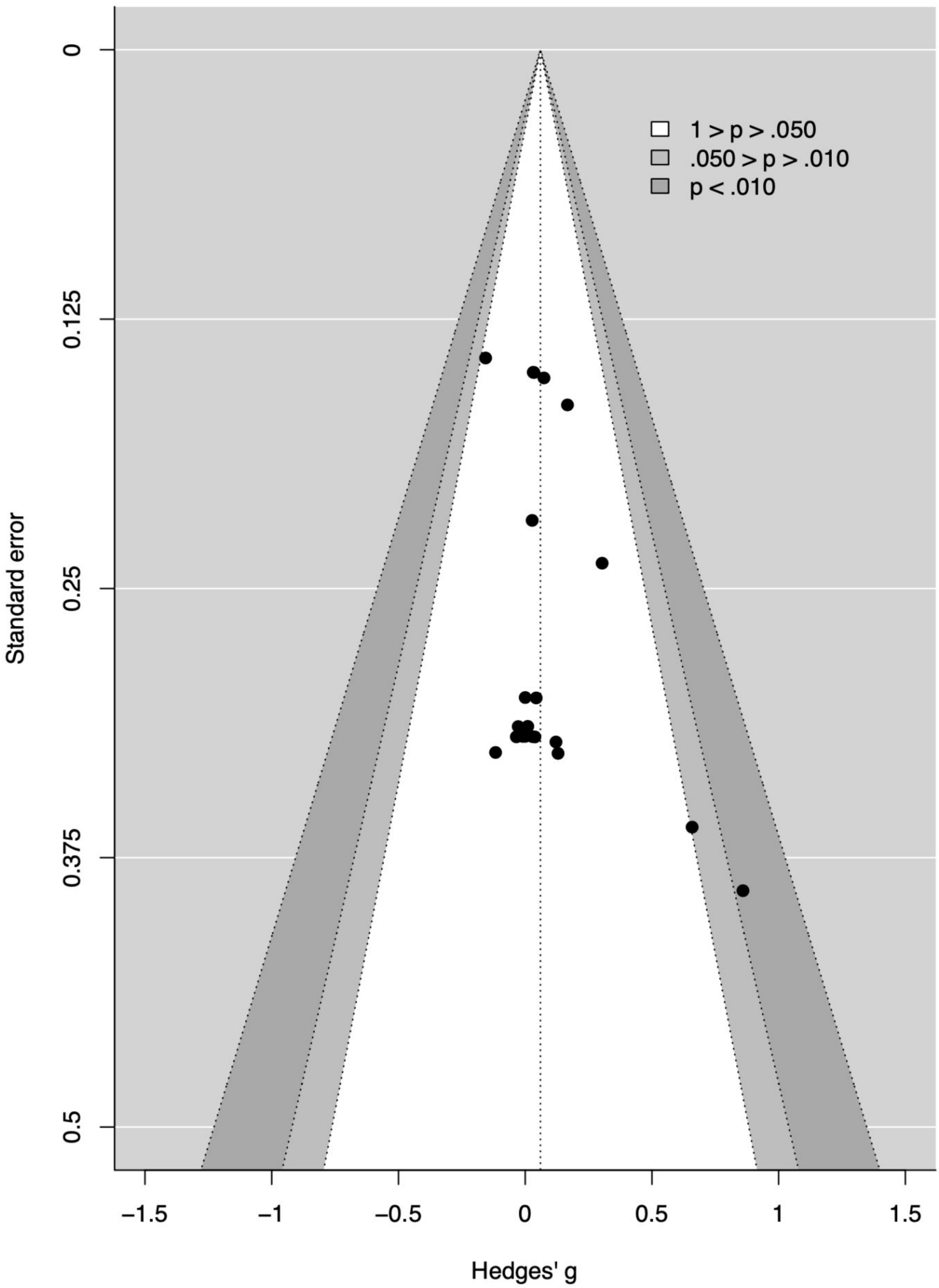


Table 1

Search terms used in the databases PubMed, Scopus, SPORTdiscus, Web of Science, ProQuest, and PsycINFO

Boolean Operator	**Search terms**
	(“athlet*” OR “sport” OR “performance”)
AND	(“breath*”)
AND	(“metronome” OR “coheren*” OR “biofeedback” OR “paced” OR “controlled” OR “diaphragmatic” OR “nostril” OR “abdominal” OR “slow” OR “deep” OR “fast” OR “rapid” OR “hyperventilation” OR “prana*” OR “biofeedback” OR “hold*” OR “Wim Hof” OR “relax*” OR “activat*” OR “apnea” OR “apnoea” OR “hypocapnia” OR “hypoventilation”)

Table 2: Summary of systematic review results

Table 1a: Summary of slow-paced breathing (SPB) studies

First author (year)	Participants	Intervention	Comparison	Outcome	Study design
Conlon et al. (2022)	67 students from a range of sports. 40 females and 27 males; Mean age of 20.17 ± 2.77 years.	Short-term 5 min SPB performed before shooting task at 6 cycles per min with 4s inhale, 6s exhale.	Watching educational video.	No significant difference in shooting accuracy.	Between-subject design.
Laborde et al. (2019)	Experiment 1: 60 sport students. 35 males, 25 females. Mean age of 25.6 years.	Short-term Slow-paced breathing exercise was performed three times for a duration of 5 min with a 1 min break between each unit, corresponding to a total of 17 min. Breathing at 6 cycles per min. Breathing intervention was performed before Burpees (experiment 1).	Control condition was watching a neutral TV documentary.	No significant difference in the number of Burpees achieved.	Within-subject design
Lim et al. (2018)	10 recreationally active participants from variety of sports Males Mean age of 24 ± 3 years.	Short-term Ergometer protocols of 4-6 min in 4 conditions: 1. free breathing, 2. breathing technique applied, 3. Fartlek protocol, 4. fartlek with breathing technique applied. 5s breath-hold and 25s free breathing. Intervention during cycling.	Free breathing throughout the ergometer protocol.	No significant change in mean power output on cycling ergometer.	Within-subject design
Pelka et al. (2017)	27 sport science graduate students-background in competitive sports. 19 males, 8 females Mean age of 25.2 ± 1.1 years.	Short-term Breathing intervention lasted 25 min (actual practice 10 min). The control condition was realised in another week.	Control condition was reading through comics.	Significant improvement in average speed.	Within-subject design

		Breathing at 6.7 cycles per min or 5 cycles per min. The breathing intervention took place between two series of 6 x 4s sprints.			
Perez-Gaido et al. (2021)	15 physically active university students. 7 males, 8 females. Mean age of 25.80 ± 4.18 years.	Short-term Breathing intervention lasted for 90s of SPB at resonance frequency (mean of 5.7 breaths/min across participants). The breathing intervention occurred during recovery after a submaximal running test.	Control condition was normal breathing during recovery.	Time spent running was significantly longer after recovery with SPB than after recovery with normal breathing.	Within-subject design
Burtch et al. (2017)	25 competitive swimmers. 14 males, 11 females. Mean age of 20 ± 1 years.	Longer-term Breathing intervention occurred over 5–6 weeks (16 sessions) in sessions of 12 x 50 m swimming repetitions. 2-3 breaths per 50m swimming. Breathing intervention occurred during swimming.	Control group (training with 8-10 breaths/ stroke matched breathing per 50 m).	No significant improvement in 200yard swimming time.	Between-subject design
Choudhary et al. (2016)	24 university state and national track athletes (5km distance runners). 12 males, 12 females Mean age of 22.5 ± 1.7 years.	Longer-term 10 sessions of 30-40 min, in which four tasks were included: A: baseline, B and C: biofeedback training and D: baseline. Resonant frequency breathing. No specification on timing of intervention in relation to exercise.	The control group did not receive any intervention.	Significant increase in 5km run time.	Between-subject design
Paul and Garg (2012)	30 basketball players. 17 males, 13 females Mean age 21.1 ± 2.8 years.	Longer-term 1st session to determine the resonance frequency, then the biofeedback	Placebo group was shown motivational basketball videos. Control group did	Significant increase in basketball performance (shooting, passing, dribbling).	Between-subject design

		sessions were given for 10 consecutive days for 20 min each. Breathing at resonance frequency. No specification on timing of breathing intervention in relation to sport.	not receive any breathing intervention.		
Raymond et al. (2005)	24 student college dancers. 12 males, 12 females Mean age of experimental group: 19.8 ± 2.2 years, control group: 21.1 ± 2.5 years.	Longer-term HRV was received for 10 sessions over a period of 4 weeks. Each session was 20 min long. Breathing at resonance frequency. No specification on timing.	Control group did not receive any breathing intervention.	Significant increase in dance performance.	Between-subject design
Stavrou et al. (2015)	28 fin-swimming youth athletes. 7 males,7 females in each group Mean age of experimental group: 15.8 ± 1 years, control group: 15.4 ± 1.4 years.	Longer-term Breathing intervention during swimming. 16-week training period in which SPB was performed in 40% of the training session.	The control group breathed at their self-selected breathing frequency.	Significant increase in performance in 400m surface fin-swimming and 50m breath-hold swimming.	Between-subject design
Vickery (2007)	24 competitive cyclists and triathletes. Males Mean age of experimental group: 38.6 ± 5.9, control group: 37 ± 10.6 years.	Longer-term 10 lab visits over 7 weeks (sessions 5-8 were breathing interventions). Breathing interventions were of 10min duration. No specification on respiratory frequency. No specification on timing of the breathing interventions in relation to sport.	Control group did not receive any breathing intervention and performed spontaneous breathing.	Significant improvement in speed, power and time in 20km cycling performance.	Between-subject design
Woorons et al. (2016)	16 triathletes. 12 males, 4 females. Mean age of experimental group: 32.5 ± 10.7 years, control group 33.5 ± 9.3 years.	Longer-term Intervention twice a week over a 5-week period. Breathing intervention during 25 m front crawl swimming sets.	Control group was swimming with normal breathing.	Significant improvement in stroke rate from pre-post intervention.	Between-subject design

Woorons et al. (2008)	15 male runners. Mean age of experimental group: 27.1 ± 6 years, control group: 30.6 ± 3.9 years.	Longer-term 4-week training protocol. Breathing intervention was performed during running.	Training under normal breathing.	No significant change in velocity at lactic threshold from pre- to post-intervention.	Between-subject design

Table 1b: Summary of breath-holding studies

First author (year)	Participants	Intervention	Comparison	Outcome	Study design
Bouten et al. (2020)	12 recreationally active male subjects performing sports on a weekly basis. Mean age of 21.6 ± 1.2 years.	Short-term Three maximal static breath-holds. Breathing intervention before cycling.	Control condition was baseline measure without breath-holding.	No significant change in performance in time and average power output.	Within-subject design
Guimard et al. (2014)	15 young competitive male swimmers. Mean age of 21.9 ± 0.9 years.	Short-term Breath-holding on 25m swimming with and without fins. Intervention was performed during swimming.	Swimming condition with normal breathing without fins.	Significant decrease in 100m swimming performance (increase in 100m time).	Within-subject design
Malakhov et al. (2014)	38 field athletics, combative and team sport athletes. 19 males, 19 females Mean age of 19.8 ± 1 years	Short-term Breath-holding in one session. Breath-holding after maximal inspiration. The breathing intervention was performed during the balancing exercises with a duration of 20 seconds.	The control condition performed normal breathing during balancing exercises (quiet breath).	No significant change in balance performance.	Within-subject design
Robertson et al. (2020)	9 well-trained swimmers. 6 males, 3 females Mean age of 19 ± 2 years.	Short-term Three breath-hold sessions. Breathing intervention during swimming.	No control condition without breath-holding.	No significant improvements in 400m swimming time, velocity and stroke rate.	Within-subject design
Stavrou et al. (2017)	10 fin-swimmers. Gender not specified. Mean age of 15.8 ± 0.5 years.	Short-term 8x 25m freestyle leg kick trials were performed under breath-holding conditions. Breathing intervention therefore occurred during swimming.	Swimming condition in which normal breathing was performed.	No significant differences in 25m swimming time.	Within-subject design

Woorons et al. (2019a)	10 highly trained Jiu-Jitsu fighters. 7 males, 3 females Mean age of 19.2 ± 2.3 years.	Short-term Voluntary hypoventilation at low lung volume Breath-holding on repeated shuttle-run sprints at maximal velocity. Normal exhalation at the start of each shuttle-run sprint and then breath-holding until sprint completion. Breathing intervention was performed during running.	Control condition was sprinting under normal breathing.	No significant change in performance in time.	Within-subject design
Woorons et al. (2017)	9 well-trained subjects-background in cycling, basketball, and rugby. 8 males, 1 female Mean age of 27.2 ± 9.3 years.	Short-term Voluntary hypoventilation at low lung volume Breath-holding on repeated sprint exercise on cycling ergometer. Normal exhalation at the start of each sprint, then breath-holding until the end of the 6-s exertion and finally a second exhalation to empty the remaining air from the lungs. Intervention was performed during cycling.	Control condition consisted of normal breathing during repeated sprint exercises on the ergometer.	No significant change in performance in mean power output.	Within-subject design
Brocherie et al. (2022)	35 high-level youth ice hockey players. Mean age of experimental 16.9±1.4 and of control 16.5±1.5. All males.	Longer-term Voluntary hypoventilation at low lung volume 10 repeated running 40m running sprint sessions were implemented over 5 weeks (2 sessions per week 48 h apart). Breath-holding occurred during 40m repeated sprints. Normal exhalation before sprint, then holding breath	Control group performed the same sprint training with normal breathing.	Significant improvement in mean velocity and percentage decrement score. No significant difference in maximum velocity.	Between-subject design

		during the sprint and performing a second exhalation after the sprint.			
Fornasier-Santos et al. (2018)	35 rugby players. Males Mean age of 18.3 ± 1.3 years.	Longer-term 4 weeks of repeated sprint training (2 sessions per week, 8 sessions in total). Voluntary hypoventilation at low lung volume Breathing intervention during sprinting: participants were told to do a normal exhalation just before the start of each sprint, then to hold their breath until the end of the 40m sprint, and finally to perform the second exhalation to empty the remaining air from the lungs.	Performed the same sprint training with normal breathing.	Significant increase in the number of sprints. No significant change in maximal velocity.	Between-subject design
Lapointe et al. (2020)	17 basketball players. Mean age 22.3 ± 1.2. 5 women, 12 men.	Longer-term Voluntary hypoventilation at low lung volume 8 repeated running sprint sessions over 4 weeks in which 6s-sprints were completed. Breath holding occurred during the sprints after exhaling, and a second exhalation was performed on completion of the sprint.	Control group performed the same sprint training with normal breathing.	No significant difference in best sprint time and mean sprint time. Percentage decrement score was significantly improved in the experimental group.	Between-subject design
Trincat et al. (2017)	16 highly trained swimmers. 9 males, 7 females. Mean age of experimental group: 15.6 ± 1.8 years, control group: 15.5 ± 1.9	Longer-term Voluntary hypoventilation at low lung volume	Control group performed the same sprint training without the breathing	Significant increase in the number of sprints performed in the experimental condition but not in the control condition	Between-subject design

	years.	Repeated sprint training of 2 weeks (6 sessions) in which the breathing intervention was performed. Breathing intervention was performed during swimming: swimmers were asked to exhale down to functional residual capacity or a little below just before starting each 15-m sprint. Then they had to push off the wall, glide and swim by trying to hold their breath up to the end of the 15 m. If they were not capable to do so, they were allowed to take an inhalation after exhaling the remaining air from the lungs and reproduce the same exhale-hold procedure to finish the sprint. At the end of each 15-m sprint, the swimmers of both groups completed the remaining 10 m at low pace while breathing normally and then recovered passively along the wall till the next sprint.	intervention.	No significant pre-post intervention difference in maximal sprint velocity in 25m swimming. No significant change in percentage decrement time score from pre-post intervention.	
Tyutyukov et al. (2015)	12 cold-water swimmers. Age 19-20 years. No gender specification.	Longer-term 8 weeks (total of 24 procedures, with various breath-holding modalities). Intervention was realized in a water basin.	The control group performed the same swimming training without the breath-hold immersions.	Significant improvement in 450m cold water swimming time. Significant performance increase in the Harvard Step Test Index (HSTI – Time to exhaustion)	Between-subject design
Woorons et al. (2019b)	18 male cyclists Age 34.6 ± 11 years	Longer-term 6 training sessions of repeated sprints in cycling over a 3-week period Repeated-sprint cycling training in hypoxic conditions, 6s all-out sprints	Same repeated-sprint training, in normoxic conditions	At Post compared to Pre, the mean power output during both the repeated-sprint ability and the Wingate tests was significantly improved in the voluntary	Between-subject design

		with start every 30s, starting in the first session with 2 sets of 6 to 8 sprints, to reach 3 sets of 8 sprints in the last session Participants were told to start each repetition by doing a normal exhalation and then to hold their breath until the end of the 6s sprint		hypoventilation condition, but not in the normoxic condition	
Woorons et al. (2020)	20 healthy males from different team sports (basketball, soccer, handball, rugby, and hockey). Mean age of 19.5±1 years.	Longer-term Voluntary hypoventilation at low lung volume 6 sessions of high-intensity training in cycling over a 3-week period. Breath-holding intervention during sport (running-field tests)	Performed the high-intensity training with normal breathing.	Significant improvement in percentage decrement score and in Yo-Yo Intermittent Recovery Level 1 test (YYIR1) (running). No significant improvement in 200m run time, mean 20m running sprint time and best 20m running sprint time.	Between-subject design

Table 1c: Summary of voluntary hyperventilation studies

First author (year)	Participants	Intervention	Comparison	Outcome	Study design
Dobashi et al. (2021)	11 trained athletes (sprinters, and badminton players) 10 males, 1 female. Mean age of 24 ± 2 years.	Short-term Participants performed 2 sessions of hyperventilation: 1) for 5 min duration 2) for 20 min Respiratory frequency was 30 breaths per minute. Immediately after the breathing intervention, the participants performed the 30s Wingate anaerobic test on a cycle ergometer.	Normal breathing	No significant differences for mean and peak power between the trials.	Within-subject design.
Fujii et al. (2015)	9 college athletes. 8 males, 1 female Mean age of 22.8 ± 2.4 years.	Short-term 30s Wingate anaerobic tests with 20 min hyperventilation performed before cycling. Breathing at 30 breaths per min.	Spontaneous breathing was performed before the Wingate anaerobic tests.	Mean power showed no significant differences. Fatigue index showed no significant differences.	Within-subject design
Gray et al. (2018)	7 female college swimmers. No information on the age.	Short-term The breathing technique was performed once for both the 50- yard and 100-yard distance. Intervention was performed before swimming. Breathing at 12 cycles per min.	Control group performed the swimming after normal breathing.	Stroke rate in 100 yards swimming showed no significant difference. Time for 100 yards swimming showed no significant differences.	Between-subject design
Jacob et al. (2015)	9 swimmers. 5 males mean age of 21 ± 8.5 years. 4 females mean age of 21 ± 8.7 years.	Short-term One 50 m front crawl sprint, one in normal conditions and one after a brief voluntary hyperventilation. The two 50	Control condition was the 50m front crawl sprint with normal breathing before.	50m swimming time significantly improved. Average velocity 50m front crawl was significantly higher. Index of coordination was	Within-subject design

		m front crawl sprints were performed on the same day, separated by 30 minutes of rest. The breathing intervention was performed before swimming. Breathing at 6 maximal respiratory cycles in 30 seconds (12 cycles per min).		significantly higher. Stroke rate increased significantly higher in the experimental group.	
Kaçoğlu and Işik. (2017)	14 female volleyball players. Mean Age 16.7 ± 1.2 years.	Short-term Hyperventilation for 30s after warm-up. 6 maximal respirations composed of 5s cycle: 2s maximal inspiration, 3s maximal expiration. Afterwards jump or sprint test was performed.	Control was normal breathing before tests.	No significant improvement in counter movement jump, squat jump, 20m sprint split time. Only 10m sprint split time showed significant improvement in the experimental group.	Within-subject design
Malakhov et al. (2014)	38 field athletics, combative and team sports athletes. 19 males, 19 females Mean age of 19.8 ± 1 years	Short-term Hyperventilation intervention performed during the balancing exercises with a duration of 20 seconds. Breathing as fast and deep as possible.	The control condition was performed at normal breathing during balancing exercises (quiet breath).	Balance performance was significantly lower in the experimental group.	Within-subject design
Sakamoto et al. (2014)	13 male university athletes from various sports backgrounds. Mean age of 21.2 ± 1.9 years	Short-term Hyperventilation was performed during recovery for 30s between 10 sets of 10 second maximal pedalling on a cycle ergometer. The breathing intervention was therefore after cycling. Breathing at 60 breaths per min.	Control condition with spontaneous breathing during recovery periods.	Significantly higher performance in mean power in the hyperventilation condition.	Within-subject design
Sakamoto et.al (2015)	15 power-trained university athletes.	Short-term	In the control condition,	No significant differences in peak torque in isokinetic concentric knee	Within-subject design

	10 males, 5 females Mean age of 21.2 ± 3.7 years.	12 repetitions of 8 sets of isokinetic knee extensions. Hyperventilation was performed for 30s between each exercise set. Therefore, the breathing intervention was performed after isokinetic concentric knee extensions. Breathing at 50 cycles per min ($PETCO_2$: 15–25 mm Hg).	spontaneous breathing was performed during the recovery periods.	extensions at 300º/s.	
Sakamoto et al. (2018)	17 power-trained university athletes (cycling, throwing, rugby, judo). 14 males, 3 females. Mean age: 20.3 ± 0.9 years.	Short-term 3 x 10 sets of standing pedalling sprints on a cycle ergometer with 60s recovery with hyperventilation for: 1) 15s 2) 45s Hyperventilation was performed at 60 cycles per minute.	Spontaneous breathing during recovery	No significant effect on peak and mean pedalling power output.	Within-subject design
Sakamoto et al. (2020)	11 power-trained men. Mixed backgrounds: throwers in athletics, rugby, judo, and middle-distance sprinters. Mean age of 22.5 ± 4.3 years	Short-term Intervention during recovery for 30s between 6 sets of bench press and then 6 sets of leg press at 80% 1RM with inter-set recovery of 5 minutes for both exercises. Intervention after bench and leg press. Breathing at 46-50 cycles per min (PETCO2: 15–25 mm Hg).	Control condition with spontaneous breathing during recovery periods.	Significant increase in the number of repetitions in bench and leg press.	Within-subject design

Table 1d: Summary of fast-paced breathing (FPB) studies

First author (year)	Participants	Intervention	Comparison	Outcome	Study design
Telles et al. (2014)	50 male participants experienced in yogic breathing. Mean age of 26.9 ± 6.2 years.	Short-term On two alternate days the participants were assessed for hand grip strength and leg and back strength, before and after high frequency yoga breathing and breath awareness. On the other two alternate days the participants were assessed for finger tapping speed and arm tapping speed, before and after high frequency yoga breathing and breath awareness. The breathing intervention was performed before the strength exercises. Breathing at 1.0 hertz (yoga breathing).	Control condition was breath awareness before the strength exercises.	Significant increase in right hand grip strength. Left hand grip strength and leg and back strength showed no significant differences. Finger and arm tapping speed increased significantly.	Within-subject design

Table 3

Full reference of the studies included in the systematic review

Number	Reference
1	Bouten, J., Colosio, A. L., Bourgois, G. I. L., Lootens, L., Van Eenoo, P., Bourgois, J. G., & Boone, J. A. N. (2020). Acute Apnea Does Not Improve 3-km Cycling Time Trial Performance. *Medicine & Science in Sports & Exercise*, 52(5), 1116-1125.
2	Brocherie, F., Cantamessi, G., Millet, G. P., & Woorons, X. (2022). Effects of repeated-sprint training in hypoxia induced by voluntary hypoventilation on performance during ice hockey off-season. *International Journal of Sports Science & Coaching*. doi:10.1177/17479541221079531
3	Burtch, A. R., Ogle, B. T., Sims, P. A., Harms, C. A., Symons, T. B., Folz, R. J., & Zavorsky, G. S. (2017). Controlled Frequency Breathing Reduces Inspiratory Muscle Fatigue. *The Journal of Strength and Conditioning Research, 31*(5), 1273-1281. doi:10.1519/JSC.0000000000001589
4	Choudhary, R., Trivedi, V., & Choudhary, S. (2016). Effect of Heart Rate Variability Biofeedback Training on the Performance of Track Athlete. *International Journal of Therapies and Rehabilitation Research, 5*(4). doi:10.5455/ijtrr.000000159
5	Conlon, A., Arnold, R., Preatoni, E., & Moore, L. J. (2022). Pulling the Trigger: The Effect of a 5-Minute Slow Diaphragmatic Breathing Intervention on Psychophysiological Stress Responses and Pressurized Pistol Shooting Performance. *Journal of Sport and Exercise Psychology*, 1-14. doi:10.1123/jsep.2021-0213
6	Dobashi, K., Fujii, N., Ichinose, M., Fujimoto, T., & Nishiyasu, T. (2021). Voluntary hypocapnic hyperventilation lasting 5 min and 20 min similarly reduce aerobic metabolism without affecting power outputs during Wingate anaerobic test. *European Journal of Sport Science, 21*(8), 1148-1155. doi:10.1080/17461391.2020.1812728
7	Fornasier-Santos, C., Millet, G. P., & Woorons, X. (2018). Repeated-sprint training in hypoxia induced by voluntary hypoventilation improves running repeated-sprint ability in rugby players. *European Journal of Applied Physiology, 18*(4), 504-512. doi:10.1080/17461391.2018.1431312
8	Fujii, N., Tsuchiya, S., Tsuji, B., Watanabe, K., Sasaki, Y., & Nishiyasu, T. (2015). Effect of voluntary hypocapnic hyperventilation on the metabolic response during Wingate anaerobic test. *European Journal of Applied Physiology, 115*(9), 1967-1974. doi:10.1007/s00421-015-3179-8
9	Gray, T. O., Pritchett, R., Pritchett, K., & Burnham, T. (2018). Pre-Race Deep-Breathing Improves 50 & 100-yard Swim Performance in Female NCAA Swimmers. *Journal of Swimming Research, 26*, 32-41.
10	Guimard, A., Prieur, F., Zorgati, H., Morin, D., Lasne, F., & Collomp, K. (2014). Acute apnea swimming: metabolic responses and performance. *The Journal of Strength and Conditioning Research, 28*(4), 958-963. doi:10.1519/JSC.0000000000000254
11	Jacob, C., Keyrouz, C., Bideau, N., Nicolas, G., El Hage, R., Bideau, B., & Zouhal, H. (2015). Pre-exercise hyperventilation can significantly increase performance in the 50-meter front crawl. *Science & Sports, 30*(3), 173-176. doi:10.1016/j.scispo.2015.02.006
12	Kaçoğlu, C., & Işik, M. M. (2017). The acute effects of the voluntary pre-activity hyperventilation on jump and sprint performance in female volleyball players. *European Journal of Human Movement*(38), 93-104.
13	Laborde, S., Lentes, T., Hosang, T. J., Borges, U., Mosley, E., & Dosseville, F. (2019). Influence of slow-paced breathing on inhibition after physical exertion. *Frontiers in Psychology, 10*. doi:10.3389/fpsyg.2019.01923
14	Lapointe, J., Paradis-Deschenes, P., Woorons, X., Lemaitre, F., & Billaut, F. (2020). Impact of Hypoventilation Training on Muscle Oxygenation, Myoelectrical Changes, Systemic [K(+)], and Repeated-Sprint Ability in Basketball Players. *Frontiers in Sports and Active Living, 2*, 29. doi:10.3389/fspor.2020.00029
15	Lim, D. J., Kim, J. J., Marsh, G. D., & Belfry, G. R. (2018). Physiological resolution of periodic breath holding during heavy-intensity Fartlek exercise. *European Journal of Applied Physiology, 118*(12), 2627-2639. doi:10.1007/s00421-018-3986-9
16	Malakhov, M., Makarenkova, E., & Melnikov, A. (2014). The influence of different modes of ventilation on standing balance of athletes. *Asian Journal of Sports Medicine, 5*(3), e22767. doi:10.5812/asjsm.22767

17	Paul, M., & Garg, K. (2012). The Effect of Heart Rate Variability Biofeedback on Performance Psychology of Basketball Players. *Applied psychophysiology and biofeedback*, 131-144. doi:10.1007/s10484-012-9185-2
18	Pelka, M., Kolling, S., Ferrauti, A., Meyer, T., Pfeiffer, M., & Kellmann, M. (2017). Acute effects of psychological relaxation techniques between two physical tasks. *Journal of Sports Sciences, 35*(3), 216-223. doi:10.1080/02640414.2016.1161208
19	Perez-Gaido, M., Lalanza, J. F., Parrado, E., & Capdevila, L. (2021). Can HRV Biofeedback Improve Short-Term Effort Recovery? Implications for Intermittent Load Sports. *Appl Psychophysiol Biofeedback*. doi:10.1007/s10484-020-09495-8
20	Raymond, J., Sajid, I., Parkinson, L. a., & Gruzelier, J. H. (2005). Biofeedback and Dance Performance: A Preliminary Investigation. *Applied psychophysiology and biofeedback, 30*, 65-73. doi:10.1007/s10484-005-2175-x
21	Robertson, C., Lodin-Sundstrom, A., O'Hara, J., King, R., Wainwright, B., & Barlow, M. (2020). Effects of Pre-race Apneas on 400-m Freestyle Swimming Performance. *The Journal of Strength and Conditioning Research, 34*(3), 828-837. doi:10.1519/JSC.0000000000002711
22	Sakamoto, A., Naito, H., & Chow, C. M. (2014). Hyperventilation as a strategy for improved repeated sprint performance. *The Journal of Strength and Conditioning Research, 28*(4), 1119-1126. doi:10.1519/JSC.0b013e3182a1fe5c
23	Sakamoto, A., Naito, H., & Chow, C. M. (2015). Hyperventilation-induced respiratory alkalosis falls short of countering fatigue during repeated maximal isokinetic contractions. *European Journal of Applied Physiology, 115*(7), 1453-1465. doi:10.1007/s00421-015-3134-8
24	Sakamoto, A., Naito, H., & Chow, C. M. (2018). Effects of Hyperventilation on Repeated Pedaling Sprint Performance: Short vs. Long Intervention Duration. *The Journal of Strength and Conditioning Research, 32*(1), 170-180. doi:10.1519/JSC.0000000000001789
25	Sakamoto, A., Naito, H., & Chow, C. M. (2020). Hyperventilation-Aided Recovery for Extra Repetitions on Bench Press and Leg Press. *The Journal of Strength and Conditioning Research, 34*(5), 1274-1284. doi:10.1519/JSC.0000000000003506
26	Stavrou, V., Toubekis, A. G., & Karetsi, E. (2015). Changes in Respiratory Parameters and Fin-Swimming Performance Following a 16-Week Training Period with Intermittent Breath Holding. *Journal of Human Kinetics, 49*, 89-98. doi:10.1515/hukin-2015-0111
27	Stavrou, V., Voutselas, V., Karetsi, E., & Gourgoulianis, K. I. (2017). Acute responses of breathing techniques in maximal inspiratory pressure. *Sport Sciences for Health, 14*(1), 91-95. doi:10.1007/s11332-017-0406-1
28	Telles, S., Sharma, S. K., & Balkrishna, A. (2014). Blood pressure and heart rate variability during yoga-based alternate nostril breathing practice and breath awareness. *Medical Science Monitor Basic Research, 20*, 184-193. doi:10.12659/msmbr.892063
29	Trincat, L., Woorons, X., & Millet, G. P. (2017). Repeated-Sprint Training in Hypoxia Induced by Voluntary Hypoventilation in Swimming. *International Journal of Sports Physiology and Performance, 12*(3), 329-335. doi:10.1123/ijspp.2015-0674
30	Tyutyukov, V. G., Safonova, G. V., & Shakirova, O. (2015). Special respiratory training for preparing cold-water swimmers. *Biology and Medicine, 7*, 1-5.
31	Vickery, R. L. (2007). *The effect of breathing pattern retraining on performance in competitive cyclists.* Auckland University of Technology,
32	Woorons, X., Billaut, F., & Vandewalle, H. (2020). Transferable Benefits of Cycle Hypoventilation Training for Run-Based Performance in Team-Sport Athletes. *International Journal of Sports Physiology & Performance, 15*(8), 1103-1108.
33	Woorons, X., Dupuy, O., Mucci, P., Millet, G. P., & Pichon, A. (2019a). Cerebral and Muscle Oxygenation during Repeated Shuttle Run Sprints with Hypoventilation. *International Journal of Sports Medicine, 40*(6), 376-384. doi:10.1055/a-0836-9011
34	Woorons, X., Millet, G. P., & Mucci, P. (2019b). Physiological adaptations to repeated sprint training in hypoxia induced by voluntary hypoventilation at low lung volume. *European Journal of Applied Physiology*, 119(9), 1959-1970. doi:10.1007/s00421-019-04184-9
35	Woorons, X., Mollard, P., Pichon, A., Duvallet, A., Richalet, J. P., & Lamberto, C. (2008). Effects of a 4-week training with voluntary hypoventilation carried out at low pulmonary volumes. *Respiratory Physiology & Neurobiology, 160*(2), 123-130. doi:10.1016/j.resp.2007.09.010
36	Woorons, X., Mucci, P., Aucouturier, J., Anthierens, A., & Millet, G. P. (2017). Acute effects of repeated cycling sprints in hypoxia induced by voluntary hypoventilation. *European Journal of Applied Physiology, 117*(12), 2433-2443. doi:10.1007/s00421-017-3729-3

37	Woorons, X., Mucci, P., Richalet, J. P., & Pichon, A. (2016). Hypoventilation Training at Supramaximal Intensity Improves Swimming Performance. *Med Sci Sports Exerc, 48*(6), 1119-1128. doi:10.1249/MSS.0000000000000863

Table 4: A comparative overview of the systematic review results

Please note that alternate and uni-nostril breathing are not included, as no studies were found on the effect of this breathing technique on physical sport performance.

Breathing Technique		**Slow-paced breathing**		**Fast-paced breathing**	**Voluntary hyperventilation**	**Breath-holding**	
Number of studies		k = 13		k = 1	k = 10	k = 14	
Effects		Longer-term	Short-term	Short-term	Short-term	Longer-term	Short-term
		$k_{studies}$ = 8; $k_{effects}$ = 13	$k_{studies}$ = 5; $k_{effects}$ = 5	$k_{studies}$ = 1; $k_{effects}$ = 5	$k_{studies}$ = 10; $k_{effects}$ = 21	$k_{studies}$ = 7; $k_{effects}$ = 20	$k_{studies}$ = 7; $k_{effects}$ = 10
Participants	Sample size	n = 15-30	n = 10-67	n = 50	n = 9-38	n = 12-35	n = 9-38
	Healthy/ clinical	healthy	healthy	healthy	healthy	healthy	healthy
	Mean age	25.8 ± 7.6	24.3 ± 1.9	26.9 ± 6.2	21.1 ± 1.9	18.0 ± 2.2	20.6 ± 3.3

	Sport background		basketball (k=1), dance (k=1), cycling (k=1), running (k=2), triathlon (k=2), swimming (k=2)	active sport science students (k=3), active students from different sports (k=2), recreationally active subjects from a variety of disciplines (k=1)	yogic breathing (k = 1)	swimming (k=2), volleyball (k=1), power-training, such as throwing or rugby (k=3), or a mix of sport backgrounds (k=4)	swimming (k=2), rugby (k=1), ice hockey (k=1), basketball (k=1), variety of sports (k=1)	swimming (k=3), Jiu-Jitsu (k=1), and a variety of backgrounds (k=3)
	Discipline investigated		basketball (k=1), dancing (k=1), cycling (k=1), running (k=2), swimming (k=3)	cycling (k=1), running (k=2), shooting (k=1) and strength exercises (burpees) (k=1)	strength exercises (k=1)	balancing (k=1), cycling (k=4), swimming (k=2), running (k=1), and strength exercises (k=3)	swimming (k=2), running (k=4), cycling (k=1)	balancing (k=1), cycling (k=2), running (k=1) and swimming (k=3)
Int	Timing	Before sport	/	k = 2	k = 1	k = 5	/	k = 1

ervention		During sport	k = 4	k = 1	/	k = 1	k = 6	k = 6
		After sport	/	k = 2	/	k = 4	/	/
		Unspecified	k = 4	/	/	/	k = 1	/
Control	Control		normal breathing, watching motivational videos	normal breathing, reading, watching TV documentary, watching educational video	breath-awareness	normal breathing	normal breathing	normal breathing
Outcomes ($k_{effects}$)	Category	Time	k = 5	k = 1	/	k = 4	k = 11	k = 5
		Strength	k = 1	k = 2	k = 3	k = 12	k = 2	k = 2
		Speed	k = 2	k = 1	k = 2	k = 1	k = 4	k = 1
		Specific	k = 5	k = 1	/	k = 4	k = 3	k = 2
	Positive effects	Time	k = 4	k = 1	/	k = 2	k = 5	/
		Strength	k = 1	/	k = 1	k = 3	k = 2	/
		Speed	k = 1	k = 1	k = 2	k = 1	k = 1	/
		Specific	k = 5	/	/	k = 2	k = 3	/
	Negative effects	Time	/	/	/	/	/	k = 1
		Strength	/	/	/	/	/	/
		Speed	/	/	/	/	/	/
		Specific	/	/	/	k = 1	/	/
	No effects	Time	k = 1	/	/	k = 2	k = 6	k = 4
		Strength	/	k = 2	k = 2	k = 9	/	k = 2

		Speed	k = 1	/	/	/	k = 3	k = 1
		Specific	/	k = 1	/	k = 1	/	k = 2
Study design	Within-subject		/	k = 4	k = 1	k = 9	/	k = 7
	Between-subject		k = 8	k = 1	/	k = 1	k = 7	/

Table 5: Risk of Bias results
D1: Risk of bias from randomisation process
D2: Risk of bias due to deviation from the intended interventions (effect of adhering to intervention)
D3: Risk of bias due to missing outcome data
D4: Risk of bias in measurement of outcome
D5: Risk of bias in selection of the reported result

	D1	D2	D3	D4	D5	Overall risk of bias judgement
Bouten et al. (2019)	+	+	+	−	−	−
Brocherie (2022)	+	+	+	−	−	−
Burtch et al. (2017)	×	+	+	−	−	×
Choudhary et al. (2016)	×	+	+	−	×	×
Conlon (2022)	+	+	+	−	−	−
Dobashi (2021)	+	+	+	−	−	−
Fornasier-Santos et al. (2018)	×	+	+	−	−	×
Fujii et al. (2015)	+	+	+	−	−	−
Gray et al. (2018)	+	+	+	−	−	−
Guimard et al. (2014)	+	+	+	−	−	−
Jacob et al. (2015)	+	+	+	−	−	−
Kaçoğlu (2017)	+	+	+	−	−	−
Lapointe (2020)	+	+	+	−	−	−
Laborde et al. (2019)	+	+	+	−	−	−
Lim et al. (2018)	+	+	+	−	−	−
Malakhov et al. (2014)	×	+	+	−	−	×
Paul and Garg (2012)	+	−	+	+	−	−
Pelka et al. (2017)	+	+	+	+	−	−
Perez-Gaido (2021)	×	+	+	−	−	×

Raymond et al. (2005)	×	−	+	+	−	×
Robertson et al. (2020)	+	+	+	−	−	−
Sakamoto et al. (2014)	+	+	+	−	−	−
Sakamoto et al. (2015)	+	+	+	−	−	−
Sakamoto (2018)	×	−	+	−	−	×
Sakamoto et al. (2020)	+	+	+	−	−	−
Stavrou et al. (2015)	×	+	+	−	−	×
Stavrou et al. (2018)	+	+	+	−	−	−
Telles et al. (2014)	×	+	+	−	−	×
Trincat et al. (2017)	×	+	+	−	−	×
Tyutyukov et al. (2015)	×	−	+	−	−	×
Vickery (2007)	×	−	+	−	−	×
Woorons et al. (2008)	×	+	+	−	−	×
Woorons et al. (2016)	×	+	+	−	−	×
Woorons et al. (2017)	+	+	+	−	−	−
Woorons et al. (2019a)	+	+	+	−	−	−
Woorons et al. (2019b)	×	+	+	−	−	×
Woorons (2020)	+	+	+	−	−	−

PRISMA 2020 Checklist

Section and Topic	Item #	Checklist item	Location where item is reported
TITLE			
Title	1	Identify the report as a systematic review.	Title Page
ABSTRACT			
Abstract	2	See the PRISMA 2020 for Abstracts checklist.	Page 1
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	Pages 2,3
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	Pages 11,12
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	Pages 12-15
Information sources	6	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	Page 12
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	Page 12
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	Pages 15, 16
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	Pages 15,16
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g. for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	Pages 15,16
	10b	List and define all other variables for which data were sought (e.g. participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.	Pages 15,16
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	Pages 16, 17.
Effect measures	12	Specify for each outcome the effect measure(s) (e.g. risk ratio, mean difference) used in the synthesis or presentation of results.	Pages 17-19.
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g. tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)).	Pages 15,16.
	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions.	Pages 17-19.
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	Page 16.
	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	Pages 17-19.
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g. subgroup analysis, meta-regression).	Pages 17-19.
	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results.	Pages 17-

PRISMA 2020 Checklist

Section and Topic	Item #	Checklist item	Location where item is reported
			19.
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).	Page 16-17.
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	Pages 17-19.
RESULTS			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	Page 20.
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	Page 20
Study characteristics	17	Cite each included study and present its characteristics.	Page 21-22
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	Pages 22
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g. confidence/credible interval), ideally using structured tables or plots.	Pages 22-25.
Results of syntheses	20a	For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies.	Page 22
	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g. confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect.	Pages 22-25
	20c	Present results of all investigations of possible causes of heterogeneity among study results.	Pages 22-25
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.	Pages 22-25
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	Pages 22-25
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	Pages 22-25
DISCUSSION			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	Pages 25-37.
	23b	Discuss any limitations of the evidence included in the review.	Pages 38-39.
	23c	Discuss any limitations of the review processes used.	Pages 39-40.
	23d	Discuss implications of the results for practice, policy, and future research.	Pages 40, 41).
OTHER INFORMATION			
Registration and	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	Page 12.

PRISMA 2020 Checklist

Section and Topic	Item #	Checklist item	Location where item is reported
protocol	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	Page 12
	24c	Describe and explain any amendments to information provided at registration or in the protocol.	Page 39.
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	Page 43
Competing interests	26	Declare any competing interests of review authors.	Page 43.
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.	Page 43.

From: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71

For more information, visit: http://www.prisma-statement.org/

Response to Reviewer Recommendations

Please, find below our response to the reviewers' recommended changes. As before, we have included the reviewers' original comments in regular typeface with our responses provided in blue. The manuscript has also been submitted with corrections highlighted in red. We are pleased that the three reviewers have responded to our manuscript with favourable comments, and we have done our best to implement all the recommended changes. In addition, through the recommendations of Reviewer 1, we noticed that we could enhance the quality of our methodological approach, and have included the following additional changes:

1) We now explain in more detail the choice of the coefficient of correlation used to present the effect sizes for within-subjects design studies and change scores for between-subjects study designs.

   "In within-subject designs or between-subject designs with change scores, the Hedges' g (SMD = MD/SDpooled) and its standard error were computed according to recommendations from Borenstein, Hedges, Higgins, and Rothstein (2009; 4.15 – page 24) and the Cochrane Handbook (Higgins et al., 2022; chapter 23, section 23.2.7.2). The standard error was computed using the imputation of a correlation coefficient at 0.6 between the performances of pre-breathing intervention and post-breathing intervention." (p. 17, l. 452-457)

2) We performed sensitivity analyses to test the reliability of the coefficient of correlation chosen.

   "To assess the reliability of this coefficient, sensitivity analyses were run up to the averaged coefficients of correlation ±0.20 per 0.05 interval (between 0.4 and 0.8). No differences in the relationships between effect sizes, significance tests, and outlier detection were identified, supporting the robustness of results." (p. 17, l. 457-460)

3) We provided all computation tables with formulae references on the OSF (10.17605/OSF.IO/XK59D). The reliability of these tables can also be checked with different r functions. For example, >library(metafor) >rma(g, Vg, data=fullData, method="DL")

"The computation tables (including all formulae references [page and formula reference number] - based on Borenstein et al., 2009) used to compute the effect sizes for the different study designs are provided on the Open Science Framework." (p.18, l.428-431)

4) We have now changed our outlier detection method to a more up to date method recommended by Viechtbauer and Cheung (2010) (Cooks' distance to studentized deleted residuals). The same outliers were detected with the studentized deleted residuals as previously with the Cook's distance.

S2

5) By scrutinizing the studies to carefully check inclusion criteria as prompted by Reviewer 1, we found one study in the slow-paced breathing acute category (the second study in Laborde et al., 2019) that should not have been included in the analysis and which has now been deleted (explaining why some of the effects have slightly changed).

We would like to thank the Editor and the reviewers for their time in reviewing this revised manuscript, and believe that by addressing their concerns we have substantially strengthened the final manuscript.

Reviewer 1

Study authors are to be commended for the considerable efforts adopted in their revised submission. Particularly in reinforcing the unique contributions of this review beyond those which have recently been published. The manuscript is strengthened as a consequence. I continue to offer suggestions in an effort refine the contribution given the targeted venue.

Author response: We would like to thank Reviewer 1 for the general positive evaluation of the revised version of our manuscript, as well as for the additional suggestions made to continue to improve our manuscript.

1. It is appreciated that more attention to psychological aspects related to breathing techniques as included in the Introduction and Discussion. A discussion of the physiological underpinnings of breathing techniques still predominates these sections. It further appears that the psychological benefits of breathing techniques is speculative or thought to be a indirect consequence of the physiological/performance effects. For example, the Laborde et al. (2022) citation is an Editorial. Further the use of less convincing language "…might" (Page 10; line 220) reinforces that the current state of knowledge of breathing techniques on psychological mechanisms is less understood (or subject to less empirical investigation). The authors acknowledge this Page 12; lines 257-259).

Thank you for pointing this out. We fully agree with Reviewer 1 that the majority of the psychological evidence related to breathing techniques in sports is still mostly related / thought to be an indirect consequence of their physiological effects. We have now added this as a limitation of our study:

> *"Fifth, it should be noted that the psychological benefits of the breathing techniques still need to be investigated further, and those reported in this paper are still largely speculative or thought to be a consequence of the physiological effects of breathing techniques. Consequently, future research should urgently consider the potentially unique psychological effects of breathing techniques in order to better understand their influence on sport performance."*

Further, we are happy to clarify the reason for citing the two Laborde et al. (2022) references:

The first one is indeed (p.4, l.101) an Editorial, referring to the body of work published within the Research Topic "Editorial: Horizon 2030: Innovative Applications of Heart Rate Variability"

Laborde, S., Mosley, E., Bellenger, C. R., & Thayer, J. F. (2022). Editorial: Horizon 2030: Innovative Applications of Heart Rate Variability. *Frontiers in Neuroscience*. doi:10.3389/fnins.2022.937086

We agree with the Reviewer that this citation, while pointing to a body of work recently published, does not accurately represent potential evidence demonstrating the links between cardiac vagal activity and psychological outcomes. We now add references to the following systematic reviews and meta-analyses establishing the link between cardiac vagal activity and psychological processes:

Forte, G., Favieri, F., & Casagrande, M. (2019). Heart rate variability and cognitive function: a systematic review. *Frontiers in Neuroscience, 13*, Article 710. doi:10.3389/fnins.2019.00710

Forte, G., Morelli, M., Grässler, B., & Casagrande, M. (2022). Decision making and heart rate variability: A systematic review. *Applied Cognitive Psychology, 36*(1), 100-110. doi:10.1002/acp.3901

Holzman, J. B., & Bridgett, D. J. (2017). Heart rate variability indices as bio-markers of top-down self-regulatory mechanisms: A meta-analytic review. Neuroscience & Biobehavioral Reviews, 74(Pt A), 233-255. doi:10.1016/j.neubiorev.2016.12.032

Mosley, E., & Laborde, S. (2022). A scoping review of heart rate variability in sport and exercise psychology. *International Review of Sport and Exercise Psychology,* 1-75. doi:10.1080/1750984x.2022.2092884

Thayer, J. F., Ahs, F., Fredrikson, M., Sollers, J. J., & Wager, T. D. (2012). A meta-analysis of heart rate variability and neuroimaging studies: implications for heart rate variability as a marker of stress and health. *Neuroscience & Biobehavioral Reviews*, 36, 747-756. doi:10.1016/j.neubiorev.2011.11.009

The second Laborde et al. 2022, is a systematic review and series of meta-analyses, including 223 studies, synthesizing the effects of slow-paced breathing on cardiac vagal activity, as indexed non-invasively via vagally-mediated heart rate variability.

Laborde, S., Allen, M. S., Borges, U., Dosseville, F., Hosang, T. J., Iskra, M., . . . Javelle, F. (2022). Effects of voluntary slow breathing on heart rate and heart rate variability: A systematic review and a meta-analysis. *Neuroscience & Biobehavorial Reviews, 138*, 104711. doi:10.1016/j.neubiorev.2022.104711

Here again, we concur with the Reviewer that this still refers to the effects of breathing techniques on physiological parameters, indirectly influencing, in turn, psychological parameters as suggested by the Neurovisceral Integration Model, which links cardiac vagal activity to psychological outcomes (Smith, Thayer, Khalsa, & Lane, 2017; Thayer, Hansen, Saus-Rose, & Johnsen, 2009). Consequently, further research specifically focusing on the unique psychological aspects is critically needed, as we now indicate in our Limitations section (see above).

Overall, we agree with the Reviewer that the current state of knowledge regarding breathing techniques and their influence on psychological processes is less understood, and we now highlight this in our Limitations sections.

2. Would prefer the term "longer-term" as opposed to "long-term" interventions given that this represents those that are delivered on > 1 occasion.

Author response: We have now corrected this throughout the manuscript.

3. One concern is again raised with respect to decisions about inclusion criteria including sampling and outcomes. It is recognised that criteria for engagement was "….regular sport and exercise was met it participants followed a sport and/or exercise training protocol…This includes athletes taking part in sport competition and exercisers actively engaged in a regular sport regimen for reasons other than competitive ones". Competition is inherent to the definition of sport. Therefore, what reasons other than competition were participants engaged in sport for? Was this measured by authors of the primary study?

Author response: This is a good point. We apologise for the unclear reporting. We actually meant that participants were either athletes taking part in sport training and sport competitions, or exercisers actively engaged in a regular exercise regimen, but not taking part in competitions. We have now rephrased it as:

> *"Consequently, participants were either athletes taking part in training and sport competitions, or exercisers actively engaged in a regular exercise regimen for reasons other than competitive ones." (p.13, l.303-305)*

Further, the title clearly identifies "sport performance" as the outcome. In the text, the authors speak to "physical sport performance". I remain unconvinced that some of the outcomes are sport performance (e.g., number of burpees, velocity at lactic threshold. And therefore wonder about their inclusion. It is unclear whether the removal of some of these studies (either as stand-alone) or as one component of the statistical corrections for multi-effects may alter findings and their subsequent implications.

Author response: We understand the difficulties with wording raised by the Reviewer. This gives us the opportunity to clarify our approach and inclusion criteria regarding sport performance outcomes. Sport performance is complex, as it relies on a large range of skills across multiple domains (Janelle & Hillman, 2003). Our approach to sport performance followed the approach usually adopted in IRSEP by systematic reviews investigating the influence of specific interventions on sport performance and includes sport performance measures beyond those which can be directly considered as outcomes of sport competitions, such as components of fitness and performance execution at technical tasks (Harris, Allen, Vine, & Wilson, 2021; Murdoch et al., 2021; Noetel, Ciarrochi, Van Zanden, & Lonsdale, 2017; Rupprecht, Tran, & Gröpel, 2021).

Harris, D. J., Allen, K. L., Vine, S. J., & Wilson, M. R. (2021). A systematic review and meta-analysis of the relationship between flow states and performance. *International Review of Sport and Exercise Psychology.* Ahead of print issue. doi:10.1080/1750984x.2021.1929402

Murdoch, E. M., Lines, R. L. J., Crane, M. F., Ntoumanis, N., Brade, C., Quested, E., . . . Gucciardi, D. F. (2021). The effectiveness of stress regulation interventions with athletes: A systematic review and multilevel meta-analysis of randomised controlled trials. *International Review of Sport and Exercise Psychology*. Ahead of print issue. doi:10.1080/1750984x.2021.1977974

Noetel, M., Ciarrochi, J., Van Zanden, B., & Lonsdale, C. (2017). Mindfulness and acceptance approaches to sporting performance enhancement: a systematic review. *International Review of Sport and Exercise Psychology, 12*(1), 139-175. doi:10.1080/1750984x.2017.1387803

Rupprecht, A. G. O., Tran, U. S., & Gröpel, P. (2021). The effectiveness of pre-performance routines in sports: a meta-analysis. *International Review of Sport and Exercise Psychology.* Ahead of print issue. doi:10.1080/1750984x.2021.1944271

Still, this comment prompted us to reflect on the markers of sport performance that could directly be considered as outcomes of sport competitions, which we identify as such in Table 1.

Table 1: Classification of sport performance measures included as competitive/non-competitive outcomes

	ShortReference	**Outcome**	**Category**	**Sport**	**Sport Competitive outcome (Y/N)**
BH_ST	Malakhov(2014)	Balance_Displacement	Specific	Balancing	N
BH_ST	Bouten(2019)	AveragePowerOutput	Strength	Cycling	N
BH_ST	Bouten(2019)	Time_3kmCycling	Time	Cycling	Y
BH_ST	Woorons(2017)	MeanPower	Strength	Running	N
BH_ST	Woorons(2019)	Time_Sprint	Time	Running	N
BH_ST	Robertson(2018)	Velocity	Speed	Swimming	N
BH_ST	Robertson(2018)	StrokeRate	Specific	Swimming	N

BH_ST	Guimard(2014)	Performance_Time_100m	Time	Swimming	Y
BH_ST	Robertson(2018)	Time_400m	Time	Swimming	Y
BH_LT	Lapointe(2020)	Average_30m_sprint	Time	Running	N
BH_LT	Lapointe(2020)	Percentage_Decrement_Score	Time	Running	N
BH_LT	Brocherie(2022)	Maximum_Velocity_40m	Time	Running	N
BH_LT	Brocherie(2022)	Mean_Velocity_40m	Time	Running	N
BH_LT	Brocherie(2022)	Percentage_Decrement_Score	Time	Running	N
BH_LT	Woorons(2020)	Distance	Distance	Running	N
BH_LT	Woorons(2020)	Percentage_Decrement_Score	Time	Running	N
BH_LT	Fornasier(2018)	MaximalVelocity_40m	Speed	Running	N
BH_LT	Fornasier(2018)	SprintNumber_40m	Specific	Running	N
BH_LT	Woorons(2019b)	MeanPowerOutputRSA	Strength	Running	N
BH_LT	Woorons(2019b)	MeanPowerOutputWingate	Strength	Running	N
BH_LT	Woorons(2020)	20m_Running_Sprint_average_velocity	Time	Running	N
BH_LT	Lapointe(2020)	Best_30m_sprint	Time	Running	Y
BH_LT	Woorons(2020)	Best_20m_Sprint	Time	Running	Y
BH_LT	Woorons(2020)	200m_Run_Time	Time	Running	Y
BH_LT	Trincat(2017)	MaximalVelocity_25m	Speed	Swimming	N
BH_LT	Tyutyukov(2015)	Time_HSTI (Harvard step test index)	Time	Swimming	N
BH_LT	Trincat(2017)	PercentageDecrement_25m	Time	Swimming	N
BH_LT	Trincat(2017)	TotalNumber_25m	Specific	Swimming	N
BH_LT	Stavrou(2018)	Time_25m	Time	Swimming	Y
BH_LT	Tyutyukov(2015)	Time_450m	Time	Swimming	Y
VH_ST	Malakhov(2014)	Balance_Displacement	Specific	Balancing	N
VH_ST	Sakamoto(2020)	Number_Repetitions_BenchPress	Strength	BenchPress	N
VH_ST	Fujii(2015)	PowerMean_30sWAnT	Strength	Cycling	N
VH_ST	Fujii(2015)	FatigueIndex	Strength	Cycling	N
VH_ST	Sakamoto(2014)	MeanPower	Strength	Cycling	N
VH_ST	Sakamoto(2018)	Peak_Pedalling_Power	Strength	Cycling	N
VH_ST	Sakamoto(2018)	Mean_Pedalling_Power	Strength	Cycling	N
VH_ST	Dobashi(2021)	Mean_Power_Cycling	Strength	Cycling	N
VH_ST	Dobashi(2021)	Peak_Power_Cycling	Strength	Cycling	N
VH_ST	Sakamoto(2015)	PeakTorque	Strength	KneeExtension	N
VH_ST	Sakamoto(2020)	Number_Repetition_LegPress	Strength	LegPress	N

VH_ST	Kaoglu(2017)	10m_Sprint	Time	Running	Y
VH_ST	Kaoglu(2017)	20m_Sprint	Time	Running	Y
VH_ST	Kaoglu(2017)	Counter_Movement_Jump	Strength	Strength	N
VH_ST	Kaoglu(2017)	Squat_Jump	Strength	Strength	N
VH_ST	Gray(2018)	StrokeRate_100Yards	Specific	Swimming	N
VH_ST	Jacob(2015)	AverageVelocity_50m	Speed	Swimming	N
VH_ST	Jacob(2015)	Index_Coordination	Specific	Swimming	N
VH_ST	Jacob(2015)	StrokeRate	Specific	Swimming	N
VH_ST	Gray(2018)	Time_100 yards	Time	Swimming	Y
VH_ST	Jacob(2015)	Time_50m	Time	Swimming	Y
SPB_ST	Laborde(2019a)	NumberBurpees	Specific	Burpees	N
SPB_ST	Laborde(2019b)	NumberBurpees	Specific	Burpees	N
SPB_ST	Lim(2018)	MeanPower_Cycling	Strength	Cycling	N
SPB_ST	Pelka(2017)	AverageSpeed	Speed	Running	N
SPB_ST	Perez-Gaido(2021)	Time_Spent_Running	Time	Running	N
SPB_ST	Conlon(2022)	Shooting_Accuracy	Specific	Shooting	Y
SPB_LT	Paul(2012)	Dribbling	Specific	Basketball	N
SPB_LT	Paul(2012)	Passing	Specific	Basketball	N
SPB_LT	Paul(2012)	Shooting	Specific	Basketball	Y
SPB_LT	Vickery(2008)	AveragePower_20km	Strength	Cycling	N
SPB_LT	Vickery(2008)	AverageSpeed_20km	Speed	Cycling	N
SPB_LT	Vickery(2008)	Time_20km	Time	Cycling	Y
SPB_LT	Raymond(2005)	TrainingScores	Specific	Dance	N
SPB_LT	Woorons(2008)	Velocity_AtLacticThreshold	Speed	Running	N
SPB_LT	Choudhary(2016)	Time_5kmRunning	Time	Running	Y
SPB_LT	Woorons(2016)	StrokeRate	Specific	Swimming	N
SPB_LT	Burtch(2017)	Time_200Yard	Time	Swimming	Y
SPB_LT	Stavrou(2015)	Time_50m	Time	Swimming	Y
SPB_LT	Stavrou(2015)	Time_400m_Fins	Time	Swimming	Y

Note: BH: breath-holding; VH: voluntary hyperventilation; SPB: slow-paced breathing; ST: short-term; LT: longer-term

Selecting only sport performance competitive outcomes would leave us with k = 19 effect sizes in comparison to the k = 69 (28%) currently included in the five meta-analyses (breath-holding short-term: k = 3 instead of k = 10; breath-holding longer-term: k = 5 instead of k = 20; voluntary hyperventilation short-term: k = 4 instead of k = 21; slow-paced breathing short-term: k = 1 instead of k = 5; slow-paced breathing longer-term: k = 6 instead of k = 13).

Given it is recommended to have at least four studies to run a meta-analysis, we reran a meta-analysis for each of the following breathing techniques:

- breath-holding longer-term (k = 6)
- voluntary hyperventilation short-term (k = 4)
- slow-paced breathing longer-term (k = 6)

Meta-analyses including only sport performance competitive outcomes

- breath-holding longer-term (k = 5)

With k = 5 (competitive outcomes), for longer-term interventions, there was no significant difference (*p* = .430) in physical sport performance between breath-holding and control conditions, k = 5, g = 0.13 (95% CI: -.28 to 0.55). The heterogeneity was large (prediction interval [-.35 to 0.61]) but entirely due to sampling error (I^2 = 0%; and Tau^2 = 0). These findings with k = 5 would differ from those obtained with k = 21 currently reported in our paper, where a significant difference was noted between breath-holding short-term interventions and the control conditions.

The finding currently reported in the manuscript: "For longer-term interventions, there was a significant difference (*p* < .001) in physical sport performance between breath-holding and control conditions, k = 20, g = 0.44 (95% CI: 0.23 to 0.66) with moderate heterogeneity in the results (prediction interval [0.16 to 0.73]) entirely due to sampling error (I^2 = 0%; Tau^2 = 0; Figure 8)."

- voluntary hyperventilation short-term (k = 4)

With k = 4 (competitive outcomes), for short-term interventions, there was no significant difference (*p* = .131) in physical sport performance between voluntary hyperventilation and control conditions, k = 4, g = 0.04 (95% CI: -.03, 0.12). There was a low heterogeneity in the results (prediction interval [-.05 to 0.14]) entirely due to sampling error (I^2 = 0%; Tau^2 = 0). These findings with k = 5 would be similar to the ones obtained with k = 21 currently reported in our paper, where no significant difference was reported between voluntary hyperventilation short-term interventions and the control conditions.

Our current finding: "For short-term interventions, there was no significant difference (*p* = .140) in physical sport performance between voluntary hyperventilation and control conditions, k = 20, g = 0.06 (95% CI: -0.02 to 0.14). There was a small heterogeneity in the results (prediction interval [g = -0.05 to 0.16]) entirely due to sampling error (I^2 = 0%; Tau^2 = 0; Figure 10)."

- slow-paced breathing longer-term (k = 6)

With k = 6 (competitive outcomes), for longer-term interventions, there was a significant difference (*p* = .049) in physical sport performance between slow-paced breathing and control conditions, k = 6, g = 0.67 (95% CI: .01 to 1.34). There was a very large heterogeneity in the results (prediction interval [-0.81 to 2.15]), with a small part representing the variance of the true effect (I^2 = 23.5%; Tau^2 = 0.21) and the rest being due to sampling error. These findings with k = 6 would be similar to those obtained with k = 13 currently reported in our paper, where a significant difference was reported between slow-paced breathing longer-term interventions and the control conditions.

Our current finding: "For longer-term interventions, there was a large difference ($p < .010$) in physical sport performance between SPB and control conditions, k = 13, g = 0.64 (95% CI: 0.31 to 0.98), demonstrating that those in the SPB conditions performed better than those in control conditions. There was a large heterogeneity in the results (prediction interval [0 to 1.29]) but entirely due to sampling error (I^2 = 0%; Tau^2 = 0; Figure 4)."

Overall, when including only sport performance competitive outcomes, three out of five meta-analyses could still be conducted, with a minimum of four studies. Out of these three meta-analyses, two would provide similar results to those currently reported (voluntary hyperventilation short-term and slow-paced breathing longer-term), while one would provide different results (breath-holding longer term, no significant difference in the revised version with k = 5, while a significant difference was found in the original version with k = 21).

In summary, when taking into account a stricter view of sport performance and constraining it to outcomes strictly linked to objective sport performance outcomes as measured during sport competitions, it would narrow down the number of total effect sizes included from k = 70 to k = 19. While we understand that this would provide a more seamless match to the outcomes observed during sport competitions, a large amount of insight is unfortunately lost. Therefore, retaining these studies is essential to maintaining the quality of the systematic review, and is also the approach used in previous research published by IRSEP (Harris et al., 2021; Murdoch et al., 2021; Noetel et al., 2017; Rupprecht et al., 2021). We have now added these references to specify our selection approach.

> *"Studies were included if they measured outcomes capturing objective measures of physical sport performance. These include time, speed, strength, or specific sport performance indexes such as stroke rate in swimming or soccer agility (based on Harris et al., 2021; Murdoch et al., 2021; Noetel et al., 2017; Rupprecht et al., 2021; Toth, McNeill, Hayes, Moran, & Campbell, 2020). These outcomes could be combined, such that a decrease in performance time, and in increase in strength or speed, represent better sport performance. Given that the scientific investigation of physical sport performance often requires breaking down its components to tease out mechanisms and specify effects, our classification of physical sport performance includes not only objective performance markers similar to those obtained as outcomes of sport competitions but also any physical outcome linked to sport performance, such as power measured during a cycling ergometer test, or bench/leg press performance (similar to Harris et al., 2021; Murdoch et al., 2021; Noetel et al., 2017; Rupprecht et al., 2021; Toth et al., 2020)." (p.14, l.342-354)*

We agree with the Reviewer that once more research becomes available, future research syntheses might consider a narrower focus on objective performance markers as observed during sport competitions. We have now added this as a limitation to our study:

> *"Seventh, this study included physical sport performance outcomes beyond those which can be considered as direct outcomes of sport competitions. While this approach allowed for a more global understanding of the influence of breathing techniques on general physical sport performance, future research is warranted to focus specifically on the outcomes of sport competitions."*

In addition, given we adopt a transparent research process we published all of the data files and R script on the Open Science Framework (10.17605/OSF.IO/XK59D), therefore offering the possibility to the interested reader to rerun the analysis without specific outcomes if they wish.

4. Care might be taken in the interpretation of the prediction interval to clarify for the reader. The prediction interval is the interval within which the effect size of a new study would fall if this study were selected at random from the same population of the studies already included in your analysis. It considers the degree of dispersion (standard deviation) within the context of the mean that is not influenced by the sample size.

Author response: Thank you for pointing this out. We have now clarified the interpretation of the prediction interval (see sentence below).

> *"The prediction interval can be defined as the interval within which the effect size of a new study would fall if this study was selected randomly from the same population of the studies already included in the meta-analysis (Ades, Lu, & Higgins, 2005; Spineli & Pandis, 2020). In other words, it tells us how the true effect varies across populations, and it does it on the same scale as the computed effect sizes, allowing us to directly evaluate the utility of an intervention. The Hartung and Knapp method was used to adjust confidence intervals and test statistics (Hartung & Knapp, 2001a, 2001b; IntHout, Ioannidis, & Borm, 2014)." (p.19, l.472-478)*

We were, however, a little unclear on your last sentence ("It considers the degree of dispersion (standard deviation) within the context of the mean that is not influenced by the sample size.") and thus, we did not include this statement. Indeed, while the sample size per study does not directly influence the prediction interval (it is not in the formula), it does indirectly (see formulae and explanations below). If it is not what you meant, would you mind to clarify to help us to understand?

All of the formulae cited below can be found, for example, in the book of Borenstein et al. (2009) ("Introduction to meta-analysis", chapter 14 and chapter 18) or in the Cochrane Handbook (Higgins et al., 2022).

The formula for the prediction interval is:

$$M \pm t^{\alpha}_{k-2}\sqrt{\tau^2 + SE(M)^2}$$

where M is the summary mean (pooled estimate) from the random effects meta-analysis, t^{α}_{k-2} is the $100(1-\frac{\alpha}{2})$% percentile of a t-distribution with k-2 degrees of freedom, k is the number of studies, $\widehat{\tau^2}$ is the between-study heterogeneity, and SE(M), the standard error of the summary mean.

In this formula, M, $\widehat{\tau^2}$, and SE(M) are indirectly influenced by the sample size per study.

- In the current manuscript, the pooled estimate we used is the Hedges' g that has a correction factor (J=1-(3/4*(ntot – 2) – 1) based on the sample size per study.

- The formula for tau² (for the DerSimonian Laird estimate) is:

$\hat{\tau^2}$ = (Q – df)/ C

In this formula, the numerator is the sum of squares that reflect variation in true effects but on a standardised scale.

The formula for Q is: Q=$\sum_{i=1}^{k} w$iyi – ($\sum_{i=1}^{k} w$iyi)²/ $\sum_{i=1}^{k} w$i

And the denominator, C, is a factor based on the study weights (applied to standardise the deviations).

C= $\sum_{i=1}^{k} w$i – ($\sum_{i=1}^{k} w$i² / $\sum_{i=1}^{k} w$i)

Where wi is the weight for study I, which is 1/vi (the within-study error variance for that study) and thus directly influence by the sample size per study.

- SE(M) is computed via the following formula: 1/$\sum_{i=1}^{k} w$ *i)

Where w*i is the weight for study i (the random effect), which is 1/(vi+tau²), and thus is also influenced by the sample size per study.

We have created an example computation table, available via the following link (10.17605/OSF.IO/XK59D), which illustrates that when changing the sample size per study, it does also change the prediction interval.

5. I appreciate the recommendations for research advanced. The authors may also want to address the comparators used (i.e., tasks performed by the control group) in their findings/implications. Effects linked to breathing techniques are relative to those by the controls. What were those in the controls asked to do? How might this have influenced

findings? If it is believed that there is minimal consistency with respect to the tasks performed by controls, this could be identified as a limitation.

Author response: Thanks for prompting this reflection about the nature of the task for the control group / condition. The diversity of these tasks can be seen in Table 2 for all breathing techniques, and include, for example, watching videos or reading, or sometimes not receiving any control task at all. As mentioned by the Reviewer, the variation in these control tasks might have also potentially influence the interpretation of findings, and we now consider this in more detail in the Limitations section:

> *"Sixth, as illustrated in Table 2, there was a large diversity of the control tasks used as comparators for the breathing interventions, ranging from watching videos to reading and in some cases no control task was provided. This diversity of control tasks may have influenced the interpretation of the findings, and future research should pay close attention to the control task chosen. The control task should be as similar as possible to the breathing technique investigated, and only differing on key breathing parameters being the focus of the investigation." (p.39, l.955-961)*

6. Please watch the redundancy between the Results and Discussion. In a number of instances, the 'numbers' and their interpretation are reported in both places.

Author response: Thank you for the suggestion. We have now decreased overlap between the Results and Discussion sections, keeping the numbers for the Results section and their interpretation for the Discussion section.

Specific Comments:

Page 2; line 49: Please change "was" to "is"

Author response: This has now been changed.

Reviewer 2

Thank you for the thorough revision of this manuscript. I have no further recommendations for this work, other than possibly considering a short note on why so many papers have been published in the last year compared to the original search and inclusion of papers.

Author response: We would like to thank the Reviewer for the positive evaluation of our manuscript. This is indeed remarkable to observe the recent increase in studies investigating the influence of breathing techniques in athletes. We do not have a clear explanation for why this is the case. We can speculate that the interest raised in the past few years about the positive outcomes associated with breathing techniques has encouraged researchers to better understand their effects. We hope that the current review will contribute to this trend, not only in terms of the quantity of studies produced, but also in relation to the quality of the methodology used following the recommendations made.

Reviewer 3

Thanks for the time taken to address my queries - your amendments are comprehensive and well thought-through, and I look forward to hopefully seeing the paper published.

Author response: We would like to thank the Reviewer for the positive evaluation of our manuscript.

Associate Editor

Thank you for your resubmission. It is clear that a lot of work went into the resubmission, and the authors are thanked and congratulated for their efforts. In his decision letter to you for the original submission, the Editor wrote, "Only upon submission of a revised manuscript can a clearer decision (reject or revision/accept) be made about the suitability of the manuscript for publication in International Review of Sport and Exercise Psychology." Reviewers' recommendations to the revised manuscript were mixed, with one recommending Reject and two recommending Accept. A key stumbling block for Reviewer 1 is decisions related to inclusion/exclusion criteria. This needs to be addressed to result in changes to criteria (and, therefore, results) or greater evidence to support and underpin the selected approach. I think it would be appropriate to give the authors a further opportunity to address the feedback given by Reviewer 1 to this revised manuscript. I urge the authors to be thorough in their responses to all comments from Reviewer 1 and to see this revision as an opportunity to remove ambiguity from their manuscript either through making changes in line with Review 1's comments or through providing greater support for decisions that the authors have taken.

Author response: Once again, we would like to thank the Editor and the three expert reviewers for their time in reviewing our manuscript, as well as the excellent input that has helped us to improve it. In this new revision, we have endeavoured to incorporate all the suggestions of Reviewer 1. We understand that the choice of sport performance indicators might have triggered some concerns, and we have now done our best to clarify our selection criteria. We have also rerun three meta-analyses without those indicators and present the results in this response letter. We look forward to the Editor and the reviewer feedback.

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