The effectiveness of inspiratory muscle training in intermittent sports: a systematic review

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Contents

Abbreviations

IMT: inspiratory muscle training
IRL: inspiratory resistive loading
MEP: maximal expiratory pressure
MIP: maximal inspiratory pressure
RCT: randomized clinical trial
RPB: rate of perceived breathlessness
RPE: rate of perceived exertion
RSAbest: repeated sprint ability test best performance time
RSAdec: repeated sprint ability test performance decrement
RSAmean: repeated sprint ability test mean performance time
VIH: voluntary isocapnic hyperpnea

Abstract

Introduction

Inspiratory muscle training (IMT) is considered an effective ergogenic aid for sports performance. IMT has been shown to improve performance in a wide range of sport modalities such as cycling, running, rowing and swimming. IMT might also be beneficial for severely deconditioned patients after critical illness. Yet, studies on this specific topic are lacking. A first step is to get insight in the potential benefits and effects of IMT in healthy people. The aim of this systematic review is to identify the current evidence with regard to the effectiveness of IMT on performance in intermittent sports. The second purpose of this bachelor thesis is to translate these findings into recommendations regarding the use of IMT in severely deconditioned patients after critical illness.

Methods

A search was conducted through PubMed in September 2022. The search included terms for sports, athletes, inspiratory muscle training, athletic performance and exercise tolerance. Studies were included if: (a) the study design was a randomized clinical trial (RCT); (b) participants practiced intermittent sport; (c) IMT was compared with a placebo or control group and (d) outcomes included sport performance. Studies were excluded if: (a) the study design was not a RCT; (b) included participants with pulmonary disease, mental – or physical disabilities; (c) IMT consisted of inspiratory muscle warm-up only. The PEDro (Physiotherapy Evidence Database) scale was used to assess the methodological quality of the included studies.

Results

The search yielded 1010 studies. 745 were excluded based on study design. After screening 265 titles and abstracts, 35 studies were selected for full-text evaluation, and finally 12 were included. The studies scored an average of 6.7 points on the PEDRO scale. Ten of the 12 studies reported an significant improvement in performance. A broad range of definitions was used to describe performance including recovery time, total distance covered, time to exhaustion and (running) speed. In addition, all studies showed a significant increase (ranging from 14% to 79%) in maximal inspiratory pressure (MIP).

Conclusion

A majority of included studies described a significant improvement in performance after IMT. This review shows that IMT seems to be an effective resource to improve performance in athletes. With regard to the working mechanism of IMT, this intervention could also be a promising intervention to improve recovery in severely deconditioned patients.

Samenvatting

Introductie

Inspiratoire spiertraining (IMT) wordt beschouwd als een effectief ergogeen hulpmiddel voor sportprestaties. Het is aangetoond dat IMT de prestaties verbetert in een breed scala aan sportmodaliteiten zoals fietsen, hardlopen, roeien en zwemmen. IMT kan ook gunstig zijn voor ernstig gedeconditioneerde patiënten na kritieke ziekte. Echter, er ontbreken studies over dit specifieke onderwerp. Een eerste stap is om inzicht te krijgen in de mogelijke voordelen en effecten van IMT bij gezonde mensen. Het doel van deze systematische review is om het huidige bewijs te identificeren met betrekking tot de effectiviteit van IMT op prestatie bij intermitterende sporten. Het tweede doel van deze systematische review is om deze bevindingen te vertalen in aanbevelingen met betrekking tot het gebruik van IMT bij ernstig gedeconditioneerde patiënten na kritieke ziekte.

Methode

In september 2022 is een zoekopdracht uitgevoerd via PubMed. De zoekopdracht omvatte termen voor sport, atleten, inspiratoire spiertraining, atletische prestatie en inspanningstolerantie. Studies werden opgenomen als: (a) de onderzoeksopzet een gerandomiseerde klinische studie was (RCT); (b) deelnemers intermitterende sport beoefenden; (c) IMT werd vergeleken met een placebo- of controlegroep en (d) resultaten sportprestaties omvatten. Studies werden uitgesloten als: (a) de onderzoeksopzet geen RCT was; (b) deelnemers met een longziekte, mentale – of fysieke handicaps waren geïncludeerd; (c) IMT alleen bestond uit een warming-up van de inspiratoire spieren. De PEDro-schaal (Physiotherapy Evidence Database) werd gebruikt om de methodologische kwaliteit van de geïncludeerde onderzoeken te beoordelen.

Resultaten

De zoekstrategie leverde 1010 onderzoeken op. 745 werden uitgesloten op basis van hun onderzoeksopzet. Na beoordeling van 265 titels en samenvattingen werden 35 studies geselecteerd voor evaluatie van de volledige tekst, en uiteindelijk werden er 12 geïncludeerd. De onderzoeken scoorden gemiddeld 6,7 punten op de PEDro-schaal. Tien van de 12 onderzoeken rapporteerden een significante prestatieverbetering. Er werd een breed scala aan definities gebruikt om prestaties te beschrijven, waaronder hersteltijd, totale afgelegde afstand, tijd tot uitputting en snelheid. Bovendien lieten alle onderzoeken een significante toename (variërend van 14% tot 79%) van de maximale inspiratiedruk (MIP) zien.

Conclusie

Een meerderheid van de geïncludeerde onderzoeken beschreef een significante verbetering van de prestaties na IMT. Deze beoordeling suggereert dat IMT een effectieve hulpbron kan zijn om de prestaties van atleten te verbeteren. Met betrekking tot het werkingsmechanisme van IMT, zou deze interventie ook een veelbelovende interventie kunnen zijn om het herstel van ernstig gedeconditioneerde patiënten te verbeteren.

Introduction

Competition drives athletes to seek new ways to improve their performance. Historically, training for high performance of athletes has focused on rigorous peripheral muscle and cardiovascular training using partial or full-body exercises. In the search for alternative techniques to surpass the plateau achieved by this classic training, inspiratory muscle training (IMT) garnered much attention (1, 2). IMT has been shown to be useful in short- and long-term continuous sports to improve the performance, such as in cycling (3, 4), rowing (5), running (4)and swimming (6). Furthermore, IMT has resulted in a better quality of life in studies including patients with heart failure or respiratory disease, such as asthma and chronic obstructive pulmonary disease (7-9).

The most used IMT technique is the inspiratory resistive loading (IRL) to improve respiratory muscle strength (10). In IRL training a subject inspires against a resistive load, which is created using a threshold- or flow resistive device. Another IMT technique applied in sports is voluntary isocapnic hyperpnea (VIH), to improve endurance. VIH is performed by breathing in a rebreathing bag at approximately 30 breaths per min for around 30 minutes (11).

During intensive exercise the respiratory muscles fatigue. To maintain the ventilatory requirements of exercise, the body responds with the metabolic reflex. Accumulation of metabolic side products in the respiratory muscles causes vasoconstriction in the limbs, thereby reducing locomotive muscle blood flow and accelerating the rate of peripheral fatigue of these muscles (12-15).
Mechanisms to explain the improved performance by IMT are (a) delay in respiratory muscle fatigue (16-18), (b) hypertrophy of the diaphragm and accessory respiratory muscles (18-20), (c) attenuation of the metabolic reflex (21-23) , (d) decrease in rate of perceived exertion and rate of perceived breathlessness (10, 22, 23) and (e) lower blood lactate levels as a result of increased breathing efficiency (24-26).

These mechanisms of IMT might also be beneficial for severely deconditioned patients after critical illness. IMT has been shown to improve inspiratory and expiratory muscle strength in critically ill patients, and was well tolerated (27). Additionally, IMT improves weaning outcomes in mechanically ventilated patients (28). However, studies on the effect on performance in deconditioned patients are scarce. Therefore, a first step is to get insight in the potential benefits and effects of IMT in healthy people. Performance for patients refers to what patients could actually do in their daily activities within their usual environment (29). Studies related to IMT and performance have focused primarily on continuous exercise. Performance in sports related studies, refers to descriptions, such as total distance covered, recovery time, duration of effort and speed. In this systematic review we focused on intermittent sports modalities, because the training structure of this type of sport – high intensity efforts of short duration followed by periods of recovery – is comparable to recommended recovery training of patients after critical illness (30).

However, the effectiveness of IMT remains debated (31, 32). Some studies reported improvements in exercise capacity (33-35) and others reported no significant effect (36-39). About two thirds have documented significant improvements (40). Besides that, IMT has been criticised as it fails to reflect dynamic inspiratory muscle function during exercise (41). Also, there is no consensus on the theory that respiratory muscle fatigue causes decrease in performance (42). Moreover, many studies on this topic are conducted with a small research population, making them underpowered to detect small effect size of performance.

The primary aim of systematic review is to identify the current evidence with regard to the effectiveness of IMT on performance in intermittent sports. The second purpose is to translate the findings into recommendations regarding the use of IMT in practice for severely deconditioned patients after critical illness.

Methods

Literature search

A literature search was performed in PubMed on September 7th 2022 to identify all clinical trials that studied IMT in intermittent sports athletes. The search included the words sports, athletes, inspiratory muscle training, athletic performance and exercise tolerance. The detailed search strategy is shown in appendix 1. No restrictions were done for publication date or language.

Screening and selection of studies

Only randomized clinical trials (RCT) were included for screening. The first author assessed the title and abstract of the retrieved articles from the electronic search for inclusion. An article was considered potentially eligible if IMT was performed in participants who practiced intermittent sports. All potentially relevant papers were retrieved as full text and checked on inclusion and exclusion criteria (also performed by the first author).
Studies were included if: (a) the study design was a RCT; (b) participants were athletes who practiced intermittent sport, such as soccer, rugby, field hockey or tennis; (c) IMT was compared with a placebo or control group, and (d) outcomes included sport performance, defined as total distance covered, recovery time, duration of effort or speed.
Studies were excluded if: (a) it was an editorial, letter to the editor, commentary, abstract, lecture, or opinion piece; (b) included participants with pulmonary disease, mental – or physical disabilities, and (c) IMT consisted of inspiratory muscle warm-up only. Also studies were the full text was not available were excluded.

Critical appraisal

All included articles were critical appraised by the first author. The PEDro (Physiotherapy Evidence Database) scale was used to assess the methodological quality of the included studies. The scale consists of 11 items. Per item there are defined notes whether to award points. If a criterion is not satisfied, no point is awarded for that item. Criterion 1 relates to external validity and criteria 2-9 to internal validity. Criteria 10-11 is used to examine the statistical information and interpretability of the results. The maximum score is 10 points, because item 1 only affects the external validity.
The study’s quality was considered poor if the PEDro score was 3 or lower, fair if the score was 4 or 5, good if the score was 6-8 and excellent if the score was 9 or 10.

Data extraction

The essential data on patient characteristics, study methods and outcome measures of the included studies were extracted and recorded in three different tables, see tables 2-4.

The following *patient characteristics* were recorded: number of participants, gender, mean age, kind of sport and competition level.

Data collected on *study methods* included: starting training intensity, progression of training, number of training sessions, used IMT device, the protocol for placebo or control group.

The following *outcome measures* were extracted from the studies: the test used to measure performance, description of performance, and the training results (primary and secondary outcomes).

Results

Study selection

The search in PubMed yielded a total of 1010 articles. Of these articles, 745 were excluded based on study design (non RCTs), using the automation tool on Rayyan. The remaining 265 studies were screened on title and abstract for eligibility, of which 230 were excluded based on population. These studies included non-athletes or subjects with disease. A full-text evaluation was done for 35 studies. 23 studies were excluded due to the following: 18 studies described continuous sports modalities, 2 studies performed inspiratory muscle warm up only, 2 studies did not report performance as an outcome and of 1 study no full-text was available. The study of Chang et al. (43) was included, because the training method for 800 meter track runners is similar to intermittent sports (44). Gething et al. (45) did not specify the included sport. However, based on the description and aim of the study, it was considered eligible. Finally, 12 studies were included (43, 45-55). Figure 1 shows the flow chart of the study selection.

Critical appraisal

One researcher (MH) assessed the quality of the studies, including the risk of bias, using the PEDro scale. All studies specified eligibility criteria, only healthy subjects were included. Besides, all studies provided point measures and measures of variability for at least one key outcome. The studies scored between 6 to 9 points, corresponding to a good to excellent quality. Five studies blinded all subjects (45-47, 50, 52). Only one study concealed allocation (46). No significant differences were found between groups at baseline regarding the most important prognostic indicators. For the critical appraisal see table 1 and appendix 2.

Baseline characteristics

The most important characteristics of the participants are presented in table 2. The publication date of the included studies ranged from July 2002 till May 2021. The total number of participants was 270, of which 234 were male and 36 were female. Eight studies only included men and 1 study only included women (52). The mean age of all participants was 22.3 years. The group sizes of participants ranged from 15 to 31. Ten studies included recreational athletes and two studies included professional athletes. Soccer was the most common sport, that was studied in nine out of 12 studies. Five studies included solely non-smokers. Most studies specified there subjects as being asymptomatic for respiratory dysfunction.

Study methods

In all studies IMT was an additional training to the regular physical training, such as soccer practice. The inspiratory muscle training group was compared to a control group in 6 studies, a placebo group

in 2 studies, a placebo and a control group in 3 studies, and one study had a control group and an alternative intervention (54).
De Sousa et al. (55) included two different inspiratory muscle training groups, one light and one heavy group with effort intensity set at 50% and 80% of the maximal inspiratory pressure (MIP) respectively. In the other studies the initial effort intensity was very similar, between 40-55% of the MIP measured at the beginning. One study of Gething et al. (45) used an intensity of 80% of the baseline MIP.
In nine studies participants performed 30 repetitions per session twice a day. The number of days with IMT per week varied from five to seven, with the number of weeks ranging from four to six. Mackala et al. (53) increased the number of repetitions from five in week one to 15 in week eight. Gething et al. (45) used the test of incremental respiratory endurance (TIRE) protocol, in which the subject performed six inspirations, rested for one minute and continued with six inspirations, with resting time being shortened after every set. Participants in the study of Ozmen et al. (51) trained for 15 minutes following a VIH training method.
Tong et al. (49) also included an inspiratory muscle warm up in their protocol. Participants performed two sets of 30 inspirations at 40% of their MIP before each workout.
The number of IMT sessions per week was heterogeneous, ranging from two sessions to fourteen per week. Additionally, the adherence in most studies was between 82% and 100%, with the exception of de Sousa (60%-65%). Three studies did not report data on adherence (43, 50, 53).
A detailed summary of the study methods is presented in table 3.

Outcomes

The tests used to compare pre- and post IMT effects varied across the studies. Four studies used the shuttle run test (SRT), three studies the level 1 Yo-Yo Intermittent Recovery test and two studies the repeated sprint ability test (RSAT). Spread over the other studies, another eight different test were used (table 3). A broad range of definitions was used to describe performance including maximum number of repetitions, total distance covered, recovery time, duration of effort and speed.
Ten of the 12 studies reported a significant improvement in performance, with effects ranging from 4% to 55%.
Archiza et. al (52) found a decrease of 4% in RSAbest, 6% in RSAmean and 30% in RSAdec. However, no significant difference was found compared to the placebo group. Also, Ozmen et al. (51) concluded performance did not significantly improve after IMT.
In addition, Guy et al. (50) found an significant improvement in the shuttle run test performance, but not in the soccer-specific fitness test.
One study reported a 27% increase in the number of repetitions with a running speed of ≥130% of the initial value during interval training (49).
In all studies a significant increase in MIP was reported. The improvement ranged from 14% to 79%. Additionally, two studies reported a significant improvement in other lung function parameters. Mackala et al. (53) found an increase in forced vital capacity (FVC) (7%), forced expiratory volume in one second (FEV1) (11%) and maximal expiratory pressure (MEP) (100%). In the study of de Sousa et al. (55) MEP increased with 38% in the high resistance group and 63% in the light resistance group.
Four studies revealed a significant decrease in the rate of perceived exertion (RPE) and the rate of perceived breathlessness (RPB), between 7% to 16% (45, 47, 49, 56). Furthermore, a decrease of 16% and 20% in blood lactate was shown in two studies (46, 50)

One study showed an 52% decrease in limb blood flow change rate (43). Additionally, Archiza et al. (52) reported a decrease of deoxyhemoglobin [HHb] and total hemoglobin [tHb] on the intercostal muscles during high intensity exercise to exhaustion, in combination with an increase of oxyhemoglobin [O2Hb] and [tHb] on the vastus lateralis muscle. Also, one study measured an increase in diaphragm thickness after IMT (10%) (54). For a detailed oversight of the results, see table 4.

Discussion

The aim of this bachelor thesis was to identify the current evidence with regard to the effectiveness of IMT on performance in intermittent sports and to translate these findings into recommendations for severely deconditioned patients after critical illness. The results indicate that IMT improves performance (described as maximum number of repetitions, total distance covered, recovery time, duration of effort and speed) in intermittent sports. A majority of the studies showed a significant improvement in performance after IMT. Additionally, MIP increased in all 12 studies. Some studies also reported increased FEV, FVC1 and MEP. Furthermore, a decrease in RPE, RPB and blood lactate was shown.

It was difficult to define performance in advance, because many studies used different tests, resulting in multiple descriptions of performance. The most common test was the shuttle run test, used in four studies, with a broad range of results. Romer et al. (46) used the shuttle run test solely to measure physiological differences, which showed an decrease in RPE and blood lactate. Guy et al. (50) reported a 12% increase in the maximum number of repetitions. De Sousa et al. (55) showed an increase in total distance covered of 54% in the high resistance group and 55% in the light resistance group. Ozmen et al. (51) measured no significant improvement.

The absence of a significant effect in Ozmen et al. (51) could be explained by its VIH training protocol. VIH has been proven to be effective in improving running performance (57). However, the training intensity in the study of Katayama et al. (57) was almost three times higher (a total number of IMT training session of 28, versus 10). This suggests applying IMT twice a week for 5 weeks, might not be sufficient to induce improvement in performance.
In addition, Archiza et al. (52) showed no significant improvement in performance compared to the placebo group. RSAbest, RSAmean and RSAdec did improve in post-intervention compared to pre-intervention. The number of participants (n = 18) might have been too small to detect a significant effect. A small research group could have made the study underpowered and prone to a type 2 error (58). A significant improvement in performance compared to the placebo group might occur if the study was performed with a larger number of participants.

All studies reported an increase in MIP after IMT. These results build on the existing evidence of McConnell et al. (59), who reported that training of the inspiratory muscles strengthens the inspiratory muscles. One study measured an increase (10%) in diaphragm thickness (54). The diaphragm plays a major role in inspiration, together with the intercostal – and abdominal muscles (60). Previous research demonstrated IMT causes structural changes (18, 61) and neural adaptations (62). This may add to increased muscle strength, endurance and efficiency.

Additionally, two studies found an increase in MEP (53, 55). This is a surprising finding, which is supported by the absence of MEP increase in the other included studies. In respiratory muscle training (RMT) both in- and expiratory muscles are trained. In IMT however, training focusses on inspiratory muscles. Therefore, one would not expect an increase in MEP. Mackala et al. (53) attribute their 100% increase in MEP to weakness in the respiratory muscles prior to the IMT. Expiratory muscles are also active in inspiration during forced ventilation (63), hence an increase in MEP after IMT can occur.

The underlying mechanisms by which IMT improves performance, are still not fully understood. Some presumptions have been made, such as a reduction in respiratory muscle fatigue and attenuation of the metabolic reflex (64). Measurements on blood flow were performed, in order to get more insight in the physiological processes induced by IMT. One study asked participants to breathe in and maintain 60% of inspiration pressure with a POWERbreathe device (43). A 52% decrease in limb blood flow change rate was reported. A lower limb blood flow change rate suggests that the distribution of blood to limb locomotor muscles remains higher during exercise. In addition, Archiza et al. (52) reported a decrease of deoxyhemoglobin [HHb] and total hemoglobin [tHb] on the intercostal muscles during high intensity exercise. Concomitantly, an increase of oxyhemoglobin [O2Hb] and [tHb] on the vastus lateralis muscle was found. This indicates that IMT was associated with a decrease of blood volume in the respiratory muscles and higher oxygenation of locomotor muscles. These results suggests IMT potentially attenuates the metabolic reflex during exercise, thereby maintaining the blood flow of the extremities. An increased blood flow may prevent accumulation of metabolic substances (65).
Affirmatory, a decrease in blood lactate of approximately 17% was found in two studies (46, 50). This data is in line with Brown et al. (66), who stated that IMT speeds lactate recovery kinetics. It is generally accepted that a surplus of blood lactate impairs exercise performance. Therefore, it might be reasonable to assume that a lower concentration of blood lactate during exercise can improve performance.

Another possible contributor to the improved performance after IMT, is the reduced RPE and RPB. Four studies showed an significant decrease (8%-16%) in RPE and RPB during exercise (45, 47, 49, 56). The structural adaptations, as mentioned above, might reduce respiratory discomfort and enhance positive sensations of respiratory efficiency during intensive exercise. Edwards et al. (67) has postulated that improvements in performance are most likely the result of a voluntary willingness to extend duration. This has implications for the tests used to examine the effect of IMT. The two studies (51, 52) without a significant effect used an incremental test, while all studies with time trial test did show significant improvement (43, 53, 54). An incremental test, such as the shuttle run test, can only be influenced by prolonging the exercise to a point of failure. Tests that allow the participant to self-impose the exercise intensity, might be more sensitive to measure an improvement in performance (59).

One study revealed a 27% increase in the number of repetitions with a running speed of ≥130% of the initial value during interval training (49). The athletes in this study were able to perform their normal physical training at a higher intensity after IMT. Therefore, an indirect benefit of IMT might be that it allows athletes to execute their regular training at a higher level and consequently improve performance even more.

It should be noted that this study used inspiratory muscle warm-up (IMW) in addition to IMT. IMW can be used without IMT. An example of IMW is 2 sets of 30 inspirations at 40% of MIP before a training or test. Studies have shown that this acute training approach improves performance too (68, 69).

This systematic review has several limitations. Firstly, for this systematic review only one database was searched (PubMed). Efforts to search CINAHL were made, but no free access was available. It is possible, that as a result, some relevant studies are not included. The number of articles included in this systematic review (n = 12) is limited. Second, the study selection was performed by one author, increasing the risk of selection bias. Third, the heterogeneity in methods, training protocols and performance outcomes, makes it difficult to make an unambiguous interpretation of the effectiveness of IMT. In total, 11 different tests and 9 descriptions of performance were used. Fourth, the external validity might be limited. The physical demands on the body in various sports modalities are different. The results might not be generalizable to other sports modalities, such as continuous sports. Although, evidence of effectiveness of IMT in continuous sports has been shown (3-6).

This systematic review included high quality studies. No restrictions were made for publication date or language, to limit selection bias. The studies had a high quality of evidence, all were RCTs. The average score on the PEDro scale was 6.7 points, meaning that the methodological quality of these studies was ‘good’. Furthermore, the search was executed systematically. This systematic review looked specifically at intermittent sports, resulting in an increased homogeneity of the results, and a possibility to translate these findings for severely deconditioned patients. While previous research has focused on IMT in continuous sports, these results demonstrate that IMT is effective in intermittent sports too. This systematic review provides a useful overview of the literature in regard to performance after IMT in intermittent sports. Lastly, by translating the findings of this review, recommendations for severely deconditioned patients have been made (see below).

IMT has been shown to improve weaning outcomes in mechanically ventilated patients (28). Additionally, IMT improves inspiratory and expiratory muscle strength in critically ill patients (27). Vorona et al. (27) also reported that IMT was a well tolerated and feasible training method. However, little is known about the effect of IMT on performance in severely deconditioned patients. Performance for patients refers to what patients could actually do in their daily activities within their usual environment (29). A study of Eggmann et al. (70) on rehabilitation of deconditioned patients, advised active participation, shorter session durations and mobilization. Additionally, Wernhart et al. (30) suggests rehabilitation training should consist of short high intensity intervals (less than one minute at 80%-85% of maximal heart rate) (30). The recommended recovery training of patients after critical illness is comparable to the training structure of intermittent sports: high intensity efforts of short duration followed by periods of rest. Therefore, it is imaginable that the improvement in performance in intermittent sports athletes after IMT, might also occur in severely deconditioned patients.

Furthermore, trained athletes experience less respiratory muscle fatigue during exercise compared with sedentary subjects (71, 72). This suggests that less fit subjects, such as severely deconditioned patients, would possibly benefit more from IMT than athletes.

Moreover, the potential physiological mechanism (as described above), by which IMT improves performance in athletes, could be applicable to deconditioned patients too. IMT influences certain processes in the body, such as the metabolic reflex, that are present in both athletes and severely deconditioned patients (73). This contributes to the likeliness of IMT being effective in deconditioned patients too. Lastly, IMT might ensure that patients experience a higher sense of autonomy, because IMT allows them to work on their recovery (even if cardiovascular training is not possible).

In spite of these similarities, there are differences between the groups. The athletes were a lot younger (mean age 22.3 years), than the average patient on the intensive care (in most cases older than 60 years) (74). The majority of athletes, in the included studies, trained (IMT) twice daily for multiple weeks, something that might not be achievable in severely deconditioned patients. Additionally, progressive dysfunction of the main respiratory muscle can be observed in these patients (75), making it difficult to predicted the effect IMT will have in these patients.

Further research is needed to show the effectiveness of IMT in severely deconditioned patients after critical illness. The six-minute walk test could be used as an outcome measure for performance. The six-minute walk test is simple test, that can be performed by a patient not tolerating maximal exercise test, and provides information regarding functional capacity (76).
Further studies are required to establish the most effective training protocol. Shei et al. (77) suggests better results can be obtained by a more specific training protocol, which is based on optimization, periodization and personalization. Therefore, different protocols for individual athletes and patients might be required to maximize the effect on performance.
Moreover, further research is needed to clarify the mechanisms by which IMT improves performance.

Conclusion

This systematic review showed that IMT improves the performance of athletes who practise intermittent sports. With regard to the physiological mechanisms and effects of IMT in relation to performance, IMT could be a promising intervention to improve physical recovery in severely deconditioned patients after critical illness. Future research is needed to investigate whether IMT contributes to the recovery of these patients.

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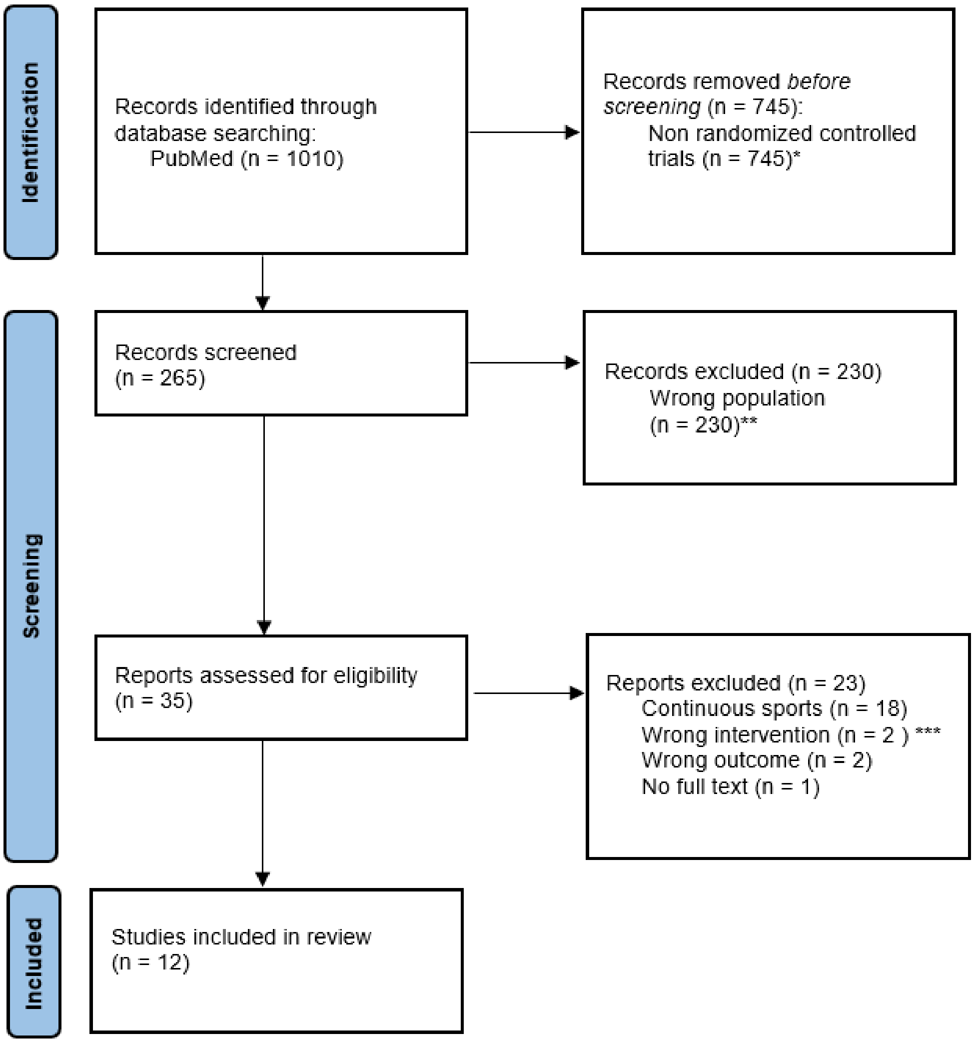
Figures and Tables

Figure 1: Flowchart of study selection

(according to the Preferred Reporting Elements for Systematic Reviews and Meta-Analyses (PRISMA))



* Excluded by automation tool, Rayyan.
** Non athletes or subjects with disease
*** Inspiratory muscle warm up only

Table 1: PEDro (Physiotherapy Evidence Database) scale quality assessment*

First author, year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Total**	**Quality**
Romer, 2002	Yes	1	1	1	1	1	0	1	1	1	1	9	Excellent
Gething, 2004	Yes	1	0	1	1	0	0	1	1	1	1	7	Good
Tong, 2008	Yes	1	0	1	1	0	0	1	1	1	1	7	Good
Nicks, 2009	Yes	1	0	1	0	0	0	1	1	1	1	6	Good
Tong, 2010	Yes	1	0	1	0	0	0	1	1	1	1	6	Good
Guy, 2014	Yes	1	0	1	1	0	0	1	1	1	1	7	Good
Ozmen, 2017	Yes	1	0	1	0	0	0	1	1	1	1	6	Good
Archiza, 2018	Yes	1	0	1	1	1	0	1	1	1	1	8	Good
Mackala, 2019	Yes	1	0	1	0	0	0	1	1	1	1	6	Good
Faghy, 2021	Yes	1	0	1	0	0	0	1	1	1	1	6	Good
Chang, 2021	Yes	1	0	1	0	0	0	1	1	1	1	6	Good
De Sousa, 2021	Yes	1	0	1	0	0	0	1	1	1	1	6	Good

*Description of PEDro categories: 1 = eligibility criteria were specified, 2 = subjects were randomly allocated to groups, 3 = allocation was concealed, 4 = the groups were similar at baseline regarding the most important prognostic indicators, 5 = there was blinding of all subjects, 6 = there was blinding of all therapists who administered the therapy, 7 = there was blinding of all assessors who measured at least one key outcome, 8 = measures of at least one key outcome were obtained from more than 85% of the subjects initially allocated to groups, 9 = all subjects for whom outcome measures were available received the treatment or control condition as allocated or, where this was not the case, data for at least one key outcome was analysed by "intention to treat", 10 = the results of between-group statistical comparisons are reported for at least one key outcome, 11 = the study provides both point measures and measures of variability for at least one key outcome.
Total score was sum of categories 2-11..

Table 2: Characteristics of study participants

First author, year	# Participants	M/F	Age mean (SD)	Sport	Competitive level
Romer, 2002	24	24/0	IMT 21.3 (1.1) PLA 20.2 (0.7)	Soccer, rugby, field hockey and basketball	Recreational and semi-professional
Gething, 2004	15	10/5	TOT 22.7 (2.3)	Whole body training	Recreational
Tong, 2008	30	30/0	IMT 21.3 (0.9) PLA 21.5 (2.1) CON 22.0 (1.9)	Soccer and rugby	Recreational
Nicks, 2009	27	20/7	IMT 19.8 (0.9) CON 19.9 (1.3)	Soccer	Professional
Tong, 2010	18	18/0	IMT 21.1 (1.1) CON 22.3 (1.0)	Soccer and rugby	Recreational
Guy, 2014	31	31/0	IMT 26.6 (8.2) PLA 23.9 (6.7) CON 21.3 (4.9)	Soccer	Recreational
Ozmen, 2017	18	18/0	TOT 22.2 (1.4)	Soccer	Recreational
Archiza, 2018	18	0/18	IMT 22.0 (3.9) PLA 20.1 (2.0)	Soccer	Professional
Mackala, 2019	16	16/0	IMT 17.6 (0.5) CON 17.7 (0.5)	Soccer	Recreational
Faghy, 2021	23	13/10	IMT 36.5 (9.4) MAS 37.7 (11.9) CON 35.2 (8.5)	High intensity interval training	Recreational
Chang, 2021	20	14/6	IMT 21.6 (2.1) CON 20.8 (1.5)	800 meter track runners	Recreational
De Sousa, 2021	30	30/0	IMTh 14.8 (1.0) IMTl 15.5 (1.4) CON 15.3 (1.4)	(Indoor) soccer	Recreational

M = male, F = female, IMT = inspiratory muscle training group, TOT = total group, PLA = placebo group, CON = control group, MAS = mask group, IMTh = inspiratory muscle training group with high resistance, IMTl = inspiratory muscle training group with light resistance, SD = standard deviation.

Table 3: Study interventions

First author, year	Study design	Starting intensity	Progression of training	# of breaths, sessions per day, - per week, # of weeks	Device	Placebo/control protocol
Romer, 2002	RCT	50% MIP	Progressive increase to maintain a 30 repetition training	30, 2, 7, 6	POWERbreathe	PLA 60 slow breaths once daily for 6 weeks with 15% MIP
Gething, 2004	RCT	80% MIP	Every training MIP reassessed	TIRE, 1,3,10	Flow resistive IRL device	PLA same training with 10 cm H2O/L/s CON no training
Tong, 2008	RCT	50% MIP	Increased by 10-15 cm H2O, to maintain a 30 repetition training	30, 2, 6, 6	POWERbreathe	PLA same training with 15% MIP CON no training
Nicks, 2009	RCT	50% MIP	Increased 1-2 times per week, to maintain a 30 repetition training	30, 2, 5, 5	Powerlung Inc., Sport Model	CON no training
Tong, 2010	RCT	50% MIP	Increased by 10-15 cm H2O , to maintain a 30 repetition training	30, 2, 6, 4 IMW 2x30 40% MIP	POWERbreathe	CON no training
Guy, 2014	RCT	55% MIP	None	30, 2, 7, 6	POWERbreathe	PLA same training with 15% MIP CON no training, also no whole body training
Ozmen, 2017	RCT	40-50% size rebreathing bag 60% MVV	None	15 min endurance, 1, 2, 5	Spirotiger	CON no training
Archiza, 2018	RCT	50% MIP	Every week MIP reassessed	30, 2, 5, 6	POWERbreathe	PLA same training with 15% MIP

Table 3. continuation

First author, year	Study design	Starting intensity	Progression of training	# Sessions	Device	Placebo/control protocol
Mackala, 2019	RCT	40% MIP	Progressive increase of 5% per week	5 reps in week 1 15 reps in week 8 2, 5, 8	Threshold IMT device (Philips)	CON no training
Faghy, 2021	RCT	50% MIP	Increased once every two weeks	30, 2, 7, 6	POWERbreathe	MAS phantom training mask worn during exercise CON no training
Chang, 2021	RCT	50% MIP	Progressive increase of 10% per week	30, 2, 5, 4	POWERbreathe	CON same training with 50% MIP
De Sousa, 2021	RCT	80% MIP IMTh 50% MIP IMTl	Increased once every two trainings	IMTh 3 sets 12 IMTl 2 sets 20 1, 3, 8	POWERbreathe	CON no training

RCT = randomized clinical trial, IMT = inspiratory muscle training group, TOT = total group, PLA = placebo group, CON = control group, MIP = maximal inspiratory pressure, IMW = inspiratory muscle warm up, IMTh = inspiratory muscle training group with high resistance, IMTl = inspiratory muscle training group with light resistance, TIRE = test of incremental respiratory endurance, MAS = mask group, MVV = maximal voluntary ventilation.

Table 4: Outcome measures

First author, year	Test used	Performance description	Primary outcome (performance)*	Secondary outcomes**
Romer, 2002	Repeated sprint ability test Shuttle run test	Total recovery time	7% ↑	MIP 31% ↑ PIF 20% ↑ RPE resp 8% ↓ RPE per 7% ↓ Blood lactate 16% ↓
Gething, 2004	Time-to-exhaustion cycling test	Duration of effort	36% ↑	MIP 34% ↑ RPE 14% ↓
Tong, 2008	Yo-Yo test (level 1)	Maximum number of repetitions	16% ↑	P0 32% ↑ Wlmax 40% ↑ Popt 38% ↑ MRPD 39% ↑ RPE/4i 11% ↓ RPB/4i 12% ↓
Nicks, 2009	Yo-Yo test (level 1)	Total distance covered	17% ↑	MIP 20% ↑
Tong, 2010	Yo-Yo test (level 1) Interval training	Maximum number of repetitions Number of repetitions in each distance with running speed ≥130% of the initial value	31% ↑ 27% ↑	P0 20% ↑ RPE 8% ↓ RPB 16% ↓
Guy, 2014	Soccer-specific fitness test Shuttle run test	Sprint times Total distance covered	- 12% ↑	MIP 15% ↑ Blood lactate 20% ↓
Ozmen, 2017	Shuttle run test	Maximum number of repetitions	-	MIP 14% ↑
Archiza, 2018	Repeated sprint ability test Time-to-exhaustion running test	RSAbest, RSAmean, RSAdec Duration of effort	- -	MIP 22% ↑
Mackala, 2019	Coopertest	Total distance covered	5% ↑	MIP 63% ↑ MEP 100% ↑ FVC 7% ↑ FEV1 11% ↑
Faghy, 2021	5 km running performance	Time to completion	6% ↑	MIP 32% ↑ Diaphragm thickness 10% ↑

Table 4. continuation

First author, year	Test used	Performance description	Primary outcome (performance)*	Secondary outcomes**
Chang, 2021	800 meter time trial test	Time to completion	4% ↑	MIP 16% ↑ Limb blood flow change rate 52% ↓
De Sousa, 2021	Shuttle run test (SRT) 3-min step test (3MST)	Total distance covered Frequency	h 54% ↑, l 55% ↑ h 20% ↑, l -	MIP h 79% ↑ MIP l 57% ↑ MEP h 38% ↑ MEP l 63% ↑

RSA = repeated sprint ability test, RSAdec = total recovery time during RSA, MIP = maximal inspiratory pressure, PIF = peak inspiratory flow, RPE resp = rate of perceived exertion respiratory muscles, RPE per = rate of perceived exertion peripheral muscles, P0 = maximal inspiratory pressure at zero flow, WImax = maximal inspiratory muscle power, Popt = optimal pressure, MRPD = maximum rate of pressure development, FVC = forced vital capacity, FEV1 = forced expiratory volume in 1 second, RSAbest = RSA best performance time, RSAmean = RSA mean performance time, RSAdec = performance decrement, * in this column all percentages represent a significant ($p < 0.05$) increase over control/placebo, ** in this column all percentages represent a significant ($p < 0.05$) increase/decrease compared to baseline, ↑ is significant increase, ↓ is a significant decrease.

Appendix 1: Search strategy

("Athletic Performance"[MeSH Terms] OR "Exercise Tolerance"[MeSH Terms] OR "Physical Endurance"[MeSH Terms] OR ("athletic performance*"[Title/Abstract] OR "sports performance*"[Title/Abstract] OR "exercise tolerance*"[Title/Abstract] OR "physical endurance*"[Title/Abstract] OR "physical stamina"[Title/Abstract])) AND ("Sports"[MeSH Terms] OR "Exercise"[MeSH Terms] OR "Athletes"[MeSH Terms] OR ("sport"[Title/Abstract] OR "Sports"[Title/Abstract] OR "Exercise"[Title/Abstract] OR "athlete"[Title/Abstract] OR "Athletes"[Title/Abstract] OR "Athletic"[Title/Abstract] OR "athletics"[Title/Abstract]) OR ("Racquet Sports"[MeSH Terms] OR "Soccer"[MeSH Terms] OR "Rugby"[MeSH Terms] OR "Basketball"[MeSH Terms] OR "Hockey"[MeSH Terms] OR "Volleyball"[MeSH Terms] OR "Football"[MeSH Terms] OR "Baseball"[MeSH Terms] OR "Cricket Sport"[MeSH Terms] OR "High-Intensity Interval Training"[MeSH Terms] OR ("intermittent sport*"[Title/Abstract] OR "intermittent train*"[Title/Abstract] OR (("intermittant"[All Fields] OR "intermittence"[All Fields] OR "intermittencies"[All Fields] OR "intermittency"[All Fields] OR "Intermittent"[All Fields] OR "intermittently"[All Fields]) OR "sports modalities"[Title/Abstract]) OR "racquet sport*"[Title/Abstract] OR "Tennis"[Title/Abstract] OR "Lacrosse"[Title/Abstract] OR "Badminton"[Title/Abstract] OR "Squash"[Title/Abstract] OR "Soccer"[Title/Abstract] OR "Rugby"[Title/Abstract] OR "Basketball"[Title/Abstract] OR "Hockey"[Title/Abstract] OR "Volleyball"[Title/Abstract] OR "american football"[Title/Abstract] OR "Football"[Title/Abstract] OR "Baseball"[Title/Abstract] OR "Cricket"[Title/Abstract] OR "High-Intensity Interval Training"[Title/Abstract]))) AND ("inspiratory training"[Title/Abstract] OR "respiratory training"[Title/Abstract] OR "respiratory muscle endurance"[Title/Abstract] OR "inspiratory muscle endurance"[Title/Abstract] OR "respiratory muscle strength"[Title/Abstract] OR "inspiratory muscle strength"[Title/Abstract] OR ("Breathing Exercises"[MeSH Terms] OR ("breathing exercise*"[Title/Abstract] OR "respiratory muscle training"[Title/Abstract] OR "inspiratory muscle training"[Title/Abstract] OR "inspiratory muscle*"[Title/Abstract] OR "expiratory muscle*"[Title/Abstract])))

Appendix 2: Critical appraisal

Article	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6	Criterion 7	Criterion 8	Criterion 9	Criterion 1	Criterion 11
Romer 20	Methods,	Methods,	Methods,	Table 1	Methods,	Methods,	?	Methods,	Methods,	Table 2	Methods, data analy
Gething 2	Methods,	Methods,	?	Table 1	Methods,	?	?	Results, ac	Results, ac	Table 3	E.g. table 3
Tong 2008	Methods,	Procedure	?	Table 1	Methods,	?	?	Method, II	Method, II	Table 3	Methods, statistical a
Nicks 200	Methods,	Methods,	?	Table 1	?	?	?	Results, de	Results, de	Table 2	E.g. table 2
Tong 2010	Methods,	Methods,	?	Table 1	?	?	?	Methods,	Methods,	Table 3	E.g. table 3
Guy 2014	Methods,	Methods,	?	Table 1	Methods,	?	?	Methods,	Methods,	Table 3	Methods, statistical a
Ozmen 20	Methods,	Methods,	?	Table 1	?	?	?	Table 1 en	Table 1 en	Results, "T	Methods, statistical a
Archiza 20	Methods,	Methods,	?	Table 1	Methods,	Methods,	?	Results, "A	Results, "A	Table 2	E.g. table 2
Mackala 2	Methods,	Methods,	?	Table 2	?	?	?	Methods,	Methods,	Table 3	E.g. table 3
Faghy 202	Methods,	Methods,	?	Table 1	?	?	?	Table 1, tr	Table 1, tr	Figure 1	E.g. figure 1
Chang 202	Methods,	Methods,	?	Table 1	?	?	?	Methods,	Methods,	Table 2	E.g. table 2
de Sousa 2	Methods,	Methods,	?	Table 1	?	?	?	Figure 1, r	Figure 1, r	Table 1	E.g. table 1