Title: The physiological effects of swim training interventions: a systematic review and meta-analysis

Running heading: Physiological adaptations of swimming

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ABSTRACT

Background Swimming is a popular and potentially health-enhancing exercise, but has received less scientific attention compared to other exercise modes.

Objectives To determine the effect of pool swim training on physiological outcomes in recreational swimmers or swimming naïve or untrained participants.

Design Systematic review with meta-analysis.

Data sources Electronic databases PubMed, EMBASE, and CENTRAL from inception to March 2017.

Eligibility criteria Randomised controlled trials (RCTs), quasi-RCTs, and controlled trials of swimming interventions in non-elite or non-competitive swimming participants, with a physiological outcome measure.

Results Our search of 6,712 records revealed 28 eligible studies. Swimming had a significant and clinically meaningful effect on maximal oxygen uptake ($\text{VO}_{2\text{max}}$) compared to control, in an analysis including multiple populations [Mean difference (MD) 6.42 ml/kg/min; 95% CI 4.34, 8.50], and subgroup analyses of children/adolescents with asthma (MD 9.67 ml/kg/min, 95% CI 5.84, 13.51) and healthy adults (MD 5.87 ml/kg/min; 95% CI 2.93, 8.81). Swimming also resulted in significant improvements in body fat % (MD -1.91 %; 95% CI -3.46, -0.36) and lean mass (MD 2.26 kg; 95% CI 0.32, 4.19). Based on limited data, swimming had similar effects to other exercise modes, except for higher post-intervention BMI values with swimming versus running in healthy adults (MD 1.18 kg/m^2 ; 0.54, 1.81).

Conclusions Swimming may offer robust beneficial effects on $\text{VO}_{2\text{max}}$ and body composition across multiple populations and effects may be comparable to other exercise modes. Future RCTs are required to establish the effectiveness of swimming on physiological outcomes in healthy populations and those with non-communicable diseases.

Key Points

- Swim training can significantly and meaningfully improve cardiorespiratory fitness across a number of populations, including children/adolescents with asthma and healthy adults.
- Swim training may result in small or unclear effects on resting lung function in children/adolescents with asthma, and significant but modest improvements in body composition healthy children/adolescents and adults, and adults with hypertension.
- From the limited data available, swim training had similar physiological effects compared to other modes of exercise (e.g., walking, running, and cycling).

1. INTRODUCTION

Swimming is an important life-saving skill but also a type of physical activity that might provide health benefits for young and adult populations, as well as patients with non-communicable disease (NCD).[1] Swimming is one the most popular modes of physical activity in U.S.A., Europe and UK[2-4] while at the same time it represents an appealing form of exercise for the elderly and individuals with NCD, due to its low impact nature.[5] However, despite its popularity and potential for benefit, swimming has received much less attention in the scientific literature compared to running and cycling, possibly due to the difficulty in taking physiological measures during swimming, the need to acquire a certain level of skill and technique to achieve a prescribed exercise intensity, and concerns over the safety of swimming for populations with NCD.[6]

The physical properties of water including its density, pressure, thermal capacity and conductivity, represent significant challenges and elicit physiological effects in an attempt to meet these demands. Within an evidence-based framework, knowledge of the long-term physiological responses to swimming is crucial to optimise the design and application of safe and effective exercise prescription. Furthermore, a greater understanding of swimming physiology would allow clinicians to identify the populations that may benefit most from swimming and those for which this particular mode of exercise might be contraindicated or require certain modifications or supervision to ensure safety.

Previous reviews of the physiology of swimming have focused more on competitive swimming[7-18] with less scientific attention on swimming in healthy or chronic disease populations. Most of the reviews dedicated to the latter, have focused on the

effects of swimming on cardiovascular physiology[5, 6, 19] or respiratory and asthma-related conditions.[20-26] Given the lack of relevant studies in this field, the aim of the present systematic review and meta-analysis was to investigate the long-term physiological effects of recreational swimming in both healthy populations and those at risk of or diagnosed with NCD.

2. METHODS

This review was written as part of commissioned work on the physiological effects of swimming by the Amateur Swimming Association. The review has been reported in accordance with the preferred reporting items for systematic reviews and meta-analyses (PRISMA) statement.

Search methods for identification of studies

Criteria for considering studies for this review can be found in Table 1. We searched the following databases to identify eligible studies: PubMed, EMBASE, and Cochrane Central Register of Controlled Trials (CENTRAL) (via the Cochrane Library, Issue 3, 2017) on the 1st March 2017. We also screened references in relevant reviews and in published eligible studies. A search algorithm was developed for Pubmed (see Table S1) and was modified for CENTRAL and EMBASE. We searched all databases from their inception to the present. We included only full publications and did not exclude based on language of publication.

Table 1. Eligibility criteria for selecting studies

Inclusion criteria
1. Study design: randomised controlled trials, quasi-randomised controlled trials, and controlled trials.
2. Types of participants: we included studies of humans of any age, who were healthy or diagnosed with non-communicable disease.
3. Published studies that compared the chronic physiological adaptations of pool swimming interventions to non-swimming comparison groups.
Exclusion criteria
1. Studies that investigated the effects of swimming in elite, competitive and/or trained populations (i.e., professional, national, international, varsity, and collegiate competitive swimmers).
2. Swim intervention studies that included only non-physiological related outcome measures (e.g., stroke rate, speed, mood, etc.).
3. Utilised water-based physical activities (e.g., water-based aerobic activities), hydrotherapy, aquatic interventions or combined interventions (e.g., swimming and caloric restriction or other physical activities), where the effects of swimming could not be isolated.
4. Studies investigating the effects of cold water or winter swimming, scuba-diving, breath-holding or water-immersion activities.

The results from the searches described above were merged and duplicate records of the same report were removed. The titles and abstracts were examined to remove obviously irrelevant reports. Two authors (IML and GSM) independently screened and assessed the records for eligibility. Full-text articles of potentially relevant reports were retrieved, examined for eligibility, and multiple eligible reports of the same trial were linked together. Non-English language trials were included and these trials were translated, where necessary, so that eligibility could be assessed and subsequently data extracted.

Data extraction

Two authors (IML and GSM) independently extracted the following data: study design; total duration; sample size; demographic information; intervention characteristics; and physiological outcome data. Multiple publications for the same trial were collated and the first or most complete report was used as the primary reference. We entered and combined the trial data using Review Manager (RevMan 5.3). We summarised the data collected from the reports in the characteristics of studies table (Table 2).

Table 2. Chronic physiological adaptations to pool swimming

HEALTHY CHILDREN and ADOLESCENTS			
First Author	Methodology	Outcome Measures (Technique)	Findings
Bielec[27]	<p>Population: 230 6th grade junior high school students (females, n=106)</p> <p>Study Design: CT</p> <p>Duration: 2 year</p> <p>Swim Intervention: 116 adolescents attended swimming (front crawl, backstroke, and breaststroke) classes once a week, for 45min within obligatory physical education</p> <p>Comparison group: 114 controls</p>	<ul style="list-style-type: none"> • Body mass, BMI • Posture, shoulder and scapula asymmetry (clinical examination) 	<p>Swimming vs. control:</p> <ol style="list-style-type: none"> 1) Body mass was significantly ↓ after 1 year in swimming vs. controls, but there was no significant difference between groups at 2 years 2) No differences in BMI and posture in swimming vs. controls 3) No improvement in scoliosis or scapula and shoulder asymmetry in swimming vs. controls 4) Gains in body mass ↓ in swimming males vs. females
Obert[28]	<p>Population: 14 pre-pubertal girls</p> <p>Study Design: CT</p> <p>Duration: 1 year</p> <p>Swim Intervention: 5 girls participated from a local youth swimming club and were followed for 1 year of swimming (breaststroke, training progressed from 10h/week training during the first 3 months, to 12h/week)</p> <p>Comparison group: 9 from a primary school acted as controls. They participated in other sports 1 to 4 h/week</p>	<ul style="list-style-type: none"> • VO₂peak, RER, VE (swim bench test), HR (ECG continuously monitored during fitness test) • Body mass, body fat % and lean body mass (via Skinfold thickness) • Maturation (Tanner test) 	<p>Swimming vs. non-swimming active control:</p> <ol style="list-style-type: none"> 1) Significant pre-post ↑ in VO₂ peak (L·min) in both groups 2) Significant pre-post ↑ in VO₂ peak (ml·min⁻¹·kg⁻¹·m_b), HRmax, VEmax (L·min), and maximal O₂ pulse in swim group only 3) No change pre-post in RER in both groups 4) Significant pre-post ↑ body mass and ↑ in lean body mass in both groups 5) No change pre-post in body fat % in swim group but significant ↑ in control group
HEALTHY UNIVERSITY STUDENTS AND ADULTS			

<p>Celik[29] Also: Ozdemir[30]</p>	<p>Population: 48 healthy with 44 completed the study, sedentary, male university students Study Design: RCT Duration: 12 weeks Swim Intervention: n=11, front crawl swimming (40min per day, 3 times/week, 30min swimming with 10min warm-up / cool-down, at 60-70% of HRres) Comparison groups: running (n=11), cycling (n=11), control (n=11) groups</p>	<ul style="list-style-type: none"> • VO₂peak (gas analysis) • Serum cartilage oligomeric matrix protein (ELISA) • BMI, body composition (DEXA) • Muscular strength (isokinetic dynamometry) 	<p>Pre-post swimming vs. running vs. cycling vs. control:</p> <ol style="list-style-type: none"> 1) Significant ↑ in VO₂peak in all exercise groups compared to control 2) Significant pre-post change in serum cartilage oligomeric matrix protein (COMP) in the swimming group vs. control, but post-intervention 30 min of walking exercise significantly ↑ serum-COMP levels of the swimming group 3) Significant ↓ in BMI in all exercise groups compared to control 4) No significant change in body fat % between groups 5) Relative isokinetic strength of the dominant leg during extension significantly ↑ only in the swimming group compared to control
<p>Cox[31] Also: Cox[32] Cox[33]</p>	<p>Population: 116 women aged 50-70 Study Design: RCT Duration: 6 month Swim Intervention: n=56, 60-70% of predicted HRmax, 45min, including 15min warm-up and stretching; initially interval then more continuous swimming (front, backstroke, breaststroke, sidestroke) Comparison group: walking (n=60) Participants further randomized to behavioral intervention or usual care. The program continued unsupervised for another 6 months</p>	<ul style="list-style-type: none"> • Predicted VO₂max and performance (12 min swim and 1.6km walking tests) • BP (automatic device) and HR • Lipids (commercial kits), glucose (automated analyzer), insulin (immunoassay) • Sodium and calcium excretion (urine sample) • Body mass, BMI, upper arm girth (tape), triceps skinfold (caliper), body fat distribution (circumference in various body parts) • Food intake (diary) and Physical activity (questionnaire) 	<p>Swimming vs. walking:</p> <ol style="list-style-type: none"> 1) Significant pre-post 6 m ↑ in predicted VO₂max and supine and standing HR were observed in both groups. No between group differences were observed at 6 m. Significant pre-post ↓ in walk time in walk test in both groups (-3.8% vs. -6.5%), but significant pre-post ↑ distance swam in swim test in swimming group but not the walking group (29.3% vs. -1.0%) 2) Significant pre-post 6 m and between groups ↑ in supine and standing SBP in the swimming group vs. the walking group (adjusted for initial BP, age,

			<p>hypertension treatment status and change in weight). (Increase in supine SBP of 4.4 mmHg, 95% CI 1.2 to 7.5, in swim group relative to walking group). No significant within groups or between groups changes in DBP were observed at 6 m</p> <p>3) No pre-post or between group difference in urinary sodium and calcium excretion, total cholesterol, HDL-C, LDL-C, and triglycerides at 6 m; however, at 12 m follow-up, total cholesterol and LDL-C increased significantly in the walking versus swimming group.</p> <p>4) No significant within or between group differences were observed for fasting glucose, glucose area under curve (AUC), fasting insulin, and HOMA-IR at 6 m and 12 m, except for a significant increase in insulin AUC at 6 m but not 12 m in walking versus swimming.</p> <p>5) Significant pre-post ↓ in body mass and BMI in swimming group but not in walking group; whereas, no between group differences were observed at 6 m, but at 12 m follow-up, the walking group had significantly higher body mass and BMI compared to swimming group</p> <p>6) Waist circumference was significant lower in the swim group vs. walk group at 6 m but not at 12 m follow-up, whereas, hip circumference was significantly lower in the swim group vs. walk</p>
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			<p>group at both 6 m and 12 m</p> <p>7) Significant pre-post ↓ in arm muscle girth in swimming group but not in walking group, but no significant pre-post changes in triceps skinfold in with groups and no between groups differences were observed at 6 m and 12 m for arm muscle girth.</p> <p>8) Calf girth was significantly lower in the swim group vs. walk group at 6 m and 12 m follow-up, but no other between group differences observed in any other anthropometric measure (forearm, chest, gluteal thigh, and mid-thigh girth)</p>
Fernandez-Luna[34]	<p>Population: 39 healthy adults (female, n=5)</p> <p>Study Design: CT</p> <p>Duration: 3 months</p> <p>Swim Interventions: a) chlorinated indoor pool (n=13); b) ozone indoor pool (n=13). Swimming training consisted of 2–3 non- consecutive sessions/week, 50min (“swimming styles technique”)</p> <p>Comparison group: controls (n=13)</p>	<ul style="list-style-type: none"> • Lung function (spirometry), • Lung epithelial damage (serum proteins CC16 and SP-D) • Health survey about frequency of health complaints during training (questionnaire) 	<p>Swimming in chlorinated pool vs. swimming in ozone pool vs. control:</p> <p>1) Significant pre-post ↑ in FVC and FEV1 in Ozone pool group, but only a significant pre-post ↑ in only FEV1 in chlorinated pool group.</p> <p>2) Significant pre-post ↓ in FEF 25-75 in chlorinated pool only</p> <p>3) No changes in pre-post forced expiratory volumes in the control group</p> <p>4) Significant pre-post ↑ in Serum CC16 in chlorinated pool only but no significant pre-post change in SPP-D occurred in any of the groups</p> <p>5) Perceived health problems were similar between swimming groups, but self-reported eye irritation was significantly ↑ in chlorinated pool</p>

			compared to ozone pool.
Lieber[35]	<p>Population: 36 sedentary males (aged: 28-35 y)</p> <p>Study Design: CT</p> <p>Duration: 11.5 weeks</p> <p>Swim Intervention: Swimming (n = 14) for 60 min at a target HR of 75% treadmill VO₂max level, 3 d/week (35 sessions).</p> <p>Comparison groups: Run training (n = 12) for 60 min at a target HR of 75% treadmill VO₂max level, 3 d/week (35 sessions), and non-swimming control (n = 10) groups</p>	<ul style="list-style-type: none"> • VO₂max and submaximal VO₂, and RER (via GXT treadmill and gas analysis) • Maximal and submaximal HR • Body mass • Body fat % and lean mass (underwater weighing) 	<p>Swimming vs. running vs. control:</p> <ol style="list-style-type: none"> 1) All groups experienced within group significant ↑ in VO₂max, but 28% and 25% ↑ in treadmill VO₂max were significantly greater than 5% ↑ in control. No between-group differences in VO₂max or RER for run and swim training. 2) Swim training and run training significantly ↓ in HR during submaximal exercise, but no change occurred in controls. Significant differences in submaximal HR response between swim and control groups. 3) Significant ↓ in body fat % and ↑ lean mass for both swim and run training groups, but not control. No significant between-group changes in body mass.
Lu and Wang[36]	<p>Population: 120 college students</p> <p>Study Design: RCT</p> <p>Duration: 12 weeks</p> <p>Swim Intervention: n=24, swimming (Front crawl and kicking drills: 50min/day, 5 days/week, 60-70% HRmax)</p> <p>Comparison groups: cycling (n=24), power striding (n=24), running (n=24), and controls (n=24)</p>	<ul style="list-style-type: none"> • BMI • Strength (isokinetic dynamometry), • Cartilage volume assessment (MRI scan) 	<p>Swimming vs. cycling vs. power striding vs. running vs. control:</p> <ol style="list-style-type: none"> 1) Significant but modest pre-post ↓ in BMI in all exercise groups compared to no change in the control group. 2) Significant pre-post ↑ in Quadriceps peak torque in the swimming and cycling groups only. 3) No pre-post changes in total cartilage volume were observed in the swimming group (significant losses were observed in the running and cycling groups).
Magel[37]	Population: 30 male, college age, recreational	<ul style="list-style-type: none"> • VO₂max, VEmax, RER (gas 	Pre vs. post-swimming

	<p>swimmers</p> <p>Study Design: CT</p> <p>Duration: 10 weeks</p> <p>Swim Intervention: n=15, interval swim (front crawl) training procedures 1 h/day, 3 days/week</p> <p>Comparison groups: 15 control participants who did not participate in any form of training</p>	<p>analysis)</p> <ul style="list-style-type: none"> HR and work time 	<p>intervention:</p> <ol style="list-style-type: none"> 1) Significantly $\uparrow$ VO_2max (380 ml/min, 11.2%), VE_{max} (14.9 L/min), and max swim time (4.0 min) evaluated by tethered swimming VO_2max test 2) Significantly $\downarrow$ HRmax (3.5 bpm) during swimming VO_2max test 3) No significant improvement in VO_2max (1.5%) when the same subjects were evaluated by the treadmill running test. 4) No significant changes in VO_2max and associated measures during running and swimming tests for control participants.
PREGNANCY			
<p>Lynch[38]</p> <p>Also:</p> <p>Lynch[39]</p>	<p>Population: 39 pregnant women</p> <p>Study Design: CT</p> <p>Duration: 12 weeks</p> <p>Swim Intervention: n=27, 3 times/week, 40min/session, <70% of HRmax) from 16 to 28 weeks of gestation. 9 women carried on swimming until 32 weeks of gestation and 7 up till the 36 week of gestation (swimming: front crawl/backstroke/breaststroke/skill drills)</p> <p>Comparison group: non-swimming pregnant controls (n=12)</p>	<ul style="list-style-type: none"> Physical work capacity and RPE (submaximal cycling test) at 16, 20, 24 and 28 weeks of gestation (and 32 and 36 of those women who continued), BP (sphygmomanometer), umbilical artery systolic/diastolic ratio Maternal and fetal HR Body mass Rectal temperature 	<p>Swimming vs. non-swimming control:</p> <ol style="list-style-type: none"> 1) Significant $\uparrow$ physical work capacity of the swimming group but not controls. Significant $\uparrow$ physical work capacity at 20 weeks and at 24 weeks of gestation (13.8% improvement over 8 weeks) but no further improvement from 24-28 weeks of gestation 2) No significant changes in relative physical work capacity were identified in either group over the 12-week training period, despite body mass increasing by approx. 6 kg in each group. 3) No significant changes in pre-exercise or exercise HR were observed over the study period. 4) Significant $\downarrow$ RPE after 4 weeks

			<p>of training (20 weeks of gestation) of swimming but no changes thereafter</p> <p>5) No differences in rectal temperature pre-post swim intervention</p> <p>6) No difference in body mass gain to 28 weeks gestation between groups</p> <p>7) No adverse responses to exercise were identified in any individuals</p> <p>Pre vs. post-swimming:</p> <p>1) Significant ↓ in HR 5 min post-swimming at all gestational weeks</p> <p>2) Mean resting HR significantly ↓ advancing gestation age, but no change was observed in exercising and post-exercise rates</p> <p>3) Significant ↓ in resting and post-swimming fetal HR with advancing gestation, but no effect on the pre- and post-exercise fetal HR differences with advancing gestational age</p> <p>4) Significant ↑ in fetal HR during and 5 min post-swimming</p> <p>5) Resting SBP and DBP remained unchanged over gestation</p> <p>6) No significant accelerations in fetal HR were detected or signs of hypoxia and no significant changes in umbilical artery systolic/diastolic ratio, pre-post swim intervention</p>
INDIVIDUALS WITH ASTHMA AND CYSTIC FIBROSIS			

Arandelovic[40]	<p>Population: 65 adults with persistent asthma (female, n=49)</p> <p>Study Design: RCT</p> <p>Duration: 6 months</p> <p>Swim Intervention: n=45, 1h swim (stroke not reported), 2 times/week (non-chlorinated pool), asthma education</p> <p>Comparison group: controls treated with inhaled corticosteroids and short acting β-2 agonist salbutamol (n=20)</p>	<ul style="list-style-type: none"> • Lung function (spirometry), • Bronchoprovocative test (dosimeter device) • Skin tests (skin prick test) 	<p>Swimming vs. controls post-intervention:</p> <ol style="list-style-type: none"> 1) Significant $\uparrow$ FEV1, FVC, PEF in the swimming group vs. controls 2) Significant better responses in the bronchoprovocative test in both groups 3) Significant $\downarrow$ in the bronchoprovocative test for atopic and atopic individuals in both groups 4) At the end of the study, hyper-responsiveness was significantly $\downarrow$ in the swim group compared to the control group <p>Pre-post swimming in swim group only:</p> <ol style="list-style-type: none"> 1) Significant pre-post $\uparrow$ in FEV1, FVC, and PEF
Huang[41]	<p>Population: 90 children with asthma</p> <p>Study Design: CT</p> <p>Duration: 1 year</p> <p>Swim Intervention: n=45 asthmatic children (females, n=12) underwent swimming training (stroke not reported) of 1h/session, 3 times/week after school hours</p> <p>Comparison group: n=45 non-participant children matched for age, gender and severity of illness</p>	<ul style="list-style-type: none"> • Physical examination • Lung function (peak flow meter) • Clinical progress (via school absenteeism, emergency room visits, hospitalization, days requiring daily medication, days of wheezing) 	<p>Pre vs. post-swimming in swimming group:</p> <ol style="list-style-type: none"> 1) Significantly $\uparrow$ lung function (PEF) by 65% and 63% at 6 m and 12 m, respectively (21% and 25% at 6 and 12 m in the control group) 2) Significantly $\downarrow$ asthma attacks, wheezing, days requiring medication, emergency hospital visits, hospitalization, absence from school <p>Swimming vs. controls post-intervention:</p> <ol style="list-style-type: none"> 1) Compared to controls, significantly better improvements were seen in asthma attacks, lung function, wheezing, days requiring medication, hospitalization, emergency visits and absence from school

Matsumoto[42]	<p>Population: 16 children with severe asthma</p> <p>Study Design: RCT</p> <p>Duration: 6 weeks</p> <p>Swim Intervention: n=8, front crawl swimming in heated pool at 30°C, 30min with 10min rest after 15min, 6 days/week</p> <p>Comparison group: non-swimming controls (n=8)</p>	<ul style="list-style-type: none"> • Aerobic capacity and HR (cycling and crawl tethered-swimming tests) • Exercise-induced bronchoconstriction (via the mean fall in FEV₁ from pre-exercise value) • Blood lactate (lactate analyzer) • Histamine challenge test 	<p>Swimming vs. controls post-intervention:</p> <ol style="list-style-type: none"> 1) Significantly ↑ mean workload at the lactate threshold on both the swimming and cycling ergometers in the swimming group vs, controls 2) No changes in mean maximal % fall in FEV₁ by absolute load at either 100% or 175% of the lactate threshold 3) No changes in histamine test <p>Pre vs. post-swimming training in the swimming group:</p> <ol style="list-style-type: none"> 1) Swimming and cycling ergometers: Significantly ↓ mean maximal % fall in FEV₁ in swimming ergometer at 175% of the lactate threshold on the relative load 2) Cycling ergometer: Absolute load significantly ↑ at both 100% and 175% of the lactate threshold
Varray[43]	<p>Population: 14 atopic children with asthma</p> <p>Study Design: RCT</p> <p>Duration: 6 months</p> <p>Swim Intervention: n=7 (male: 6, female: 1, age: 11.4±1.5 years), Aerobic training: 3 months- participants swam for 10 minutes at 3 times of their own ventilatory threshold velocity. A session ran for an hour and there were two different sessions per week. High intensity training 3-6 months- consists of a series of 25 m crawls performed at maximal speed, repeated 6 times in one series, with 1 minute break in between. A session consisted of 2 series for a total of 12 25m crawls. 2 sessions per week.</p> <p>Comparison group: Not specified, assumed treatment as per normal with no further interventions (n=7, male: 6, female: 1, age: 11.4±1.8 years)</p>	<ul style="list-style-type: none"> • VO₂max • Ventilatory threshold • HRmax • Lung function: FEV₁, FVC, FEF_{25%-75%} in litres and as % predicted 	<p>Swimming vs. controls:</p> <ol style="list-style-type: none"> 1) Significant ↑ in VO₂max in the swim group vs. control. 2) Significant ↑ in ventilatory threshold in the swim group vs. control. 3) No significant difference in any measure of lung function between groups. 4) Parents reporting participants in the swimming group did not have any decrease in frequency of wheezing attacks or use of regular asthma medication.

Varray[44]	<p>Population: 18 asthmatic children</p> <p>Study Design: RCT</p> <p>Duration: 3 months</p> <p>Swim Intervention: n=9 (male: 7, female: 2) age: 10.3±1.3 years), 2 supervised swimming sessions per week for a period of 3 months. Each session lasted 1 hour within which the children swam at least 3 times at their own ventilatory threshold velocity for 10 minutes.</p> <p>Comparison group: n=9, non-swimming usual care (male: 7, female: 2, age: 11.7±0.5 years)</p>	<ul style="list-style-type: none"> • VO₂max • Ventilatory threshold • Resting pulmonary function, Rate of perceived dyspnoea 	<p>Swimming vs. controls:</p> <ol style="list-style-type: none"> 1) Significant ↑ in VO₂max in the swim group vs. control. 2) Significant ↑ in ventilatory threshold in the swim group vs. control. 3) No significant difference in any measure of lung function between groups. 4) Rate of perceived dyspnoea ↓ after swim training
Wang and Hung[45]	<p>Population: 30 children with mild, moderate, or severe persistent asthma</p> <p>Study Design: RCT</p> <p>Duration: 6 weeks</p> <p>Swim Intervention: n=15, swimming (front crawl/backstroke) 3 x 50min sessions / week, 65% of HRmax, in a non-chlorinated pool</p> <p>Comparison group: non-swimming controls (n=15)</p>	<ul style="list-style-type: none"> • Lung function (spirometry) • Clinical progress (peak expiratory flow and daily assessment of asthma severity) 	<p>Pre vs. post-swimming training in the swimming group:</p> <ol style="list-style-type: none"> 1) Significantly improvement in FEV1, FEF50, FEF25-75 at 6 weeks <p>Swimming vs. controls post-intervention:</p> <ol style="list-style-type: none"> 1) No differences in FEV1, FEF50, FEF25-75 at 6 weeks 2) Significant ↑ PEF in swimming both at 3 and 6 weeks vs. controls 3) Significant improvement in asthma severity after the intervention only in the swimming group
Weisgerber[46]	<p>Population: 8 children with moderate persistent asthma</p> <p>Study Design: RCT</p> <p>Duration: 5-6 weeks</p> <p>Swim Intervention: n=5, 2 times/week, 45min/session (front crawl/backstroke swimming)</p> <p>Comparison group: non-swimming controls (n=3)</p>	<ul style="list-style-type: none"> • Pulmonary function (spirometry) • Asthma symptoms (questionnaire) 	<p>Swimming vs. controls post-intervention:</p> <ol style="list-style-type: none"> 1) No changes in pulmonary function (i.e., PEF, FVC, FEV1, or FEF25-75) or asthma symptoms
Weisgerber[47]	<p>Population: 61 children with mild, moderate, or severe persistent asthma</p> <p>Study Design: RCT</p> <p>Duration: 9 weeks</p> <p>Swim Intervention: high-intensity swimming programme with 27 x 1 hour sessions. 30 mins standardised swimming instruction and 30 min of</p>	<ul style="list-style-type: none"> • Fitness (VO₂max, Coopers 12 min walk/run test, exercise time, peak HR) • FEV1 % • Symptoms (questionnaires) • Urgent asthma visits 	<p>Swimming vs. golf:</p> <ol style="list-style-type: none"> 1) VO₂max improved by 5% in the golf group vs -3.1% in the swim group, but this was not a statistically significant difference. 2) FEV1 % predicted was significantly greater in the

	<p>vigorous swimming consisting of 4 phases: interval training (12-15 min periods swim 20-80s full-speed drills of flutter-kicking, water jumping, introductory front crawl, introductory back stroke, then rest for 20-80s), endurance training, relay races, and water games. (n=35 age: 10.7±1.9 years)</p> <p>Comparison group: moderate-intensity activity golf programme 27 x 1-hr sessions.(n=26, age: 9.9±1.8 years)</p>		<p>swimming group vs. golf group.</p> <ol style="list-style-type: none"> 3) No significant difference in the Coopers 12-minute walk-run test between swimming training and golf groups 4) No significant difference was found for symptoms between swimming and golf exercise groups 5) Five symptom exacerbations occurred during 700 person-sessions of the swimming programme (7.1 per 1000 sessions) and one symptom exacerbation occurred during 425 person-sessions of golf (2.4 per 1000 sessions) 6) No significant difference in urgent asthma physician visits between the swimming training and golf groups
Wicher[48]	<p>Population: 71 children and adolescents with moderate asthma</p> <p>Study Design: RCT</p> <p>Duration: 12 weeks</p> <p>Swim Intervention: 60 minutes session x twice weekly classes. 2 levels swimming training according to previous experience: Level I (n = 26): adaptation to the water, breathing with full immersion, floating, swimming and basic diving, Level II (n = 4): children who had the skills described plus learning front and back crawl. (n=30, age: 10.4±3.1 years)</p> <p>Comparison group: non-swimming controls (n=31, age: 10.9±2.6 years)</p>	<ul style="list-style-type: none"> • Spirometric assessment: FVC, FEV1, FEF 25-75% • Methacholine challenge test: provocative concentration of methacholine causing a 20% fall in FEV1 (PC20) 	<p>Pre vs. post-swimming vs. control:</p> <ol style="list-style-type: none"> 1) Significant pre-post ↑ in PC20, maximal inspiratory pressure, and maximal expiratory pressure were found in the swimming group, with significant between group's changes in PC20. 2) No significant change in FVC, FEV1, FEF 25-75% for swimming training compared with control. 3) No participant was admitted to hospital for asthma attacks during in the "run in" or during the training period in either the swimming or control group.

Edlund[49]	<p>Population: 23 boys and girls (females, n=9)</p> <p>Study Design: CT</p> <p>Duration: 12 weeks</p> <p>Swim Intervention: Swimming pool of 32°C to 35°C, 60min, 3 days / week, with intensities of 60-75% of HRmax in the first 5 weeks, progressively building up to 70-85% during the last 4 weeks (n =13) (swim stroke not provided)</p> <p>Comparison group: n=10 non-swimming controls</p>	<ul style="list-style-type: none"> • VO₂peak, VE, VCO₂ and RER directly measured only in 12 participants (gas analysis); in 8 it was predicted (equation) • HR (ECG) • Pulmonary function (respirometer) • Clinical Analysis of the disease status 	<p>Swimming vs. controls post-intervention:</p> <ol style="list-style-type: none"> 1) No significant differences in directly measured VO₂peak, VE any pulmonary function parameters 2) VO₂peak predicted from equations significantly ↑ in the swimmers but not controls 3) No significant differences in body mass 4) Significant improvements in clinical disease status only in the swimming group
WOMEN WITH OBESITY			
Gappmaier[50]	<p>Population: 38 middle-aged women with obesity (25-47% body fat)</p> <p>Study Design: RCT</p> <p>Duration: 13 weeks</p> <p>Swim Intervention: Swimming (alternating breast-, side-, and backstroke) at 70%of HRmax (220-age), 4 times per week, for 10 mins for 3 weeks and 40 mins for 10 weeks (n = 20). Restricted fat and refined carbohydrate intake diet (but not caloric restriction)</p> <p>Comparison groups: Walking on land (n = 19) and walking in 29°C water (n = 19). 4 times per week, for 10 mins for 3 weeks and 40 mins for 10 weeks. Restricted fat and refined carbohydrate intake diet (but not caloric restriction)</p>	<ul style="list-style-type: none"> • VO₂max (predicted via Astrand bicycle test) • Body mass • Body fat (underwater weighing technique) • SKF thickness of subscapular and triceps • Thigh, abdominal, and hip circumference 	<p>Swimming vs. walking on land vs. walking in water</p> <ol style="list-style-type: none"> 1) No significant differences between groups for any measure 2) Significant within-group ↓ in body mass, body fat %, and SKF and girth measurements and ↑ in VO₂max. Lean mass only ↑ pre-post in the swimming group.
Gwinup[51]	<p>Population: 29 premenopausal women with obesity (30-40% body fat)</p> <p>Study Design: RCT</p> <p>Duration: 6 months</p> <p>Swim Intervention: Front crawl or backstroke Swimming (n = 8). Exercise began at 5 to 10 mins each day, and systematically increased by at least 5 mins daily at weekly intervals to achieve 60 mins per day.</p>	<ul style="list-style-type: none"> • Resting heart rate • Body mass • SKF subcutaneous panniculus was carefully measured over the middle of the extensor surface of the non-dominant arm, using the Lang skinfold caliper 	<p>Swimming vs. walking on land vs. stationary cycling</p> <ol style="list-style-type: none"> 1) Skinfold thickness and body mass showed a comparable reduction in the walkers and the cyclists, while the swimmers had no change in skinfold thickness or body mass. 2) No between-group changes in resting HR were observed.

	<p>Comparison groups: walking (n = 11) and stationary cycling (n = 10) Exercise began at 5 to 10 mins each day, and systematically increased by at least 5 mins daily at weekly intervals to achieve 60 mins per day.</p>		
INDIVIDUALS WITH HYPERTENSION			
<p>Mohr[52]</p> <p>Also: Mohr[53] Connolly[54] Nordsborg[55]</p>	<p>Population: 83 premenopausal obese mildly hypertensive women</p> <p>Study Design: Quasi-RCT</p> <p>Duration: 15 weeks</p> <p>Swim Interventions: a) n=21, moderate-intensity swimming group with continuous front crawl for 1h with participants encouraged to swim as far as possible, b) n=21, high-intensity swimming group doing 6–10 30sec bouts of all-out front crawl swimming interspersed by 2 min of passive recovery</p> <p>Comparison groups: soccer (n=20) and controls (n=20)</p>	<ul style="list-style-type: none"> • Performance via a 10min swimming test and a repeated sprint test and Yo-Yo fitness test, • HR (monitor) and SBP, DBP, MAP (automatic monitor) • OGTT, insulin, glucose and lipids (enzymatic kit), sICAM-1 and sVCAM-1 (ELISA) • Muscle samples from the medial part of the vastus lateralis muscle and the posterior (90% of samples) or anterior (10% of samples) part of the deltoideus muscle (biopsy), muscle glycogen, citrate synthase, 3-Hydroxyacyl-CoA dehydrogenase, complex i-v, phosphofructokinase protein expression • Body composition (DEXA), waist-to-hip ratio and waist circumference; • BMC and BMD (DEXA), bone turnover markers (biomarkers) 	<p>High vs. moderate-intensity swimming vs. controls post-intervention:</p> <ol style="list-style-type: none"> 1) Significant ↑ in Yo-Yo fitness test in both swimming groups but not controls 2) Significant ↓ SBP in both swimming groups but not controls 3) No differences in HR, MAP and DBP 4) No differences in fasting plasma glucose and lipids 5) Significantly ↓ fasting plasma insulin, insulin sensitivity and sVCAM-1 only with high-intensity but not moderate-intensity or controls 6) Significantly ↓ sICAM-1 with high-intensity and controls but not moderate-intensity 7) Significantly ↑ citrate synthase in both muscle groups after both high and moderate intensity swimming, and after high intensity swimming was higher in deltoideus than in vastus lateralis 8) Significantly ↑ 3-Hydroxyacyl-CoA dehydrogenase in deltoideus after high and moderate intensity training, while in the vastus lateralis it increased only with

			<p>high-intensity</p> <p>9) Significantly $\uparrow$ complex I-V in deltoideus muscle after high and moderate intensity swimming but significantly $\uparrow$ muscle glycogen only after high-intensity swimming</p> <p>10) Significant $\downarrow$ body mass, waist circumference, total fat mass and body fat in both swimming groups but not controls</p> <p>11) Significantly $\downarrow$ hip circumference with moderate intensity but not high-intensity or controls</p> <p>High vs. moderate-intensity swimming vs. soccer vs. controls post-intervention:</p> <p>1) Significantly $\uparrow$ total leg BMC, femoral shaft and trochanter BMD, and bone turnover biomarkers in soccer but none of the other groups</p> <p>2) No changes in total leg BMD, total body BCM and BDM or pelvic and arm BCM and BDM</p>
Silva[56]	<p>Population: 46 individuals with mild and moderate hypertension</p> <p>Study Design: CT</p> <p>Duration: 10 weeks</p> <p>Swim Intervention: n=23, 3 weekly 50min front crawl swim sessions, stating at an intensity of 40%HRmax)</p> <p>Comparison group: non-swimming controls (n=23)</p>	<ul style="list-style-type: none"> • BP every week for 10 weeks (automated monitor) • Body mass 	<p>Pre vs. post-intervention in swimming group:</p> <p>1) Significant $\uparrow$ SBP (4.89 mmHg) and DBP (6.52 mmHg)</p> <p>Swimming vs. controls post-intervention:</p> <p>1) No changes in body mass and BMI</p>

Nualnim[57]	<p>Population: 43 individuals with prehypertension and stage 1 hypertension (females, n=11)</p> <p>Study Design: Quasi-RCT (randomization was eliminated for those strongly objecting their allocation)</p> <p>Duration: 12 weeks</p> <p>Swim Intervention: n=24, supervised 15-20 minutes/day, 3-4 days/week at 60-75% of HRmax (swim stroke not provided)</p> <p>Comparison group: relaxation (n=19)</p>	<ul style="list-style-type: none"> • VO_2peak (gas analysis), • Bilateral brachial and ankle BP (automated device) and carotid and femoral pulse-wave velocities (tonometry), 24h BP (ambulatory monitor), • SV, CO and FMD (ultrasound), • carotid arterial compliance, cardiovagal baroreflex sensitivity (beat-to-beat BP) • Body composition (DEXA) 	<p>Swimming vs. controls post-intervention:</p> <ol style="list-style-type: none"> 1) No significant changes detected in VO_2peak 2) Significantly ↓ resting SBP, daytime SBP and carotid systolic pressure in swimming group only 3) Significantly ↑ carotid artery compliance, FMD, cardiovagal baroreflex sensitivity in swimming group only 4) No significant changes in any other blood pressure and hemodynamic assessments 5) No significant changes detected in glucose, hemoglobin, cytokines, lipids and body composition 6) SV and CO data not reported
Tanaka[58] Also: Tanaka[59]	<p>Population: 18 (female n=8) hypertensive patients with uncomplicated stage 1 or 2 hypertension</p> <p>Study Design: CT</p> <p>Duration: 10 weeks</p> <p>Swim Intervention: n=12, supervised swimming (front crawl), 60min/sessions, 3 days per week on alternate days at 60% of HRmax)</p> <p>Comparison group: non-swimming controls (n=6)</p>	<ul style="list-style-type: none"> • Resting HR, BP, MAP • Casual forearm vascular resistance (plethysmography) • resistance (plethysmography) • Lactate and RPE • Plasma and blood volume (Evans dilution method) • Glucose (hexokinase/glucose 6 phosphate dehydrogenase method), insulin (radioimmunoassay), lipids (enzymatic method) • Plasma epinephrine and norepinephrine (radioenzymatic technique), • Body composition (hydrostatic weighing), BMI, waist to hip ratio and circumference 	<p>Swimming vs. controls post-intervention:</p> <ol style="list-style-type: none"> 1) Significant ↓ in resting and supine SBP in swimming group 2) No changes in resting DBP, supine DBP and casual forearm vascular resistance 3) Significant ↓ resting HR, RPE and blood lactate in swimming group 4) No changes in plasma and blood volume, catecholamines, glucose, insulin and lipids 5) No changes in body mass, lean body mass and body fat
INDIVIDUALS WITH OTHER CONDITIONS			

<p>Alkatan[60] Also: Alkatan[61]</p>	<p>Population: 48 sedentary middle-aged and older adults with OA, 40 completed the study Study Design: RCT Duration: 12 weeks Swim Intervention: n=20, front crawl/breaststroke swimming from 20min progressively up to 40-45min/day, 3 days/week, from 40-50% progressively up to 60-70% HRmax Comparison group: cycling (n=20)</p>	<ul style="list-style-type: none"> • Fitness (6min walking test) • Heart rate • Brachial and ankle BP • Carotid-femoral pulse wave velocity (all the 3 above with automated vascular testing device) • Central systolic BP, pulse pressure • FMD and carotid arterial diameter (ultrasound) • Lipids, inflammatory and metabolic biomarkers • Body mass and composition (DEXA and circumferences) • Strength (isokinetic dynamometry) 	<p>Swimming vs. cycling post-intervention:</p> <ol style="list-style-type: none"> 1) Significant ↑ in 6-min walking test and carotid artery compliance in both groups 2) Significantly ↑ FMD only in the swimming group 3) Significantly ↑ glycated hemoglobin and interleukin 6 in both groups 4) Significantly ↓ carotid-femoral pulse wave velocity, carotid artery stiffness index, carotid artery distensibility, body mass, waist and hip circumferences, visceral adiposity in both groups 5) Significantly ↑ left and right grip strength, isokinetic knee peak torque at 60° and 120° in both groups 6) No significant changes in BP, SBP, DBP, pulse pressure, HR, carotid intima media thickness, BMI lipids, glucose, and other cytokines, body fat % and lean body mass in either group
<p>Casey and Emes[62]</p>	<p>Population: 28 adolescents with Down-syndrome (females, n=12) Study Design: RCT Duration: 12 weeks Swim Intervention: n=14, front crawl swimming, 3 times/week, 1 hour/session Comparison group: non-swimming controls (n=14)</p>	<ul style="list-style-type: none"> • Maximum phonation duration, initiation volume, mean expired airflow (all with a speech respiratory test) 	<p>Swimming vs. controls post-intervention:</p> <ol style="list-style-type: none"> 1) No significant changes in any of the speech respiratory variables

Stephen[63]	<p>Population: 89 Aboriginal children with tympanic membrane perforation</p> <p>Study Design: RCT</p> <p>Duration: 4 weeks</p> <p>Swim Intervention: n=41, 5 days/week, 45 min/session in a chlorinated pool (swim stroke not provided)</p> <p>Comparison group: non-swimming controls (n=48)</p>	<ul style="list-style-type: none"> • Otoloscopic signs of ear discharge in the canal/middle ear space (tympanometry, otoscopy and video otoscopy) • Respiratory bacteria (swab collection and microbiology) 	<p>Swimming vs. controls post-intervention:</p> <ol style="list-style-type: none"> 1) 24 of 41 swimmers had ear discharge at 4 weeks compared with 32 of 48 non-swimmers 2) No significant changes in the microbiology of the nasopharynx or middle ear in swimmers or non-swimmers
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Abbreviations. RCT: randomized controlled trial, HR: heart rate, HRmax: maximum heart rate, HRres: heart rate reserve, BP: blood pressure, SBP: systolic blood pressure, DBP: diastolic blood pressure, MAP: mean arterial pressure, BMI: body mass index, RPE: rate of perceived exertion, FEV1: forced expiratory volume in during the first second of forced breath, FVC: forced vital capacity, FEF50: forced expiratory flow at 50% of the forced vital capacity, FEF25-75: average forced expiratory flow during the mid (25 - 75%) portion of the forced vital capacity, PEF: peak expiratory flow, DEXA: dual energy x-ray absorptiometry, VO₂: oxygen uptake, LDL: low density lipoprotein, MRI: magnetic resonance imaging, CC16: Clara cell secretory protein, SP-D: surfactant protein D, RER: respiratory exchange ratio, RPE: rate of perceived exertion, ECG: electrocardiogram, FMD: flow mediate dilation, SV: stroke volume, CO: cardiac output, FMD: flow mediated dilation, BMC: bone mineral content, BMD: bone mineral density, OGTT: oral glucose tolerance test, sICAM-1: soluble intracellular adhesion molecule 1, sVCAM-1: soluble vascular cell adhesion molecule 1, VE: Minute ventilation.

Risk of bias assessment of articles

The Cochrane Collaboration's 'risk of bias' tool was used to assess possible sources of bias.[64] We graded each domain as having 'low', 'high' or 'unclear' risk of bias and conflicts not due to assessor error were resolved by consensus (IML and GSM). If there was evidence of a large risk of bias the findings were interpreted cautiously. The assessment of risk of bias was displayed in a 'risk of bias' graphs (Figure 2 and Table S3). To aid interpretation, in each forest plot presented in the results section, we included the summary of the risk of bias in each study involved.

Measures of treatment effect

All physiological outcome measurements were presented as continuous data across included studies. For selected outcomes, we extracted group means for change from baseline to end of intervention and immediately post-intervention values with the corresponding standard deviations (SD) and the number of participants assessed for each outcome per group. Where standard errors (SE), confidence intervals (CI), or t-values were provided instead of SD, we used the RevMan 5.3 calculator to convert them to SD.

For studies using the same scale to measure a continuous outcome, we calculated mean differences (MD) and 95% CI using change from baseline to end of intervention values, or where not available, the immediate post-intervention values were used. Only a limited number of studies provided change from baseline values, therefore, analyses combined change and post-intervention values. If different scales were used to measure the same continuous outcome across studies, we calculated a standardised mean difference (SMD) and 95% CI. For SMD analyses, change and post-intervention values cannot be combined, and therefore, we combined only

change or post-intervention values depending on whichever was reported most. Where possible we also interpreted the results based on important clinically meaningful effect for outcomes [e.g., 5% loss in body mass [65] and 3.5 ml/kg/min change in VO₂max.[66] We reported qualitatively outcomes where data were not presented in sufficient detail or where data was available from single studies.

Unit of analysis issues

Where trials have more than one applicable swim training group,[34, 52] we combined outcome data from both groups as recommended in the Cochrane Handbook for Systematic Reviews of Interventions.[64] For the main analyses, we compared swim training groups to non-swimming comparison groups for each outcomes.

Assessment of heterogeneity

A random-effects model was selected for all analyses a priori, due to the diversity of populations.[67] Inconsistency of results for each outcome was evaluated using the I² statistic, which describes the percentage of variability in the point estimates that is due to heterogeneity rather than sampling error.[64] We interpreted heterogeneity in accordance with the following recommendations of Higgins et al. (2011):[64]

- 0% to 40%: might not be important;
- 30% to 60%: may represent moderate heterogeneity
- 50% to 90%: may represent substantial heterogeneity
- 75% to 100%: considerable heterogeneity

If there was evidence of at least substantial heterogeneity we explored its source by study population groups. There were insufficient studies available (<10) to

investigate publication bias via visual inspection of planned funnel plots for signs of asymmetry.

Data synthesis

To establish the robustness of an overall effect of swim training across populations, we combined studies that measured the same outcome in random-effects model meta-analyses where data were available from at least two studies.[67] In each analysis, we separated outcome data according to population subgroup, and presented subtotal summary statistics, in addition to the total summary statistic. Where there were insufficient studies to compare swim training to other modes of exercise (e.g. walking, running, etc.), these comparisons were presented in forest plots without meta-analyses, and reported qualitatively.

Sensitivity analysis

Where possible, we conducted a sensitivity analysis to assess the influence of study design on the effect of swim training by removal of quasi-randomised or controlled trials from the analysis. In outcomes where at least substantial statistical heterogeneity ($I^2 \geq 50\%$) was found, we conducted sensitivity analyses to assess the robustness of the review results by removing the most extreme values and those studies that seemed to be estimating a different effect, and explored the contribution of each population to heterogeneity.

3. RESULTS

Description of included studies

Results of the search

The literature search yielded 6,712 potentially relevant articles. Tracking the reference lists of eligible articles and previous relevant reviews led to the inclusion of 11 additional articles. After removal of duplicates, screening of titles and abstracts, and full-texts, we found 28 eligible trials, with 71 studies excluded with reasons (see Figure 1 and Table S2). One study[68] is awaiting assessment because the full-text could not be accessed.

Insert Figure 1. here

Study design and population of included studies

The 28 eligible trials consisted of 16 RCTs, 3 quasi-RCT, and 9 CTs. Eligible studies investigated the effects of swim training on physiological outcomes in healthy children and adolescents (2 CTs[27, 28]), adults (6 studies: 3 RCTs,[29, 31, 36]; 3 CTs,[34, 35, 37]), as well as pregnant women (1 CT[38]) and individuals with obesity (2 RCTs[50, 51]), asthma (9 studies: 8 RCTs,[40, 42-48] 1 CT[41]), down-syndrome (1 RCT[62]), cystic fibrosis (1 CT[49]), hypertension (4 studies: 3 quasi-RCT,[52, 57, 59] 1 CT[56]), osteoarthritis (1 RCT[60]), and perforated tympanic membrane (1 RCT[63]). Five trials had multiple associated publications (13 additional articles).

Intervention and comparison details of included studies

There were a total of 1,479 participants in the eligible studies, with 702 participating in a swim training group and 487 in a non-exercise control (23 studies), 108 in a walking group (4 studies[31, 36, 50, 51]), 13 in a walking in water group (1 study[50]), 35 in a running group (2 studies[29, 36]), 65 in a cycling group (4 studies[29, 36, 51, 60]), 20 in a soccer group (1 study[52]), and 26 in a golf group (1 study[47]). Three of the studies that compared swimming to other modes of exercise,

also had a non-exercise control group.[29, 36, 52] Two of the studies compared two different swim interventions, with one comparing swimming in a chlorinated pool versus an ozone pool[34] and the other comparing moderate-intensity swimming to high-intensity swimming.[52]

Most of the studies were of short-durations, with 21 (75%) of the studies consisting of interventions durations of 15 weeks or less (mode duration=12 weeks in 10 studies; range=4 weeks to 2 years). Two studies had a duration of one year,[28, 41] whereas, one study consisted of a 2-year intervention.[27]

Outcome details of included studies

Fifteen (54%) eligible studies included anthropometric or body composition measures. Sixteen (57%) studies consisted of cardiorespiratory fitness outcomes, with 10 of these studies including either a direct (8 studies[28, 35, 37, 43, 44, 47, 49, 57]) or estimated (3 studies[29, 31, 50]) measure of VO_2 max. Only one study measured VO_2 max directly during pool tethered swimming.[37] Muscular strength measures were included in three studies.[29, 36, 60] Six (22%) studies included a resting cardiovascular measure (e.g., resting heart rate and blood pressure),[31, 51, 52, 57, 58, 60] whereas, two studies only included these measures in the swim group only.[38, 56] Lung function outcomes were reported in eleven (41%) studies.[34, 40-49] Blood biomarker assessments were reported in seven (26%) studies. See table 2 for the characteristics and outcomes of the studies.

Risk of bias of included studies

A summary of risk of bias in each study is presented in Figure 2 (see also a summary of the risk of bias across studies in Table S3). Only five (18%) studies were

at a low risk of selection bias because they reported to have adequately generated their randomised sequence and concealed allocation to the intervention. All included trials included were at high risk for performance bias because, owing to the nature of swimming, it was not possible to blind the trial personnel and participants. Twenty-four (86%) studies were considered to be at a high risk for detection bias because they did not state that outcome assessors were blinded to group assignment. Nine (32%) studies with high participant withdrawal rates were judged to be at high risk of attrition bias.[38, 40, 41, 46-51] We considered 26 (93%) studies to be at an unclear risk for reporting bias, because no study protocol paper or trial registration was available, the information was insufficient to judge this item for those studies. One study[63] was at a low risk of reporting bias, because the published paper included all outcomes that were reported in a prospective trial registration. Another study[60] was considered to be at high risk of reporting bias, because one of the outcomes (C-reactive protein) listed in a trial registration was not included in the published paper. Three (11%) studies were at high risk for selection bias, because groups were insufficiently similar at baseline.[38, 49, 58]

Insert figure 2 here

Effects of intervention

Summary of findings for each pooled analysis are presented in Tables S4-36.

Cardiorespiratory fitness and muscular strength outcomes

A statistically significant and clinically important (≥ 3.5 ml/kg/min) effect on relative VO_2max was found for swimming, compared to control, in an analysis of children/adolescents who were healthy and those with asthma or cystic fibrosis, and

adults who were healthy and those with hypertension (MD 6.42 ml/kg/min, 95% CI 4.34 to 8.50, $I^2=60\%$, 8 studies, 178 participants) (see Figure 3). In a sensitivity analysis, the removal of the two most extreme values[29, 57] reduced the heterogeneity to 0% and maintained the overall significant effect. The effect was also robust with the inclusion of only RCTs in the analysis (MD 3.00 ml/kg/min, 95% CI 0.21 to 5.79, $I^2=76\%$, 3 studies, 55 participants).

Insert figure 3 here

In the first of two possible subgroup analyses, post-intervention relative VO_2 max values were significantly higher after swim training versus control in children/adolescents with asthma (MD 9.67 ml/kg/min, 95% CI 5.84 to 13.51, $I^2=0\%$, 2 studies, 32 participants). Similarly, swim training had a significant effect on relative VO_2 max compared to control in healthy adults (MD 5.87 ml/kg/min, 95% CI 2.93 to 8.81, $I^2=76\%$, 3 studies, 77 participants), compared to control. Removal of the most extreme value [29] in this analysis reduced heterogeneity to 0% and the effect was maintained, whereas, analysis by RCT only was not possible due to the availability of only one RCT. No significant differences were found on VO_2 max for swimming compared to running in a pooled analysis of healthy adults, or single studies comparing swimming to golfing in children/adolescents with asthma,[47] and cycling in healthy adults.[29] One study found superior effects on VO_2 max for six months of walking compared to swimming.[31]

A small but statistically significant effect on post-intervention maximal minute ventilation values was found for swimming vs. controls in an analysis combining data from children/adolescents who were healthy or asthmatic, and healthy adults (SMD 0.99, 95% CI 0.06 to 1.92, $I^2=60\%$, 3 studies, 58 participants). No significant overall

or subgroup effects of swimming, compared to controls, were observed for any other maximal exercise variable. A pooled analysis of seven studies revealed a significantly higher immediately post-intervention submaximal exercise performance compared to controls (SMD 0.64, 95% CI 0.14 to 1.13, $I^2=61\%$, 208 participants). An analysis of only RCTs revealed a significantly greater workload at lactate/ventilatory threshold intensity in children/adolescents with asthma (SMD 1.40, 95% CI 0.56 to 2.25, $I^2=38\%$, 3 studies, 48 participants).

A significant improvement in exercise time during graded exercise testing was found for swimming compared to controls in a pooled analysis of two CTs involving children/adolescents with cystic fibrosis and healthy adults (MD 4.27 mins, 95% CI 2.11 to 6.42, $I^2=0\%$, 50 participants). One study each reported that swimming significantly improved distance covered during Yo-Yo intermittent exercise test compared controls in adults with hypertension,[52] and during a 6-min walk test compared to a walk group in healthy women. No significant differences in post-intervention peak quadriceps torque values were found between swimming and control, walking and running groups of healthy adults, and cycling in adults with osteoarthritis.[29, 36, 60]

Resting cardiovascular and vascular function outcomes

Pooled analysis of resting heart rate, and resting systolic, diastolic, and mean arterial blood pressure was possible only for adults with hypertension. No significant effect of swimming compared to control or to walking in analysis involving healthy women or women with obesity, was found for any of these outcomes. Individual studies have found significant effects on resting heart rate for swim training compared to cycling in adults with osteoarthritis,[60] and significant effects in favour of walking versus

swimming for systolic blood pressure and diastolic blood pressure in healthy women.[31]

For vascular responses, studies involving individuals with hypertension have reported significant improvements in carotid artery compliance, flow-mediated dilation, and cardiovagal baroreflex sensitivity,[57] but not in casual forearm vascular resistance,[58] after swimming interventions. Alkatan et al.[60] found that endothelial function improved significantly after swimming but not post-cycling training in adults with osteoarthritis.

Lung function outcomes

Pooled analysis of two RCTs,[45, 46] FEV1% predicted in children/adolescents with asthma was only slightly statistically significantly greater in the swimming group compared to control (SMD 0.97, 95% CI 0.28 to 1.65, $I^2=0\%$, 38 participants). Besides FEV1 % predicted, no significant effects of swimming compared to controls were found for any other lung function measure in combined population analyses or in separate subgroup analysis of children/adolescents with asthma.

In the only study to compare the effects of swimming to other exercise modes on lung function, the swimming group had significant increases in FEV1% predicted compared to a golf group.[47] Compared to controls, studies have reported significant reductions in bronchial hyper-responsiveness in adults with asthma,[40] and in children/adolescents with asthma, improvements in exercise-induced bronchoconstriction,[42] methacholine challenge test performance, and maximal inspiratory and maximal expiratory pressure.[48] Children/adolescents with cystic fibrosis reported a significant improvement in clinical disease state after a swimming intervention vs. controls,[49] whereas, an RCT found that swimming did not improve

respiratory aspects of speech production in individuals with Down syndrome.[62]

Blood biomarker outcomes

Only pooled analysis of studies consisting of adults with hypertension was possible for total cholesterol, LDL-cholesterol, HDL-cholesterol, and triglycerides concentrations,[52, 57, 58] and plasma glucose concentrations[57, 58] only. No significant differences were found between swimming and control groups for any of these blood biomarkers.

Cox and colleagues[31] found that of glucose- or insulin-related outcomes, only insulin area under the curve was significantly higher in a walking group compared to a swimming group immediately post-intervention, but not six months later. Conversely, the authors[31] reported significantly increased total cholesterol and LDL-cholesterol in the walk group compared to the swimming group six months after completion of the intervention, but not immediately post-intervention. With regards to other biomarkers, glycated haemoglobin and interleukin-6 significantly improved after both swimming and cycling in adults with osteoarthritis,[60] whereas, another study found that high-intensity, but not moderate-intensity, swimming improved insulin sensitivity, insulin and expression of adhesion molecules linked with endothelial dysfunction in hypertensive women.[52]. The same study[52] also reported that citrate synthase, 3-hydroxyacyl-CoA dehydrogenase and complex i-v in the deltoid muscle, all significantly increased after both high-intensity and moderate-intensity swimming. No significant changes were observed in any other blood biomarker in the included studies.

Anthropometric and body composition outcomes

No significant effects on body mass or BMI were found for swim training versus control in any of the pooled analyses. Although no data were provided, one study[37] reported no significant changes in body mass in either a swim training or control group. However, another study[51] found significantly greater weight loss in a cycling intervention compared to swimming in women with obesity. In comparisons of exercise modes, the only significant finding was that run training reduced BMI to a greater extent than swimming in an analysis of two RCTs including healthy adults (MD 1.18 kg/m², 95% CI 0.54 to 1.81, I²=0%, 68 participants).

Swim interventions significantly reduced body fat % in an analysis consisting of healthy children/adolescents and adults, and adults with hypertension, compared to controls (MD -1.91%, 95% CI -3.46 to -0.36, I²=22%, 6 studies, 186 participants). Only one of the six studies included in this analysis was an RCT. No significant effects of swimming were observed in any of the subgroup analyses, compared to control or walking in healthy women/women with obesity and run training in healthy adults, or in a single study of swimming versus cycling in adults with osteoarthritis.[60] However, one study[29] found that healthy adults had a significantly greater reduction in body fat % with cycling compared to swimming.

Overall, there was a significant increase in lean mass for swimming versus control in an analysis consisting of healthy children/adolescents and adults, and adults with hypertension (MD 2.26 kg, 95% CI 0.32 to 4.19, I²=81%, 5 studies, 161 participants) (see Figure 4). The removal of the most extreme value,[58] reduced the heterogeneity to 0% and maintained the overall significant effect. Sensitivity analysis by study design was not possible due to a lack of RCTs in the analysis. No effects on lean mass were found for swim training versus control in a subgroup analysis of adults with hypertension, or in single studies compared to walking either on land or

water in women with obesity[50], or cycling in adults with osteoarthritis.[60]

Insert figure 4 here

In pooled analysis of two studies involving 80 individuals with hypertension, post-intervention waist circumference was significantly higher in swimming versus control interventions (MD 4.03 cm, 95% CI 2.59 to 5.49, $I^2=0\%$), but no effects were found for hip circumference values. However, the two studies included in these analyses were quasi-RCTs, and in one study[58] there were waist circumference imbalances at baseline. In regards to other related outcomes, the only significant findings was that arm and calf girths were significantly lower in a swimming group compared to a walking group in one study.[31]

4. DISCUSSION

Summary of main results

To the best of our knowledge, this is the first review synthesising the evidence about the physiological effects of swim training in non-elite and non-trained healthy and NCD populations. A statistically and clinically significant effect on $VO_2\text{max}$ was found for swimming compared to control in pooled analysis of combined populations and separate analyses of children/adolescents with asthma and healthy adults. A small but statistically significant effect of swim training versus control was found for FEV1% predicted in children/adolescents with asthma. Swimming was associated with significant reductions in body fat % and increases in lean mass in combined population's analyses. In adults with hypertension, there was a significant decrease in body fat % and increase in waist circumference with swimming versus control, but no effect on any other cardiovascular, blood biomarker, or anthropometric measure.

Based on limited data, the effects of swimming on all outcomes analysed were similar to other exercise modes, apart from slightly higher BMI after a swimming intervention compared to running in healthy adults.

Overall completeness and applicability of evidence

From a comprehensive search of the three major electronic databases (CENTRAL, EMBASE, and PubMed) and reference lists of eligible studies and relevant reviews we identified 28 studies (1,479 total participants), including 16 RCTs, three quasi-RCTs, and nine CTs. However, limited studies were available for subgroup analyses and most included studies were potentially under-powered due to small sample sizes (median, intervention n=18 and control n=14). Furthermore, no RCTs were available for healthy children/adolescents and those with cystic fibrosis, pregnant women, and individuals with hypertension. Pooling of study data was limited by the broad range of outcomes assessed in studies, which meant many of the outcomes were examined in single studies or populations. Therefore, as a result of few adequately sized studies available in each population for each outcome, it is difficult to generalise the findings of the current review. In particular, blood biomarker and resting cardiovascular results are limited largely to adults with hypertension, and lung function data are predominantly based on children/adolescents with asthma. Therefore, complete evidence of the chronic physiological effects of swimming is absent for many of the populations included in the current review and those that have not yet been studied, such as individuals with arthritis, cancer, coronary heart disease, or type I and II diabetes.

The majority of swimming interventions were short-duration (≥ 12 weeks), with only seven (25%) studies consisting of interventions at least six months duration.

Therefore, the long-term effects of swim training are not well known. Furthermore, the practicality of the interventions in the included studies varied from a more realistic 1-3 sessions per week (20 studies) to swim training programmes of sixty minutes daily[51] or six 30-minute sessions a week[42] that would be more difficult to follow and adhere to outside a study environment.

Quality of the evidence

Most studies were judged at high risk of selection bias, performance bias, and detection bias. Almost a third of the studies at a high risk of attrition bias, and all but two trials were at an unclear risk of reporting bias. In addition, there was also evidence moderate to considerable heterogeneity ($I^2=30-100\%$) in many of the comparisons; however, most of this inconsistency was explained by the study population and removal of the most extreme values, in addition to study design, in the few instances an RCT only analysis could be performed. From the fifteen (54%) studies reported adherence data, adherence to the swimming interventions was generally good (range=76-99%). Most studies had acceptable attrition rates, although nine (32%) studies had particularly high participant withdrawal rates. Therefore, at least in the studies that report these data, adherence and attrition rates in swimming interventions appear to be comparable to other exercise modes.

Potential biases in the review process

In spite of our comprehensive search, it is possible that we may have missed eligible studies. A relatively high number (n=11) of studies were identified through searching the reference lists of eligible studies and relevant reviews, perhaps due to inadequate cataloguing of swimming studies (older studies in particular) in these databases. Due to a lack of adequate study numbers we could not perform

publication bias analysis. Although we set no language restrictions, we included only full publications which may contribute to publication bias. However, unpublished or studies only published in abstract form tend to be of poor methodological quality and have not undergone peer-review.[69, 70] Therefore, it is unclear whether the addition of unpublished studies would have influenced the findings of this current review without adding considerable risk of bias.

Agreements and disagreements with other studies or reviews

To the best of our knowledge, the current review is the only study to systematically review and pool data from swim training studies from all available populations. In the most recent and comprehensive systematic review and meta-analysis of the effects of swimming on lung function of children/adolescents with asthma, Beggs et al.[21] also found significant effects on FEV1%predicted with swimming compared to controls. However, unlike Beggs et al.[21] we found no significant effect on FEV1. The probable reason for this discrepancy is the inclusion of data from a conference abstract[71] not included in the current review.

5. CONCLUSIONS

In pooled analysis of combined populations and various subgroup analyses, swimming had significant favourable effects on VO_2max , body fat % and lean mass, compared to control. Swimming also led to small but significant improvements in FEV1 % predicted in children/adolescents with asthma, and significant reductions in body fat % but increases in waist circumference in adults with hypertension. Based on meta-analysis of limited data, there were no differences between the effects of swimming compared to walking, running, or cycling in any of the comparisons made, except for slightly higher post-intervention BMI values with swim versus run training.

However, the findings presented must be interpreted with caution considering the dearth of RCT evidence for the populations included in the review, risk of bias, and evidence of heterogeneity across comparisons. Therefore, future well-designed and reported RCTs are required to establish the efficacy and effectiveness of swim training on physiological outcomes in various populations including children and adolescents, sedentary adults, older adults, and individuals with non-communicable diseases.

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