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Effects of Low Volume, High-Intensity Training on Performance in Competitive Swimmers: A Systematic Review

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ABSTRACT

The purpose of this systematic review was to examine the extent and quality of the current research literature in order to determine the effects of low volume, high intensity training (HIT) on physiological performance and swimming performance in competitive swimmers.

The methodology followed the PRISMA-P protocol. A search of relevant databases and conference proceedings was performed until December 2015. The inclusion criteria was: a) competitive swimmers, b) ≥ 4 weeks HIT intervention, c) comparison group had to involve a higher training volume, d) outcome measures of physiological and swimming performance, e) all experimental study designs. Quality assessment was performed using the Quality Index checklist.

Results indicate that of the 538 studies retrieved, 7 studies met the inclusion criteria. Six out of the 7 studies found that a HIT intervention resulted in significant improvements in physiological performance. Four of the 7 studies found that HIT resulted in significant improvements in swimming performance, whilst none of the 7 studies resulted in a reduction in physiological or swimming performance.

Despite the positive findings of this review, the short study duration is a limitation to a number of the studies. The current evidence on the effects of HIT on performance is promising however it is difficult to draw accurate conclusions until further research has been conducted.

INTRODUCTION

Swimming has been part of the Olympic programme since the establishment of the first modern Olympic Games in 1896. Over this time the sport has progressed to become one of the largest Olympic sports with 32 pool events ranging in distance from 50 to 1500 meters. The Gold Medal winning times at the London 2012 Olympics ranged in duration from 21.34 seconds for the 50 m event to approximately 14 minutes 31.02 seconds for the 1500 m event. Twenty six out of thirty two (81%) Olympic level swimming events are competed over a race distance of 200 m or less, for a typical duration of less than 2 minutes 20 seconds.

Swimming coaches are widely acknowledged to place a strong emphasis on developing a swimmer's aerobic energy system throughout their career through the use of low intensity aerobic training, this is a common training practice across all age cohorts and swimming events (43, 69). Greyson et al. (23) suggest that developing the aerobic energy system in swimmers is crucial in order to improve recovery from high-intensity training sets and competition, to maximise the development of the diaphragm and thorax during maturation and to target the optimal window for aerobic development as proposed in the Long Term Athlete Development (LTAD) model (4).

Swimming coaches typically prescribe low intensity aerobic training in large quantities with the aim of enhancing swimming performance, this is commonly referred to as high volume training (HVT). The relevance of HVT to the physiological requirements of many swimming events has been questioned in the scientific literature (3, 10, 11, 36, 56) as 81% of Olympic level events are competed over 200 m or less, for a typical duration of less than 2 minutes 20 seconds. This issue is a long standing topic of discussion among swimming coaches (22, 57, 64-66), and has been referred to as the "Quality vs Quantity debate" (44, 58). On the quality side of the debate there is the suggestion that the focus of the swimming program should be on low volume training at high intensities, whereas the quantity side suggest that high volume training at lower intensities will enhance swimming performance (44, 58). The recent success of competitive swimmers who train using the Ultra-Short Race-Pace Training (USRPT) method has further fuelled this debate (5, 7, 55, 67). USRPT is defined as high intensity swimming in sets that match the best achieved velocities of individuals' races and consists of a high number of repetitions over short distances with brief rests, generally no longer than 20 seconds (54).

To date, there are no peer-reviewed studies investigating the USRPT training method. The definition of USRPT would classify it as a variation of high-intensity training (HIT) which is defined as repeated bouts of high intensity exercise from maximal lactate steady state to supramaximal exercise intensity, interspersed with recovery periods of low intensities or complete rest (24). In recent years, HIT has become a training methodology that is receiving an increasing amount of investigation as it may allow for a reduction in the overall training distance/time (volume), through an increase in training intensity (39). HIT interventions have been performed in a large variety of sporting events such as rowing (2, 14, 29), middle to long distance running (16, 19, 28), cycling (12, 40, 53, 68), tennis (20) and soccer (15, 18, 61, 62). Sports that are characterised by performing HVT such as cycling, long distance running, rowing and swimming have been found to benefit from HIT interventions (38).

A reduction in training volume through implementing a HIT intervention could potentially have many beneficial effects on the overall health and longevity of competitive swimmers. An excessive focus on HVT has been linked to an increased risk of shoulder injury (42, 50, 59) and overtraining syndrome (26, 52) in competitive swimmers. In addition, high volumes of training from a young age have been suggested to increase risk of early specialisation (30, 45, 47, 48), therefore training methods that may allow for a reduction in training volume are of interest. A sound scientific evidence base for the adoption of this traditional HVT approach to competitive swimmers remains equivocal. Previous systematic reviews have investigated swimming energetics in elite swimmers (3, 9, 10) however a detailed review of the current research involving HIT interventions in competitive swimmers is lacking. The purpose of this systematic review was to examine the extent and quality of the current research literature in order to determine the effects of HIT on physiological performance and swimming performance in competitive swimmers.

METHODS

Experimental Approach to the Problem

The methodology outlined in the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA-P) document was used in this systematic review (60). In accordance with the guidelines outlined in the PRISMA-P document, the systematic review was registered with the International Prospective Register of Systematic Reviews (PROSPERO) on 18th December 2015 and was last updated on the 2nd March 2016 (registration number CRD42015030049). The structure of this systematic review involved the following 5 stages.

Stage 1: A comprehensive search of the MEDLINE, SPORTDiscus, ScienceDirect and PubMed databases was conducted on the 16th December 2015. The health sciences university librarian assisted in the development of the specific search strategy. The following search strategy was used swim* AND (Comp* OR youth OR young OR elite OR national OR regional OR international OR master) AND (intensity OR high intensity training OR reduc* volume OR low volume) NOT (rat OR mouse OR mice OR fish). The search was limited to the English language, human subjects and studies published after 1970. In addition to database searching, manual searches were performed among the references from the Biomechanics and Medicine in Swimming Conference (volume 1, 1970 to volume 12, 2014) and the Journal of Swimming Research. Prominent authors in the subject area were also contacted in order to locate any additional relevant studies and manual searches were performed among the reference lists of the identified studies.

Stage 2: Studies were eligible if they met the inclusion criteria outlined in Table 1. Competitive swimmers were defined as male or females, ≥10 year's old, training ≥3 days per week for ≥3 years and competing at a minimum of regional level. The outcome measures of physiological performance included peak or maximal rate of oxygen consumption (VO_{2peak} or VO_{2max}), sub-maximal lactate indices (Lac_{submax} - velocity at blood lactate concentrations of 2 $mmol \cdot l^{-1}$ and 4 $mmol \cdot l^{-1}$) and peak lactate indices (Lac_{peak} - peak rate of lactate accumulation post exercise). The outcome measure of swimming performance was defined as a maximal time trial (TTP) or competitive performance (CP) over any distance. The lead author (FJN) performed a detailed investigation during the planning stage of the review to ensure that the selected outcomes were relevant.

TABLE 1: INCLUSION CRITERIA

Stage 3: The first stage of screening the studies was conducted by two reviewers (FJN and EB) who independently screened the literature titles and abstracts before comparing results. The second stage involved the independent reviewers (FJN and EB) retrieving and screening full text studies, the results were then compared to determine inclusion in the systematic review. Once a final decision had been reached through consensus, the selected studies were included for further analysis in the systematic review. The PRISMA flow chart of the study selection process is summarised in Figure 1.

***FIGURE 1: PRISMA FLOW CHART ***

Stage 4: Quality assessment of the 7 studies that met the inclusion criteria was performed using the Quality Index checklist (QI) proposed by Downs and Black (13). The QI has been shown to be a valid and reliable tool for assessing the methodological quality of both randomised controlled trials and non-randomised controlled studies (13). The QI consists of 27 items that are divided into 5 subscales: reporting (10 items), external validity (3 items), internal validity – bias (7 items), internal validity – confounding (6 items) and power (1 item). The QI has a maximum score of 32 points with each item scoring 0 or 1, except for a 2 point score for describing the distribution of principle confounders, and a 5 point score for a sufficient power calculation. Two independent reviewers (FJN and EB) evaluated each of the 7 studies using the QI. Consensus was achieved on scores given to the 7 studies. A third reviewer was not needed to resolve differences in scores and the Kappa value for all 7 studies was 1.0 (perfect agreement).

Stage 5: The 7 selected studies were not suitable for quantitative synthesis (meta-analysis) due to a lack of homogeneity in terms of study design and data analysis. As a result, a qualitative synthesis was used to summarise and explain the characteristics and findings of the included studies. The format used for the qualitative synthesis included information about the study citation, description of participants (demographics, competitive level, training history), description of intervention (duration, intervention, comparison group), performance outcome measures and results. Two independent reviewers (FJN and EB) manually extracted the article data using tables created on Microsoft Excel™ and results were compared. Authors of included articles were contacted in the absence of the required information.

RESULTS

The QI was selected due to the absence of a validated quality assessment tool for assessing the methodological quality of sports performance studies. The QI score of the 7 studies had a mean of 16.1 points (range: 7 to 22) out of a maximum of 32 possible points (Table 2). Across the 7 studies, the strengths were reporting and internal validity - bias. The weaknesses were external validity, internal validity - confounding and power. None of the studies provided a power calculation therefore the power item received 0 out of 5 in all studies. ***TABLE 2: QUALITY INDEX CHECKLIST***

Seven studies investigated the effects of a HIT intervention on physiological performance and swimming performance in youth swimmers (17, 63), elite swimmers (34), university swimmers (27, 33, 70) and master swimmers (51). Six out of the 7 studies found that a HIT intervention resulted in significant improvements to physiological performance, both aerobic (17, 27, 33, 51, 63, 70) and anaerobic (63, 70). Four of the 7 studies found that HIT resulted in significant improvements to swimming performance, both time trial performance (TTP) and competitive performance (CP) in events from 50 to 2000 m (33, 51, 63, 70). None of the 7 studies resulted in a reduction in physiological or swimming performance following a HIT intervention.

Sperlich et al. (63) scored 22/32 on the QI which was the highest score received out of the 7 studies. Sperlich et al. (63) compared a HIT and HVT intervention during a 5 week randomised cross-over study involving 26 youth swimmers. The HIT group experienced a 20.1% increase in Lac_{peak} ($p < 0.01$, effect size = 0.43) whereas the HVT group experienced a 30.1% decrease in Lac_{peak} ($p < 0.01$, effect size = 0.51). This increase in Lac_{peak} in the HIT group may lead to a greater contribution of anaerobic pathways therefore increasing power production while sprinting. In addition, Sperlich et al. (63) found significant increases in cycling VO_{2peak} for the HIT group (+10.2%; effect size = 0.57) and HVT group (+8.5%; effect size = 0.46; $p < 0.05$). Swimming performance was also found to significantly improve during 50 and 100 m CP (+14.8%; $p < 0.01$; effect size = 0.48) and 2000 m TTP (+2.8%; $p = 0.04$; effect size = 0.17) for the HIT group. The authors suggested that the 20.1% increase in Lac_{peak} may have influenced the 14.8% increase in 50 and 100 m CP for the HIT group. However, no significant changes were found to 100 m TTP following both interventions ($p = 0.20$) and the authors provided no reasons as to why this may have occurred. Despite this, the positive findings of the study indicate that a HIT intervention consisting of an average weekly training volume of 5.5 km was a more effective swimming training strategy for youth swimmers than a HVT intervention consisting of an average weekly training volume of 11.9 km.

A similar study by Faude et al. (17) scored 19/32 on the QI and compared a HIT and HVT intervention during a 4 week randomised cross-over study involving 10 youth swimmers. The findings indicated that there was a significant increase in Lac_{submax} (velocity at blood lactate concentrations of 4 $mmol \cdot l^{-1}$) in both the HIT and HVT group ($p = 0.01$), which indicates an improvement in aerobic endurance capacity in the participants. However there was no significant improvement in 100 and 400 m swimming performance for both groups. The HIT intervention comprised of 81.2 ± 7.4 km total training volume performed over 4 weeks and the HVT intervention comprised of 167.8 ± 23.7 km. Therefore the HIT group performed around 50% less training volume but had a similar training effect.

Kilen et al. (34) investigated the effects of a HIT intervention during a 12 week randomised controlled study involving 41 elite swimmers. This was the only eligible study that involved national level elite swimmers and had the second highest QI score of 20/32. The findings indicated that the HIT intervention and control group's training resulted in no significant improvements to physiological performance (swimming VO_{2max}) or swimming performance (100 and 200 m). The authors suggested that the swimmers had been performing HIT as part of their normal training program for a number of years and an upper limit may exist to the amount of HIT that can be applied and still yield further physiological adaptation. Despite this, the HIT intervention involved 50% less training volume per week (17.7 km) when compared to the control group who performed 35.3 km per week. Therefore the HIT intervention was as successful as the control group's training despite the 50% reduction in training volume per week.

Kame, Pendergast and Termin (33) investigated the effects of a HIT intervention during a 1 year controlled longitudinal study involving 17 university swimmers. The QI score for the study was 7/32, with the study scoring poorly on all 5 QI subscales. The HIT intervention resulted in a 20% increase in tethered swimming VO_{2max} measured from pre-season to post-season (3.12 ± 0.11 to 3.91 ± 0.1 L/min; $p = 0.000$). Improvements in 50 to 1650 yard CP were greater than the improvements during the previous HVT season that was used as a control (2.6 ± 0.5% and 2.2 ± 0.7% respectively), however insufficient data was provided in the study to support this as a significant finding.

A similar study by Termin and Pendergast (70) scored 12/32 on the QI and investigated the effects of a HIT intervention during a 4 year uncontrolled longitudinal study involving 22 university swimmers. The HIT intervention resulted in a 27% increase in Lac_{peak} during the first year ($p \leq 0.05$), however Lac_{peak} was not found to significantly increase in year 2, 3 and 4. In addition, there was a 48% increase in swimming VO_{2max} (3.28 ± 0.12 to 4.86 ± 0.63 L/min), this was divided into increases of 20%, 9%, 8% and 5% from year 1 to year 4, respectively. The observed increases in physiological performance during the 4 year period were reflected in significant improvements to competitive performance. There was a 10% improvement in 100 yard (91.44m) CP and an 8.3% improvement in 200 yard (182.88 m) CP over a 4 year period. The percentage improvements for the 100 yard (91.44 m) CP were 2, 4, 2 and 4%, for year 1 to 4 respectively. The percentage improvements for the 200 yard (182.88 m) CP were 1.9, 3.1, 2 and 1.3%, for year 1 to 4 respectively.

In addition, Houston et al. (27) investigated the effects of a HIT and HVT intervention during a 6.5 week non-randomised controlled study involving 10 university swimmers. The QI score for the study was 15/32. The findings indicated that there was significant increases in treadmill running VO_{2max} for the HIT group (+10.5%) and HVT group (11.1%; $p < 0.05$), however there was no significant increases in tethered swimming VO_{2max} for both groups and the authors suggested that this finding was unexpected. There were no significant improvements in swimming performance for both groups.

Pugliese et al. (51) scored 18/32 on the QI and investigated the effects of a HIT and HVT intervention during a 6 week interrupted time-series study involving 10 masters swimmers. The HIT intervention resulted in a 12.4 ± 5.3% increase in Lac_{submax} (velocity at blood lactate concentrations of 4 $mmol \cdot l^{-1}$) ($p = 0.004$) and 100 m TTP (+1.2 ± 0.8%; $p = 0.001$). However there was no significant changes in VO_{2peak}, 400 m and 2000 m TTP in the HIT group. In addition, the HVT group significantly improved VO_{2peak} (11.9 ± 4.9%; $p = 0.002$), 400m TTP (+2.8 ± 1.8; $p = 0.002$) and 2000 m TTP (+3.4 ± 2.9%; $p = 0.025$). The authors suggested that the lack of improvements in middle to long distance swimming performance (400 and 2000 m) and VO_{2peak} during the HIT intervention was unexpected. However the authors suggested that the first training intervention (HVT) may have influenced the second intervention (HIT) as only 14 days separated both interventions, therefore this may be a limitation of the study.

TABLE 3: CHARACTERISTICS OF PARTICIPANTS

TABLE 4: DESCRIPTION OF STUDIES

DISCUSSION

The purpose of this systematic review was to examine the extent and quality of the current research literature in order to determine the effects of HIT on physiological performance and swimming performance in competitive swimmers. The 7 eligible studies that were found during this review extended to a wide range of competitive swimmers and included youth swimmers (17, 63), elite swimmers (34), university swimmers (27, 33, 70) and master swimmers (51). The QI score of the 7 studies had a mean of 16.1 points (range: 7 to 22) out of a maximum of 32 possible points. Six out of the 7 studies found that a HIT intervention resulted in significant improvements to physiological performance, both aerobic (17, 27, 33, 51, 63, 70) and anaerobic (63, 70). Four of the 7 studies found that HIT resulted in significant improvements to swimming performance in events from 50 to 2000 m (33, 51, 63, 70). None of the 7 studies resulted in a reduction in physiological or swimming performance following a HIT intervention. Despite these positive findings there are limitations to a number of the studies.

Four studies were short in duration lasting between 4 and 6.5 weeks (17, 27, 51, 63). The four studies involved a 40 – 50% decrease in normal training volume in the HIT group and it is logical to question if the additional rest during the 4 to 6.5 week study period may have influenced results in the HIT group. This may not be dissimilar to the concept of tapering prior to a swimming competition which has been found to enhance swimming performance (49, 71, 72). Tapering is a common practice in the final weeks prior to a major competition and involves reducing training volume with or without increased training intensity. The aim of a swimming taper is to enhance recovery from high training volumes and thus competitive performance. Trinity et al. (71) investigated the effects of a 3 week competitive taper in 24 male elite swimmers that were separated into two groups. The first group reduced training volume from an average of 45,000 m per week to 20,000 m per week over a 3 week period and this resulted in a 4.4% increase in swim performance velocity ($p < 0.05$). The second group reduced training volume from an average of 55,000 m per week to 25,000 m per week over a 3 week period and this resulted in a 4.7% increase in swim performance velocity ($p < 0.05$). Similarly, a second study by Trinity et al. (72) investigated the effects of two different types of 3 week tapers in 7 female university swimmers over 2 seasons. The tapers both involved a reduction in training volume from 45,000 - 55,000 m per week to 20,000 m week in combination with different volumes of HIT. The first taper consisted of HIT for 15 to 20% of the total training load and the second taper consisted of HIT for 30 to 32% of the total training load. The first taper resulted in resulted in a 5.3% improvement in swim performance velocity ($p = 0.005$). The second taper resulted in a 2.7% improvement in swim performance velocity ($p < 0.001$) A reduction in training volume over a tapering period appears to enhance swimming performance therefore the results of short duration HIT interventions should be considered with caution. Two longitudinal studies of 1 year and 4 years duration were conducted but both studies had the lowest QI scores of the review (7/32 and 12/32) due to numerous methodological flaws related to all 5 subscales on the QI (33, 70). It was clear that physiological performance and swimming performance did significantly improve in both studies however due to the lack of an appropriate control group in both studies, it is logical to question if similar or greater improvements to performance could have occurred during a HVT intervention of the same duration.

The exercise modalities used to assess VO_{2peak} and VO_{2max} in two studies are questionable (27, 63). Sperlich et al. (63) used a bicycle ergometer to assess VO_{2peak} which may not entirely reflect swimming specific aerobic capacity and is therefore a limitation to the study. This was acknowledged by the authors as previous pilot testing had been performed through assessing VO_{2peak} in a swimming flume but this proved difficult to implement due to the age and experience of the participants (10.5 ± 1.4 years). Houston et al. (27) used a treadmill to assess VO_{2max} which again may not entirely reflect swimming specific aerobic capacity, however tethered swimming was also used to assess VO_{2max}. The challenges of physiological testing within an aquatic environment and of performing intervention studies that involve altering a coaches training program must be acknowledged while considering these limitations. Despite this, none of the 7 studies resulted in a reduction in physiological or swimming performance following a HIT intervention and many of the studies resulted in a significant improvement to performance. This is an interesting finding and appears to suggest that traditional HVT may not be the only training methodology for competitive swimmers, which has increasingly been suggested by swimming coaches who have had success using HIT swimming programs (7, 22, 57, 64, 67).

Traditional HVT methodologies for competitive swimmers have been investigated and the findings do not appear to provide any strong evidence in support of this approach. Costill et al. (11) investigated the effects of a 6 week period of increased training volume on physiological adaptations and swimming performance in 24 university swimmers. The 6 week period involved a group that trained once per day with an mean training volume of 4950 m per day (short group) and another group that gradually increased the training volume to 9435 m per day, spread over two sessions per day (long group). The results indicated that the additional training volume performed by the long group did not enhance their aerobic or anaerobic capacities over the short group ($p < 0.05$). A similar study by Ryan, Coyle and Quick (56) investigated the effects of increased training volume on Lac_{submax} (velocity at blood lactate concentrations of 4 $mmol \cdot l^{-1}$) during a 5 month study involving 14 elite swimmers. The results indicated that when training volume was increased from 34,000 yards (31,090 m) per week to 54,000 yards (49,378 m) per week during the first month of the study, Lac_{submax} increased by 15% ($p < 0.05$). However further increases in training volume up to a maximum of 72, 000 yards (65,837m) per week over the remaining 4 months of the study, resulted in no significant improvement in Lac_{submax}. The authors concluded that increasing training volume above 54,000 yards (49,378m) per week had no effect on Lac_{submax}.

There are concerns that high volumes of training may increase risk of early specialisation in youth athletes (30, 45, 47, 48). Early specialisation refers to the concept of a child participating in year-round intensive training within a single sport at the exclusion of others (74) and can potentially have many negative consequences such as an increased risk of injury (30, 31, 47); overtraining and early dropout (8, 30, 47); reducing the individual's all round motor skill development (41, 46) and reduced performance later in their athletic career (6, 21). A swimming Long Term Athlete Development (LTAD) model that was previously in use recommended that males aged 9 – 12 and females aged 8 – 11 should be performing 8,000 – 16,000 m over 4-6 pool sessions per week (1). The LTAD model further suggested that males aged 12 – 15 and females aged 11 – 14 should perform 24,000 – 32,000 m over 6 – 12 sessions per week. Similar training practices for youth swimmers are evident in the literature (25, 35). It is highly questionable how youth swimmers could commit to these training recommendations without early specialisation within the sport. Two studies in this systematic review involving youth swimmers found that HIT interventions comprising of 40 – 50% less training volume for a duration of 4–5 weeks significantly enhanced physiological performance and swimming performance (17, 63). Clearly more research is needed in this area due to the risks associated with early specialisation.

Swimming performance has been shown to be determined by a number of different anthropometrical, physiological and biomechanical parameters (32, 37, 73). Biomechanical parameters have been suggested as one of the best determinants of swimming performance (32, 37, 73). Swimming coaches suggest that large amounts of practice are needed to develop swimming technique (23) and this is perhaps one of the incentives for HVT, particularly in youth swimmers who need time to develop their technical capacity. Despite this, investigating the effects of HIT on biomechanical parameters related to swimming technique was outside the scope of this review due to a lack of reporting in a number of the eligible studies (27, 34, 51, 63). In future interventions, biomechanical parameters should be investigated in order to establish the effects of HIT and/or HVT on swimming technique. A particular focus should be placed on investigating the effects of HIT on mature swimmers who already have an established technical capacity. This systematic review should be used as a guideline by swimming coaches and researchers in the design of future HIT interventions. Controlled studies of a longer duration are needed (≥ 12 weeks) that include a definite decrease in training volume while increasing training intensity and assessing any potential effects using outcome measures of physiological, biomechanical and swimming performance.

PRACTICAL APPLICATIONS

Swimming coaches are widely acknowledged to prescribe HVT in order to enhance performance in competitive swimmers across all age cohorts and swimming events. HIT may be an alternative training method. Despite the positive findings of this review, the short study duration is a limitation to a number of the studies. The current evidence on the effects of HIT on performance is promising however it is difficult to draw accurate conclusions until further research has been conducted.

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TABLES

Table 1. Inclusion criteria
• Competitive swimmers. • Intervention consisted of HIT for ≥4 weeks. • Comparison group had to involve a higher training volume (distance or duration) per session. • Outcome measures of physiological performance and swimming performance. • All experimental study designs

Table 2. Quality Index checklist

Sub-scales	Sperlich et al. (62)	Faude at al. (17)	Kilen at al. (34)	Kame, Pendergast and Termin (33)	Termin and Pendergast (69)	Houston et al. (27)	Pugliese et al. (50)
1. Reporting (x/11)	11	10	10	3	7	8	10
2. External Validity (x/3)	1	1	1	0	1	1	0
3. Internal Validity - Bias (x/7)	5	4	5	2	2	4	5
4. Internal Validity - Confounding (x/6)	5	4	4	2	2	2	3
5. Power (x/5)	0	0	0	0	0	0	0
Total Score (x/32)	22	19	20	7	12	15	18

Table 3. Characteristics of participants

Authors	*N*	Gender (M/F)	Age (years ± SD)	Competitive level	Training history
Sperlich et al. (62)	26	13 M/13 F	10.5 ± 1.4	Regional to national youth level	Training ≥4 days per week and competing for ≥3 years in 50 - 100m events.
Faude et al. (17)	10	6 M/4 F	16.6 ± 1.4	Regional to national youth level	Training on average 20 hours per week and competing in 100 - 400m events. Nine out of ten swimmers were ranked in the top 10 or better in the national age group rankings.
Kilen et al. (34)	41	30 M/11 F	20 ± 2.7	Elite senior level	Training ≥5 years for 8 -16 hours per week with an average weekly training volume of 20,000 - 60,000m and competing in 50 - 200m events. Two swimmers specialized in 400m and 800m events.
Kame, Pendergast and Termin (33)	17	17 M/0 F	19.06 ± 0.22	Competitive university level	Division 2 swimmers. Previous season's training consisted of 2 sessions per day covering a total distance of 10,000 – 12,000 yards
Termin and Pendergast (69)	22	22 M/0 F	19.0 ± 0.2	Competitive university level	Division 1 swimmers. Pre-college training volume of 60000 – 80000 yards per week. 100 yard freestyle PB times of 48.66 ± 0.7sec and 200 yard freestyle PB times of 1:50.17 ± 2.72sec.
Houston et al. (27)	10	7 M/3 F	19.8 ± 0.4	Competitive university level	Training 9.4 ± 3.7 years. Only 4 swimmers had trained in the 4 months prior to the study.
Pugliese et al. (50)	10	10 M/0 F	32.3 ± 5.1	Elite masters level	Training 11 ± 4 years on average 3km per day, 3 times per week and competing in 50 - 400m events. Competed at World masters championships.

Table 4. Description of studies

Authors, year	Duration (weeks)	Study design	Intervention group	Control/comparison group	Physiological performance outcome measure(s)	Swimming performance outcome measure(s)	Results
Sperlich et al., 2010	5 weeks	Randomised cross-over study	5 sessions per week 5.5km average TV per week 30 minutes HIT at 92% of PB time 27.4km total TV	5 sessions per week 11.9km average TV per week 60 minutes HVT at 85% of PB time 59.6km total TV	VO_{2peak} during cycling incremental step test Lac_{peak} post 100m TTP	100m and 2000m TTP 50m and 100m CP	Significant improvements in physiological performance and swimming performance
Faude et al., 2008	4 weeks	Randomised cross-over study	6 sessions per week 40% ↓ in TV and 50% ↑ in HIT 79.6 ± 13.7% of training at ≤ 101% IAT and 20.5 ± 6.7% of training at > 101% IAT. 81.2 ± 7.4km total TV	6 sessions per week 30% ↑ in TV 92.9 ± 7.5% of training at ≤ 101% IAT and 7 ± 2.5% of training at >101% IAT 167.8 ± 23.7km total TV	Lac_{submax} during IST Lac_{peak} post IST, post 100m and 400m TTP	100m and 400m TTP	Significant increase in physiological performance (Lac_{submax}) for both groups No significant improvement in swimming performance for both groups

Kilen et al., 2014	12 weeks	Randomised controlled study	5 – 7 sessions per week 17.7km average TV per week 50% ↓ in TV and 100% ↑ in HIT	5 – 7 sessions per week 35.3km average TV per week Regular training schedule	VO_{2max} during IST	100m TTP 200m CP	No significant improvements in physiological performance and swimming performance for both groups
Kame, Pendergast and Termin, 1990	1 year	Controlled longitudinal study	1 session per day 1 hour HIT session 3000 yards per day	2 sessions per day 10,000 - 12,000 yards per day	VO_{2peak} during tethered IST	50, 100, 200, 500, 1000 and 1650yard CP	Significant improvement in physiological performance and swimming performance
Termin and Pendergast, 2000	4 years	Uncontrolled longitudinal study	4 Training Phases Phase 1: 2-3 weeks of low speed swimming Phase 2: 6-7 weeks of aerobic power intervals at 115-129% VO_{2max} Phase 3: 15-16 weeks of anaerobic	No control/comparison group	VO_{2max} during IST	100 and 200 yard CP	Significant improvements in physiological performance and swimming performance

			intervals over 25-50 yards Phase 4: 3 weeks of 25 yard maximal velocity intervals				
Houston et al., 1981	6.5 weeks	Non-randomised controlled study	≥ 4 sessions per week 1650m average TV per session HIT consisted of 23 - 183m intervals with rest durations of 70 - 140% of interval time.	≥ 4 sessions per week 3200m average TV per session MIT consisted of 183 – 457m intervals with rest durations of 5 - 15% of interval time.	VO_{2max} during tethered swimming and treadmill running	23,91 and 457m TTP	Significant improvements in physiological performance in both groups No significant improvements in swimming performance for both groups
Pugliese et al., 2015	6 weeks	Interrupted time-series study	3 sessions per week 50% ↓ in TV 6000m average TV per week	3 sessions per week 30% ↑ in TV 12000m average TV per week	VO_{2peak} during arm ergometer incremental test Lac_{submax} during IST	100, 400 and 2000m TTP	Significant improvement in physiological performance and swimming performance for both groups

*TV = training volume; PB = personal best; VO_{2peak} = peak rate of oxygen consumption; VO_{2max} = maximal rate of oxygen consumption; Lac_{submax} = velocity at blood lactate concentrations of 2 $mmol \cdot l^{-1}$ and 4 $mmol \cdot l^{-1}$; Lac_{peak} = peak rate of lactate accumulation post exercise ; TTP = swimming time trial performance; CP = competitive

swimming performance; IST = incremental swimming test; CON = control group; MIT = moderate intensity training; IAT = individual anaerobic threshold

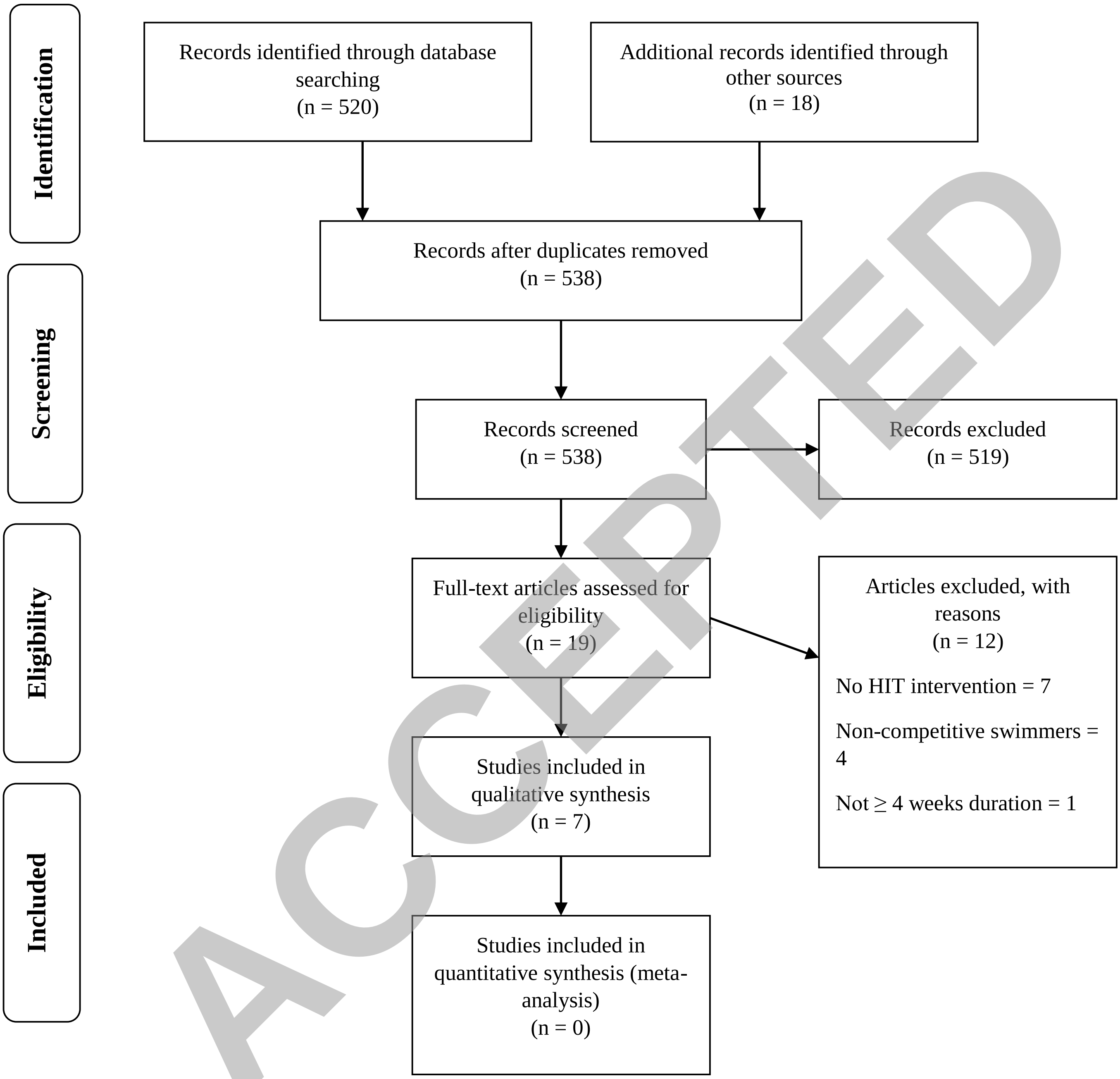

Figure 1. PRISMA Flow Chart