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Review article

A Systematic Review and Meta-Analysis: Biomechanical Evaluation of the Effectiveness of Strength and Conditioning Training Programs on Front Crawl Swimming Performance

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Abstract
The objectives of this systematic review were to summarize and evaluate the effectiveness of strength and conditioning trainings on front crawl swimming, starts and turns performance with relevant biomechanical parameters. Four online databases including PudMed, ESCSOhost, Web of Science and SPORTDiscus were searched according to different combination of keywords. 954 articles were extracted from databases, and ultimately 15 articles were included in this study after removal of duplicate and articles screening according to inclusion and exclusion criteria. Meta-analyses were adopted when appropriate and Egger's regression symmetry was adopted to assess the publication bias and the results were presented with forest plots and funnel plots respectively. Fifteen articles studied the effects of strength and resistance, core, and plyometric trainings. The quality of the investigation was assessed by the checklist developed by Downs and Black. Most of the investigations found out that training programs were beneficial to front crawl sprinting swimming performance, stroke biomechanics, force, and muscle strength. First, strength and resistance trainings and core trainings were effective on sprinting performance enhancement. Second, resistance trainings were found to have positive effects on stroke rate. Plyometric trainings were beneficial to start performance, while there was no sufficient evidence for confirming the positive improvement on turn biomechanical, also overall swimming performance, after weeks of plyometric trainings. Strength and Conditioning trainings are suggested to implement in regular training regime regarding to the positive effects on swimming performance, including starts, turns and front crawl swim, and relevant biomechanical parameters, instead of swimming training only. Further research with higher quality is recommended to conduct and more investigations on the training effects to other stroke styles are also suggested.

Key words: Swimming biomechanics, swimmers, stroke rate, stroke length, sprint swimming, muscle strength.

Introduction

Swimming is a highly competitive sport and only a small difference in time can influence the results in matches, especially in sprinting events. Only 0.01s and 0.02s differences existed between the first two places in Men and Women 50m Front Crawl (FC) events in Rio 2016 Olympic games respectively (Committee). Swimming has 4 different strokes with overall time of a match based upon Start, Stroking, and Turn. Previous studies have reported improvement in these three phases can improve the overall swimming performance (Bishop et al., 2013; Cossor and Mason, 2001; Craig et al., 1985; Jesus et al., 2011).

Different investigations have conducted to find what factors were contributed to swimming performance. Correlation studies were showed that muscle strength is an important contributing factor for enhancing swimmers' performance in stroking phase (Hawley et al., 1992; Keiner et al., 2019; Sharp and Troup, 1982; Tanaka et al., 1993). Also, evidence showed muscle strength is highly correlated with swimming velocity too, the stronger the muscle strength, the faster the swimming velocity. This relationship is especially stronger between upper limb strength and swim performance (Pérez-Olea et al., 2018; Smith et al., 2002), as swimmers are required to generate powerful propulsive action for each stroke (Sharp and Troup, 1982). In addition to understanding the importance of muscle strength, there was research investigated on the contribution of stroke biomechanics in swimming performance. For example, it has been reported that stroke length (SL) is a good predictor for swimming velocity and associated with performance, while stroke rate (SR) is also associated with sprinting performance (Craig et al., 1985; Smith et al., 2002; Wakayoshi et al., 1995). Along with this, it has also been reported that a higher SR and/or maintenance or lengthening of SL, swimmers would have better performance and generate higher propulsive force (Chollet et al., 1997; Hellard et al., 2008; Ribeiro et al., 2013).

Apart from swimming performance, starts and turns performance also contributed to the swimming performance. It has been reported that start time contributes near 30% of the swimming time in sprinting events (Bishop et al., 2013; Cossor and Mason, 2001; Lyttle and Benjanuvatra, 2005) and recently, research found that combined start and turn performance, they contributed 30% to the final race time (Morais et al., 2019). For performing explosive starts, these are also imperative in competitions as start is also crucial in overall performance (Vantorre et al., 2014). Reaction time might also be an important factor in the final swimming time, normal reaction time for a start would be around 0.70s (Everett, 2015) and with a faster reaction time performed during start might help to enhance performance (Da Silva et al., 2020; Ruschel et al., 2007). Moreover, effective block start requires high muscle strength, mostly from lower limbs (Lyttle and Ostrowski, 1994; West et al., 2011), in order to produce high impulse on the starting blocks. A higher impulse will lead to a higher take-off velocity, and forceful leg propulsion to cover longer distance in flight phases. Researchers reported there was strong

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correlation between lower body strength with start performance as measured by start time to 15m in FC swimming ($r = -0.66$ to -0.74) (West et al., 2011).

In addition, turn is also an imperative part in competitions, as effective turn can minimize overall swimming time (Pereira et al., 2008). Furthermore, an effective turn will allow swimmer to generate higher impulse while pushing off the wall that leads to a longer distance before coming out from the water surface (Jones et al., 2018). Studies revealed there was moderate to high correlation between impulse produced during the wall push-off motion (Takahashi et al., 1983), the swimming time to 6m and with the propulsive velocity exiting the turn (Nicol and Kruger, 1979).

In order to improve and promote the performance of swimming athletes, coaches and trainers will explore different training methods that includes dry-land and underwater trainings. In recent years, Strength and Conditioning (S&C) training programs have become more popular. S&C trainings include strength training with added weight in nearly maximal effort, resistance training like using drag suits, and plyometric training with different jumping movements, have attracted their attention for implementing in swimming practices. Numerous studies have explored the effects of programs on sports performance with encouraging results reported, for example, promoting sports performance in running, soccer and rugby (Balsalobre-Fernández et al., 2016; Sander et al., 2013; Speranza et al., 2016; Styles et al., 2016) and preventing sports injuries (Faigenbaum and Myer, 2010; Hewett et al., 1999). Given the positive results of S&C programs contributing to performance improvements in other sports, S&C training programs have been implemented into swimming training and aimed to help swimmers achieving better results. Different studies have reported there were beneficial effects of S&C programs on swimming performance after weeks of trainings (Crowley et al., 2017; Morouco et al., 2012; Weston et al., 2015). Despite this research, the effects of S&C programs on swim performance and related biomechanical parameters are still not comprehensive enough. Furthermore, a limitation of the body of research is that there has been a focus on the effectiveness of the S&C programs on swimming performance, only one review recently summarize and evaluate the effects on biomechanical aspects in swimming (Amaro et al., 2019), but rarely evaluate together with biomechanics parameters and its effect on swimming performance. Thus, there is a need for providing more evidence-based information, i.e. meta-analysis, regarding the effects of longitudinal S&C trainings on biomechanical parameters of swimming performance, especially on FC swimming performance, as FC is the fastest style among 4 swimming styles, and most competitions were performed in FC style, thus more investigations put their focus in FC instead of other stroke styles. Along with this, it is important to conduct a systematic review and meta-analysis on the effects of S&C programs on biomechanical parameters to provide comprehensive information to relevant parties. Therefore, the purpose of this study was to perform a systematic review and meta-analysis to summarize and quantify the effects of longitudinal S&C trainings on FC swimming, starts and turns performance with relevant biomechanical parameters. Secondly, to evaluate the effectiveness of S&C training programs on swim performance from biomechanical aspect.

Methods

Database search

This systematic review followed the guidelines of PRISMA for the screening process (Moher et al., 2009). Four databases were searched, including PudMed, ESCSOhost, SPORTDiscus and Web of Science, and the search conducted in October 2020. Different combinations of keywords were used for searching the articles published from January 1985 to October 2020 (Table 1). Besides, citations and references list tracking were processed manually to extract more relevant studies.

Table 1. Keywords Search Strategy. 4 databases were searched to identified eligible articles by different keywords.

Database	Keywords
PudMed **ESCSOhost** **SPORTDiscus** **Web of Science**	1. Motion analysis OR Biomechanical analysis OR Kinematics OR Kinetics AND 2. Swimming OR Swimmer OR Swim AND 3. Strength and Conditioning training OR Plyometric training OR Resistance training OR Core training OR Power training AND 4. Performance

Selection process

After the extraction of articles from databases, 2 reviewers were invited to proceed the screening procedure according to the guidelines of PICO to set the inclusion and exclusion criteria and defining the research question, which PICO stands for Patient/Population, Interventions, Comparison and Outcomes respectively. First, titles and abstracts were screened and after that, full-text screening procedure was executed for those were eligible to be included by the same reviewers. The inclusion and exclusion criteria were as the follows:

Characteristics of participants (P – Population)

Recruited participants should be swimmers that were regularly trained, or with competitive, regional, national, and international levels. Articles recruited triathletes, water-polo athletes, synchronized swimming athletes or paraplegic swimmers as participants were excluded in our study.

Characteristics of interventions (I – Interventions)

Studies must implement S&C training programs as interventions, which conducted over 3 weeks or above (longitudinal interventions) were included, with consideration of the outcome's significance and outcomes would be measurable. If studies were measuring the acute effects of interventions or did not implement any S&C trainings during intervention period would be excluded. S&C trainings included strength and resistance trainings, plyometric trainings, and core trainings. Strength trainings involve training to improve muscle strength and endurance of athletes as the same as resistance training. While resistance trainings in swimming will be more specific with different instrument or equipment, for example drag suit, tethered swimming, and water parachute. For plyometric trainings, these involve different jumping trainings that require athletes perform with maximum force in a very short period of time, and core trainings requires athletes engages abdominal and back muscles through different exercises.

Characteristics of studies (C – Comparison)

Longitudinal intervention studies, either randomized or non-randomized studies, were eligible to be included, pre and post comparison within the experimental groups would also be accepted. But cross-sectional studies, systematic reviews, or meta-analyses were excluded. Articles published in peer reviewed journals and written in English were included, however, books, chapters, conference papers or thesis were excluded in this review paper.

Outcomes measurement (O – Outcomes)

Interventions studies should report and measure performance change as outcome measures, either measuring starts, turns or swimming time performance, and should record the change in biomechanical measurements, including kinetics, kinematics factors that relevant to swimming performance. For example, stroke biomechanics including SL, SR, and muscle strength by force or torque measurement. If the study only reported performance as outcome measures without biomechanical parameters, those studies would not be included in this study.

Quality assessment

Quality Assessment checklist developed by Down and Blacks (1998) was adopted in this systematic review (Appendix 1), as there was no a validated quality assessment tool available for evaluating sports performance. This checklist included in total 27 items, with 5 subscales, Reporting (10 items), Internal Validity in Bias (7 items) and Confounding (6 items), External Validity (3 items) and Power (1 item), and higher score represents higher quality of study. Each included article would be appraised with this checklist by 2 appraisers individually, if disagreement was found, a meeting was held to let 2 appraisers discuss until they had same decisions on each item.

Publication bias

Publication bias is referred studies are more likely to be published with statistically significant results in journals, compare with those with non-significant results (Petitti, 1994), which might affect the estimation of the treatment effects (Sun et al., 2018). Publication bias was assessed by using Egger's regression asymmetry test through Comprehensive Meta-Analysis Version 3 software (Biostat, Inc., Englewood, NJ, USA). A p-value smaller than 0.1 (two-tailed test) was indicating the existence of publication bias.

Statistical analysis

Meta-analysis was performed for if more than 3 studies used the same outcome measurements. Results from some eligible studies were extracted to do calculation and then input into review software package - Review Manager Version 5.4 (The Nordic Cochrane Center, Copenhagen, Denmark). Random effects model was adopted in all analyses, as this model assumed the treatment effect can vary across studies (heterogeneity of study), e.g. characteristics of participants, training programs (Riley et al., 2011), while standardized mean differences (SMD) were used in meta-analyses, as different instruments were adopted by different studies (Andrade, 2020) and aimed to summarize the effects of different S&C training programs. If meta-analyses could not be conducted, results were described and analyzed in wordings instead.

Results

One hundred sixty one studies were found after comprehensive search in four databases, and citation and references list checking, 15 articles were eligible to include in this systematic review, and the flow of screening process was shown in Figure 1. The oldest study was published in 2006 (Girold et al., 2006) and the most updated studies were published in 2020 (Born et al., 2020; Karpiński et al., 2020). Among 15 articles, 10 articles investigated the effects on FC swimming (Amaro et al., 2017; Aspenes et al., 2009; Garrido et al., 2010b; Girold et al., 2006; 2007; 2012; Gourgoulis et al., 2019; Morais et al., 2018; Patil et al., 2014; Sadowski et al., 2012), while 4 articles investigated on starts (Bishop et al., 2009; Born et al., 2020; Rebutini et al., 2016; Rejman et al., 2017) and only 1 investigated on swimming, starts and turns performance (Karpiński et al., 2020). The intervention durations were varied, from 3 weeks to 34 weeks, mostly were applied for 6 weeks (Amaro et al., 2017; Born et al., 2020; Karpiński et al., 2020; Patil et al., 2014; Rejman et al., 2017; Sadowski et al., 2012). The characteristics and of all 15 studies were summarized in the Table 2 and Table 3.

Type of trainings

There were 10 articles implemented strength and resistance trainings (Amaro et al., 2017; Aspenes et al., 2009; Born et al., 2020; Garrido et al., 2010b; Girold et al., 2006; 2007; 2012; Gourgoulis et al., 2019; Morais et al., 2018; Sadowski et al., 2012), and 3 studies implemented plyometric trainings (Bishop et al., 2009; Rebutini et al., 2016; Rejman et al., 2017) as interventions respectively and only 2 articles have investigated the effects of core trainings (Karpiński et al., 2020; Patil et al., 2014).

Characteristics of participants

Eight articles recruited subjects from regional level or above (Amaro et al., 2017; Bishop et al., 2009; Born et al., 2020; Girold et al., 2007; 2012; Karpiński et al., 2020, Morais et al., 2018; Rejman et al., 2017), 7 studies recruited those with regular training or competitive swimmers as participants (Aspenes et al., 2009; Garrido et al., 2010b; Girold et al., 2006; Gourgoulis et al., 2019; Patil et al., 2014; Rebutini et al., 2016; Sadowski et al., 2012). The number of recruited subjects were ranged from 9 to 60, in total 351 swimmers were included in this study and the mean age of participant was over 12 years old.

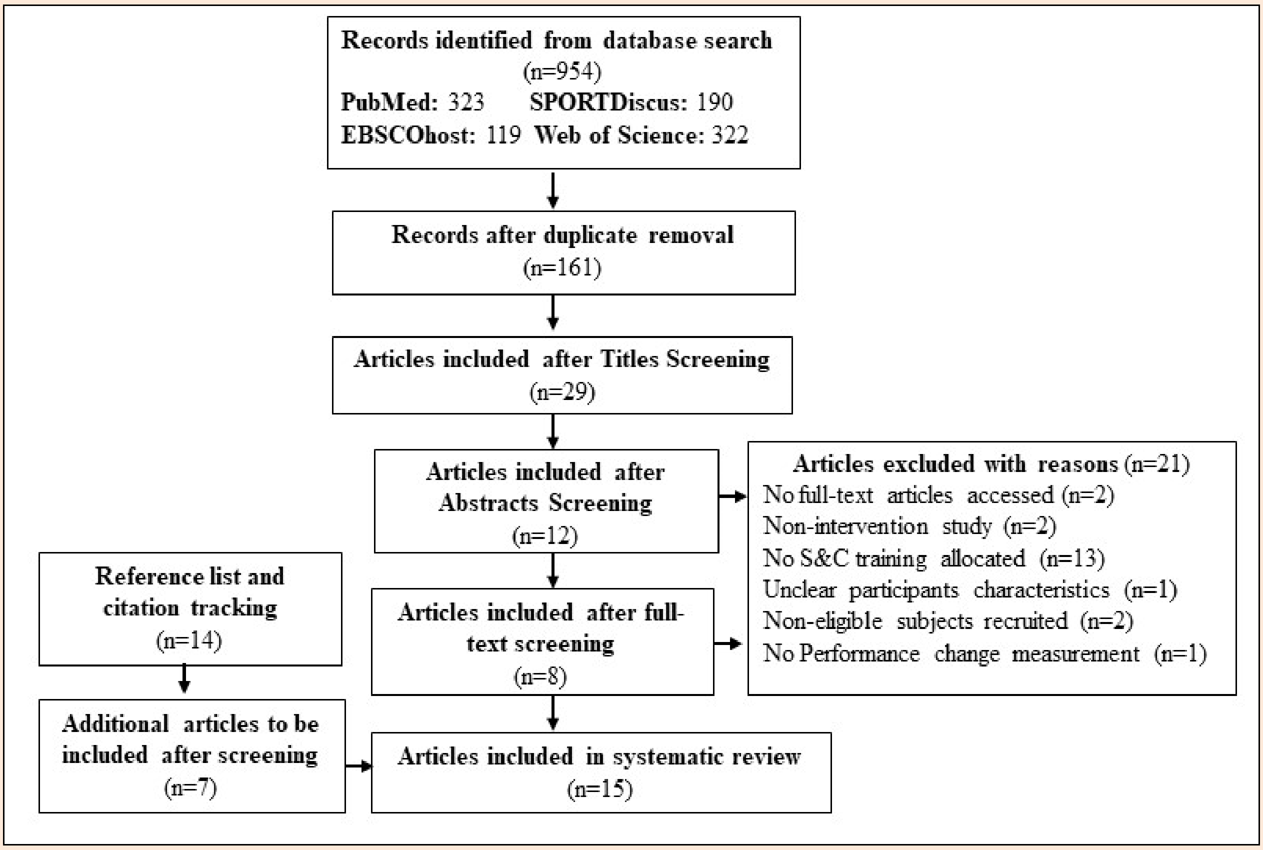

Figure 1. PRISMA flow chart of articles screening procedure.

Quality assessment

The score of Down and Black for 15 included studies was ranged from 4 to 13 out of 27, mean score was 9.2. The highest score was the study investigating plyometric training on start performance (Bishop et al., 2009), while the lowest score was the study evaluating the power training on swimming performance and relevant parameters (Sadowski et al., 2012). Reporting subscale presented with better performance among 5 subscales, mostly reported with detailed information and characteristics of their studies, i.e., study objectives and results of main outcomes, and the interventions and participants characteristics etc. However, no study has reported the lists of principal confounders. Besides, most of the studies showed poor performance in external validity, internal validity – bias and confounding and power subscales. As no study has adopted randomization for sampling during subject recruitment, thus the scores in external validity subscale were relatively low. For the internal validity – bias and confounding subscales, studies did not blind the objectives and outcome measurements, neither to the participants or assessors, which caused a low score profile in bias subscales. Also, most of the studies did not report clearly on the recruitment details, and only few mentioned whether randomized allocation to groups have been done and some have reported the loss to follow up, which further contributed low score profile in confounding subscale. For power subscale, poor performance was found, as only few studies have done the calculation of sufficient number of participants to detect significant differences.

Swimming performance

As mentioned, 11 studies investigated the effectiveness of different types of S&C training programs on the swimming performance (Table 4), all studies investigated FC performance, but no other swimming style performance were evaluated (Amaro et al., 2017; Aspenes et al., 2009; Garrido et al., 2010b; Girold et al., 2006; 2007; 2012; Gourgoulis et al., 2019; Karpiński et al., 2020; Morais et al., 2018; Patil et al., 2014; Sadowski et al., 2012). Most studies showed encouraging results that swimming performance were significantly improved ($p < 0.05$), except Sadowski's study, insignificant improvement was shown in intervention group ($p > 0.05$) (Sadowski et al., 2012). Some studies presented with the effect sizes (ES), which were ranged from trivial to large on swimming performance, mostly were in sprinting events, i.e., 50m FC swim. Only two studies assessed the effects on in middle distance swim (200m and 400m FC swim) and showed significant improvement after weeks of training ($p < 0.05$) (Aspenes et al., 2009, Gourgoulis et al., 2019). Although some studies did not demonstrate significant changes after different S&C trainings, but most of the experimental groups also showed trends of improvement, i.e., faster swimming time or more time improvement than control groups.

Table 2. Characteristics of Included Studies studying swimming performance (n = 11).

Author (Year)	Quality Assessment	Subject Characteristics	Age (Mean±SD)	S&C Training Intervention	Performance Measurements	Outcome Measurements
Karpinski et al (2020)	12	**N=16:** 16M National level	EG: 20.2 ± 1.17 CG: 20.0 ± 1.9	**Core strengthening training (6-week)** EG: Core Strengthening Training CG: Normal Training	**50m FC Swim**	**Stroke Biomechanics** SL & SR
Gourgoulis et al (2019)	9	**N=12:** 12F Regularly trained and Moderate performance level	Overall: 13.08 ± 0.9	**In-water resistance training (11-week)** EG: Resistance training with Water Parachute CG: Normal Training	**50, 100, 200m FC Swim**	**Stroke Biomechanics** SL, SR, Mean Swimming Velocity
Morais et al (2018)	8	**N=27:** 11M, 16F Regional/National Level	Overall: 13.3 ± 0.85	**In-water & dry-land S&C Training (34-week)**	**100m FC Swim**	**Stroke Biomechanics** SL, SF, & SV **Muscle Strength** Throwing Velocity
Amaro et al (2017)	12	**N=21:** 21M National Level	EG1: 12.7 ± 0.8 EG2: 12.7 ± 0.8 CG: 12.6 ± 0.8	**Dry-land S&C training (6-week)** EG1: Sets & Repetitions Training EG2: Explosiveness Training CG: Normal Training	**50m FC Swim**	**Muscle Strength** Vertical Jump Ball Throwing
Patil et al (2014)	11	**N=60:** 38M, 22F Competitive Level	M: 14.7 ± 1.29 F: 13.4 ± 1.50	**Core strengthening training (6-week)** EG: Core Strengthening CG: Normal Swimming Training	**50m FC Swim**	**Stroke Biomechanics** SR, SL, SV **Muscle Strength** Functional Core Muscle Strength
Girold et al (2012)	11	**N=24:** 12M, 12F National Level	Overall: 21.8 ± 3.9	**Dry-land strength or Electrical Stimulation (ES) Training (4-week)** EG1: Strength Training EG2: ES Training CG: Normal Training	**50m FC Swim** (Expressed in Mean Velocity)	**Stroke Biomechanics** SL, SR **Muscle Strength** Extension Peak Torque
Sadowski et al (2012)	4	**N=26:** 26M Regularly Trained	Overall: 14.0 ± 0.5	**Dry-land Power Training (6-week)** EG: Power Training with Ergometer CG: Normal Training	**25m FC Swim** (Expressed in SV)	**Stroke Biomechanics** SF, Distance Per Stroke **Muscle Strength** Isometric Shoulder Strength Test Tethered Swimming Force
Garrido et al (2010)	7	**N=25:** 14M, 11F Competitive Level	Overall: 12.08 ± 0.76 EG: 12.0 ± 0.78 CG: 12.18 ± 0.75	**Combined Strength and Aerobic Training (8-week)** EG: Strength Training CG: Normal Training	**25m, 50m FC Swim** (Expressed in SV)	**Swimming Biomechanics** Active Drag, Drag Coefficient **Muscle Strength** 6RM Bench Press & Leg Extension Tests, CMJ & Ball Throwing

Unit: m: meter. Abbreviations: CG: Control Group; CMJ: Countermovement jump test; EG: Experimental Group; ES: Electrical Stimulation; F: Female FC: Front Crawl (Freestyle); M: Male; RM: Repetition(s); RAS: Resisted & Assisted Training; S&C: Strength and Conditioning; SD: Standard Deviation; SF: Stroke Frequency; SL: Stroke Length; SR: Stroke Rate; SV: Swimming Velocity.

Table 2. Continued …..

Author (Year)	Quality Assessment	Subject Characteristics	Age (Mean±SD)	S&C Training Intervention	Performance Measurements	Outcome Measurements
Aspenes et al (2009)	10	**N=20:** 8M, 12F Regularly Trained	EG: 17.5 ± 2.9 CG: 15.9 ± 1.1	**Combined Strength and Endurance Training (11-week)** EG: Maximal Strength and Endurance Training CG: Normal Training	**50m, 100m, 400m FC Swim**	**Stroke Biomechanics** SL, SR, Maximum SV (**25m sprint) **Muscle Strength** Bilateral Shoulder Extension Measurement Tethered Swimming Force
Girold et al (2007)	8	**N= 21:** 10M, 11F Regional/National Level	Overall: 16.5 ± 3.5	**Dry-land strength training OR resisted & assisted training (RAS) (12-week)** EG1: Strength Training EG2: RAS Training CG: Normal Training	**50m FC Swim**	**Stroke Biomechanics** SL, SR **Muscle Strength** Flexion & Extension Peak Torque
Girold et al (2006)	10	**N=37:** 16M, 21F Competitive Level	Overall: 17.5 ± 3.5	**Resisted or Assisted sprint training (3-week)** EG1: Resisted Training EG2: Assisted Training CG: Normal Training	**100m FC Swim**	**Stroke Biomechanics** SR **Muscle Strength** Flexion & Extension Peak Torque

Unit: m: meter. Abbreviations: CG: Control Group; CMJ: Countermovement jump test; EG: Experimental Group; ES: Electrical Stimulation; F: Female FC: Front Crawl (Freestyle); M: Male; RM: Repetition(s); RAS: Resisted & Assisted Training; S&C: Strength and Conditioning; SD: Standard Deviation; SF: Stroke Frequency; SL: Stroke Length; SR: Stroke Rate; SV: Swimming Velocity.

Table 3. Characteristics of included studies studying starts and turns performance (n=5).

Author (Year)	Quality Assessment	Subject Characteristics	Age (Mean±SD)	S&C Training Intervention	Performance Measurements	Outcome Measurements
Born et al (2020)	9	**N=21:** 9M, 12F National/Interna-tional Level	EG1: 17.1 ± 2.6 EG2: 17.1 ± 2.7	**Maximal strength or vertical jump trainings (6-week)** EG1: Maximal Strength Training EG2: Vertical Jump Training CG: N/A	**FC Start Performance Test**	**Kinematic Parameters:** - Time on the block - Takeoff horizontal velocity - Takeoff angle **Kinetic Parameters:** - Peak power - Peak resultant horizontal & vertical force - Peak horizontal rear foot force - Peak resultant grab force
Karpinski et al (2020)	12	**N=16:** 16M National level	EG: 20.2 ± 1.17 CG: 20.0 ± 1.9	**Core strengthening training (6-week)** EG: Core Strengthening Training CG: Normal Training	**FC Swim Block Start & Turn Performance**	**Start Performance** - Entry Distance & Velocity - Time in the air (Flight Time) - Dive angle - Reaction time (Start Time) **Turn Performance** - Time 5m after flip turn - Average Velocity after the flip

CG: Control group; EG: Experimental group; F: Female FC: Front Crawl (Freestyle); M: Male; N/A: Not applicable; S&C: Strength and Conditioning; SD: Standard Deviation.

Table 3. Continued …..

Author (Year)	Quality Assessment	Subject Characteristics	Age (Mean±SD)	S&C Training Intervention	Performance Measurements	Outcome Measurements
Rejman et al (2017)	6	**N=9:** 9M National Level	Overall: 21.89 ± 3.41	**Plyometric training (6-week)** EG: Plyometric training CG: N/A	**Swimming Block Start Performance**	**Temporal Parameters:** - Start, Take off, Flight, and Glide time **Spatial Parameters:** - Take-off, Entry, Glide angle **Velocities:** Average & Instantaneous Take-off, Flight, & Glide velocities
Bishop et al (2009)	13	**N=22:** Sex: Not mentioned Regional Level	EG: 13.1 ± 1.4 CG: 12.6 ± 1.9	**Plyometric training (8-week)** EG: Plyometric training CG: Normal Training	**Swimming Block Start Performance**	**Start Performance** - Swim time to 5.5m - Angle out of blocks (Dive Angle) - Angle of entry into water (Entry Angle) - Distance to head contact (Flight Distance) - Time to head contact (Flight Time) - Velocity of take-off to contact
Rebutini et al (2016)	9	**N=10:** 7M, 3F Competitive or regularly trained	M: 22 ± 1.4 F: 21.3 ± 7.6	**Plyometric long jump training (9-week)** EG: Plyometric long jump training CG: N/A	**Swimming Block Start Performance**	**Kinematic Parameters** - Horizontal & Vertical Displacement of Centre of Mass - Horizontal Velocity at Water Entrance - Horizontal & Vertical Take-off Velocity - Peak of Joint Angular Velocities of Hip and Knee **Kinetic Parameters** - Rate of Torque Development of Hip & Knee - Peak Torque of Hip & Knee - Peak Horizontal & Vertical Force - Impulse - Angle of Resultant Force

CG: Control group; EG: Experimental group; F: Female FC: Front Crawl (Freestyle); M: Male; N/A: Not applicable; S&C: Strength and Conditioning; SD: Standard Deviation.

Table 4. Results of Included Studies studying swimming performance (n=11).

Author	S&C Training Intervention	Performance	Stroke/Swimming Biomechanics	Strength Test
Karpinski et al (2020)	**Core strengthening training (6-week)** EG: Core Strengthening Training CG: Normal Training	**50m FC (s):** EG: 25.24±0.35; 24.94±0.49 CG: 26.82±1.09; 26.64±1.19 Sig. improvement in EG with moderate ES (p<0.001, ES:0.71)	**SL (m):** EG: 1.63±0.15; 1.58±0.16 CG: 1.59±0.06; 1.59±0.08 **SR (cycle/s):** EG: 1.02±0.08; 1.03±0.08 CG: 0.97±0.04; 0.97±0.05 No sig. change in SL & SR in EG with trivial to small ES (p>0.05, ES: 0.19-0.36)	N/A
Gourgoulis et al (2019)	**In-water resistance training (11-week)** EG: Resistance training with Water Parachute CG: Normal Training	**50m FC (s):** EG: 35.92±1.96; 34.77±2.13 CG: 35.67±3.50; 35.60±3.04 **100m FC (s):** EG: 77.73±5.25; 73.75±5.21 CG: 78.00±7.46: 77.10±8.24 **200m FC (s):** EG: 172.00±12.98; 159.17±10.68 CG: 171.17±14.47; 170.17±13.75 All had sig change in EG with large ES (p<0.05, ES: 1.09-3.66)	**SL (m):** EG: 1.41±0.19; 1.38±0.18 CG: 1.45±0.15; 1.47±0.18 **SR (cycle/s):** EG: 0.94±0.10; 0.98±0.09 CG: 0.91±0.10; 0.89±0.12 - No sig. changes in SL & SR (p>0.05) - **Trend of improvement in EG **Mean SV (m/s):** EG: 1.32±0.05; 1.34±0.05 CG: 1.30±0.10; 1.30±0.12 Sig. change with large ES in EG (p<0.01, ES: 2.43)	N/A
Morais et al (2018)	**In-water & dry-land S&C training (34-week)**	**100m FC (s):** Pre: 68.72±5.57; Post: 66.23±5.23 - Sig. improved with moderate ES (p<0.001, ES – total eta-square: 0.56)	**SL (m):** 1.69±0.11; 1.70±0.12 No sig changes with moderate ES (p=0.83, ES: 0.40) **SF (Hz):** 0.82±0.07; 0.86±0.08 Sig increase with small ES (p=0.04, ES: 0.12) **SV (m/s):** 1.39±0.10; 1.44±0.09 Sig. increase with moderate ES (p<0.001, ES: 0.40)	**Throwing Velocity (m/s):** 6.58±0.96; 7.20±0.75 Sig improved with moderate ES (p<0.001, ES: 0.31)
Patil et al (2014)	**6-week Core strengthening training** EG: Core Strengthening CG: Normal Swimming Training	**50m FC Swim (s):** EG: 36.74±6.76; 35.71±6.52 CG: 35.76±4.12; 35.33±4.43 Sig change in EG (p<0.05) Sig. diff between groups (p<0.05)	**SL (m):** EG: 1.37±0.37; 1.43±0.37 CG: 1.35±0.28; 1.37±0.26 No sig. changes in EG (p>0.05) **SR (cycle/s)** EG: 63.48±11.28; 62.49±9.23 CG: 64.50±9.91; 63.70±7.87 No sig. changes in EG & CG (p>0.05) **SV (m/s):** EG: 1.40±0.22; 1.44±0.23 CG: 1.42±0.16; 1.44±0.18 Sig. change in EG (p<0.05)	**Functional Core Muscle Strength:** EG: 0.67±0.76; 2.53±1.33 CG: 0.67±0.59; 1.03±0.83 Sig. improvement in EG (p<0.05) Sig. diff between EG & CG (p<0.05)

Units – 1/min: 1 per minute; cm: centimeter; cycle/s: cycle per second; cycle/min: cycle per minute; Hz: Hertz; m: meter; m/s: meter per second; N: Newton; s: second; °/s: degree per second.
CG: Control Group; CMJ: Countermovement jump; CON: Concentric; ECC: Eccentric; EG: Experimental Group; ES: Electrical Stimulation; F: Female FC: Front Crawl (Freestyle); ISO: Isometric; M: Male; NR: Not Reported; RAS: Resisted & Assisted training; RM: Repetitions; S&C: Strength and Conditioning; SF: Stroke Frequency; SL: Stroke Length; SR: Stroke Rate; SV: Swimming Velocity.

Table 4. Continued …..

Author	S&C Training Intervention	Performance	Stroke/Swimming Biomechanics	Strength Test
Amaro et al (2017)	**Dry-land S&C training (6-week)** EG1: Sets & Repetitions Training EG2: Explosiveness Training CG: Normal Training	**50m FC (s):** EG1: 33.92±1.47; 34.52±1.52 EG2: 33.43±2.83; 32.35±2.36 CG: 33.76±3.14; 33.63±3.71 No sig. change in all groups after training (p>0.05)	N/A	**Vertical Jump (cm):** EG1: 25.70±3.29; 29.28±3.06 EG2: 29.70±4.73; 31.85±4.78 CG: 25.44±4.47; 27.32±6.94 Sig. improved in both EGs with moderate ES (p<0.05, ES: 0.487-0.617) **Ball Throwing (m):** EG1: 4.53±0.61; 4.81±0.59 EG2: 4.07±0.54; 4.78±0.49 CG: 3.98±0.89; 4.25±0.78 Sig. improved in EG2 with large ES (p<0.001, ES: 0.856)
Girold et al (2012)	**4-week Dry-land strength or Electrical Stimulation (ES) Training** EG1: Strength Training EG2: ES Training CG: Normal Training	**50m FC Swim (Mean Velocity):** EG1: 2±1.3% EG2: 1.7±0.5% CG: Not mentioned Sig. improved in both EGs (p<0.05) No sig. diff. between EGs (p>0.05)	**SL (m):** EG1: 2.05±0.01; 2.11±0.01 EG2: 2.12±0.12; 2.17±0.14 CG: 2.08±0.03; 2.10±0.02 Sig. improved in EG1 (p<0.05) No sig. diff. between groups (p>0.05) **SR (cycle/min):** EG1: 54.7±4.1; 55.9±2.7 EG2: 52.9±3.5; 54.3±2.6 CG: 53.5±2.4; 53.9±2.3 No sig. change in all groups (p>0.05)	**Extension – CON 60°/s & 180°/s:** EG1: 11.2±13.6% (60°/s); 16.9±11.7% (180°/s) EG2: 14.8±7.2% (60°/s); 13.9±5.6% (180°/s) CG: 2.2±7.4% (60°/s); 1.2±0.7% (180°/s) Sig. increase in both EGs (p<0.05) No sig. diff. between EGs (p>0.05) **Extension – ISO & ECC 60°/s:** EG1: 2.7±2.1% (ISO); 4.6±6.1% (ECC) EG2: 13.5±10.9% (ISO); 22.9±6.6% (ECC) CG: 1.6±0.9% (ISO); 6.1±1.5% (ECC) Sig. change in EG2 (p<0.05)
Sadowski et al (2012)	**6-week dry-land power training** EG: Power Training with Ergometer CG: Normal Training	**25m FC Swim (SV):** EG: +1.30% (p>0.05) CG: +1.16% (p>0.05) No sig. improvement in both groups	**SF (1/min):** EG: -4.30% (p>0.05) CG: +6.28% (p>0.05) -Sig. diff. between groups after 6-week (8.92%, p<0.03) **Distance Per Stroke:** EG: +5.98% (p>0.05) CG: -5.36% (p>0.05) Sig. diff. between groups after 6-week (32.34%, p<0.001)	**Isometric Shoulder Strength Test (Shoulder Flexion):** EG: +5.34% (p>0.05) CG: +5.69% (p>0.05) No sig. improvement in both groups (p>0.05) **Tethered Swimming Force (N):** EG: +9.64% (p<0.02) CG: +2.86% (p>0.05) Sig. improvement in EG, but not CG
Girold et al (2006)	**3-week Resisted or Assisted sprint training** EG1: Resisted Training EG2: Assisted Training CG: Normal Training	**100m FC Swim (s):** EG1: 67.43±4.40; 66.05±4.00 EG2: 62.46±5.32; 61.9±4.85 CG: 68.15±6.18; 68.35±5.91 Sig. improvement in both EGs (p<0.05)	**SR (cycle/min):** EG1: 42.32±4.98; 43.01±3.91 EG2: 41.92±2.75; 43.47±3.11 CG: 43.50±4.92; 42.2±3.56 Sig. increase in both EGs in 2nd 50m (p<0.05)	**Extensor – ISO** Sig. change in EG1 (p<0.05) **Flexor – CON 60°/s** Sig. change in EG1 (p<0.05) **Flexor – CON 180°/s** Sig. change in both EGs (p<0.05)

Units – 1/min: 1 per minute; cm: centimeter; cycle/s: cycle per second; cycle/min: cycle per minute; Hz: Hertz; m: meter; m/s: meter per second; N: Newton; s: second; °/s: degree per second.
CG: Control Group; CMJ: Countermovement jump; CON: Concentric; ECC: Eccentric; EG: Experimental Group; ES: Electrical Stimulation; F: Female FC: Front Crawl (Freestyle); ISO: Isometric; M: Male; NR: Not Reported; RAS: Resisted & Assisted training; RM: Repetitions; S&C: Strength and Conditioning; SF: Stroke Frequency; SL: Stroke Length; SR: Stroke Rate; SV: Swimming Velocity.

Table 4. Continued …..

Author	S&C Training Intervention	Performance	Stroke/Swimming Biomechanics	Strength Test
Garrido et al (2010)	**8-week combined strength and aerobic training** EG: Strength Training CG: Normal Training	**25m FC Swim (SV):** EG: +4.45% (p<0.01) CG: NR (p>0.05) **50m FC Swim (SV):** EG: +1.94% (p<0.01) CG: +1.88% (p<0.05) No sig. differences between groups More improvement in EG	**Active Drag (N) & Drag Coefficients:** EG: No sig. change after 8-week (p>0.05) CG: No sig. change after 8-week (p>0.05)	**CMJ (cm):** EG: Sig. increased (p<0.01) CG: Decreased (p-value: NR) No sig. diff. between groups after 8-week **Ball Throwing Distance (m):** EG: 1kg: p<0.05; 3kg: p<0.01 CG: No sig. change No sig. diff. between groups **6RM Bench Press:** EG: +43% (p<0.01); CG: +15% (p<0.05) More improvement in EG **6RM Leg Extension:** EG: NR (p<0.01); CG: NR (p<0.05) More improvement in EG
Aspenes et al (2009)	**11-week combined Strength and endurance training** EG: Maximal Strength and Endurance Training CG: Normal Training	**50m FC Swim (s):** EG: 28.88±2.00; 28.55±1.80 CG: 29.35±1.72; 29.16±1.76 No sig changes in both groups (EG: p=0.11; CG: NR) **100m FC Swim (s):** EG: 63.00±4.12; 62.05±3.82 CG: 64.08±4.18; 64.06±4.80 No sig changes in both groups (EG: p=0.12; CG: NR) **400m FC Swim (s):** EG: 290.43±16.26;286.43±16.64 CG: 290.08±16.20; 290.40±18.24 Sig changes in EG (p<0.05)	**SL (m):** EG: 1.68±0.17; 1.73±0.16 CG: 1.74±0.13; 1.80±0.15 **SR (Hz):** EG: 0.953±0.090; 0.930±0.074 CG: 0.885±0.078; 0.872±0.078 **Maximum SV (m/s):** EG: 1.59±0.11; 1.60±0.10 CG: 1.53±0.08; 1.56±0.07 **25m sprint No sig. change in any strokes kinematics parameters (p>0.05)	**Bilateral Shoulder Extension Measurement** EG: 318.8±89.8; 383.5±89.3 CG: 277.9±44.2; 310.7±56.2 Sig change in EG (p<0.01) & CG (p<0.05) Sig diff. between groups (p<0.05) **Tethered Swimming Force (N):** EG: 124.9±23.2; 133.5±21.9 CG: 114.4±17.3; 118.1±18.3 Sig change in EG (p<0.01) Sig higher in EG than CG after training (p<0.05)
Girold et al (2007)	**12-week Dry-land strength training OR resisted & assisted training (RAS)** EG1: Strength Training EG2: RAS Training CG: Normal Training	**50m FC Swim:** EG1: 2.8±2.5% EG2: 2.3±1.3% CG: 0.9±1.2% Sig. improvement in both EGs (p<0.05)	**SL (m):** EG1: 1.61±0.11; 1.59±0.09 EG2: 1.58±0.08; 1.56±0.09 CG: 1.56±0.09; 1.56±0.08 No sig. changes in all groups (p>0.05) **SR (cycle/min):** EG1 48.9±4.98; 50.7±3.71 EG2: 48.2±3.5; 49.5±3.4 CG: 47.8±3.7; 48.7±3.7 Sig. increased in EG2 and CG (p<0.05) No sig. change in EG1 (p>0.05)	**Flexors - ISO:** Sig. increase in both EGs (p<0.05) **Flexors – CON 60°/s:** Sig increase in EG2 (p<0.05) **Extensors – CON 60°/s & 180°/s:** Sig. increase in both EGs (p<0.05)

Units – 1/min: 1 per minute; cm: centimeter; cycle/s: cycle per second; cycle/min: cycle per minute; Hz: Hertz; m: meter; m/s: meter per second; N: Newton; s: second; °/s: degree per second.
CG: Control Group; CMJ: Countermovement jump; CON: Concentric; ECC: Eccentric; EG: Experimental Group; ES: Electrical Stimulation; F: Female FC: Front Crawl (Freestyle); ISO: Isometric; M: Male; NR: Not Reported; RAS: Resisted & Assisted training; RM: Repetitions; S&C: Strength and Conditioning; SF: Stroke Frequency; SL: Stroke Length; SR: Stroke Rate; SV: Swimming Velocity.

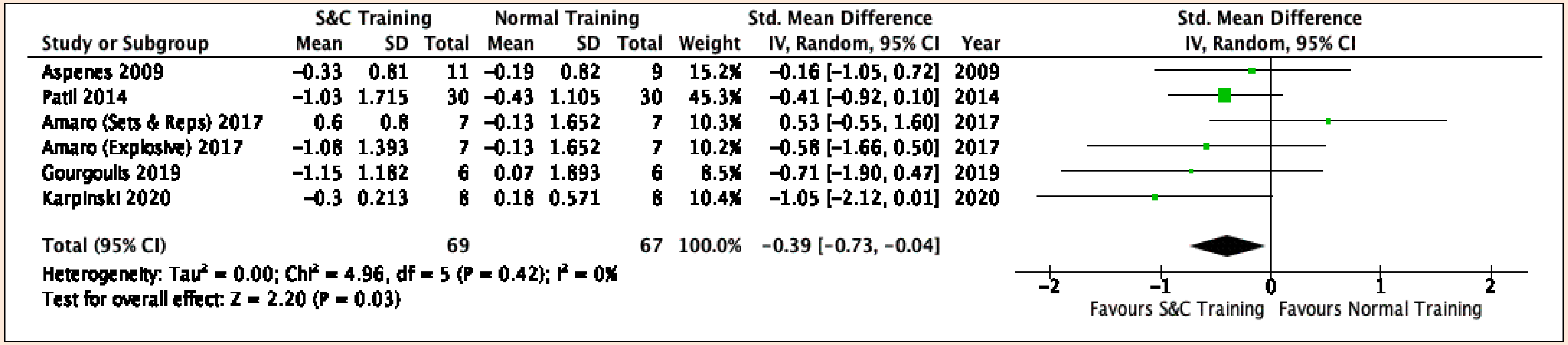

Figure 2. Forest Plot of 50m FC Swim. CI: Confidence Interval; I^2: I-squared (Heterogeneity); S&C: Strength and Conditioning; Sets & Reps: Sets & Repetitions Training; SD: Standard Deviation; SMD: Standard Mean Difference; Z: Z-value.

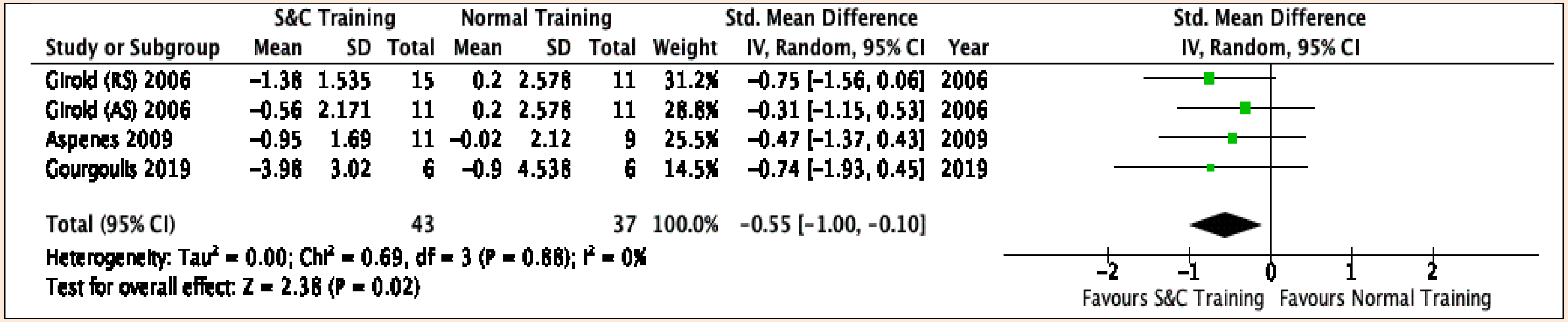

Figure 3. Forest Plot of 100m FC Swim. AS: Assisted Training; CI: Confidence Interval; I^2: I-squared (Heterogeneity); RS: Resisted Training; S&C: Strength and Conditioning; Sets & Reps: Sets & Repetitions Training; SD: Standard Deviation; SMD: Standard Mean Difference; Z: Z-value.

Moreover, there was evidence revealed that performance difference existed between intervention and control groups, the statistical analysis indicated that S&C training groups favor more improvement in 50m FC swimming time. With significant effect (pool SMD: -0.39; 95% Confidence Interval (95%CI): -0.73 to -0.04; Z-value (Z) = 2.20, p = 0.03), one study showed a large effect of the intervention (SMD = -1.05), and some demonstrated moderate effects (SMD = - 0.71 to -0.41). The I-squared test showed the homogeneity among 5 studies with I-square value was smaller than 50% (I-squared (I^2) = 0%) (Figure 2). While for 100m FC swim, similar results were found that better 100m swim performance demonstrated in S&C training intervention groups, and the statistical analysis (Figure 3) demonstrated significant result (pool SMD: -0.55; 95%CI: -1.00, -0.10; Z = 2.38, p = 0.02) in intervention groups. Studies presented small to moderate effects on 100m performance with SMD ranged from -0.75 to -0.31. The I^2 test showed the homogeneity among 3 studies as I^2 value was equal to 0%.

According to the Egger's Regression Asymmetric test in Comprehensive Meta-analysis software, the results found that there were no significant publication bias in both 50m and 100m FC swimming performance analysis with p = 0.92 and p = 0.67 respectively.

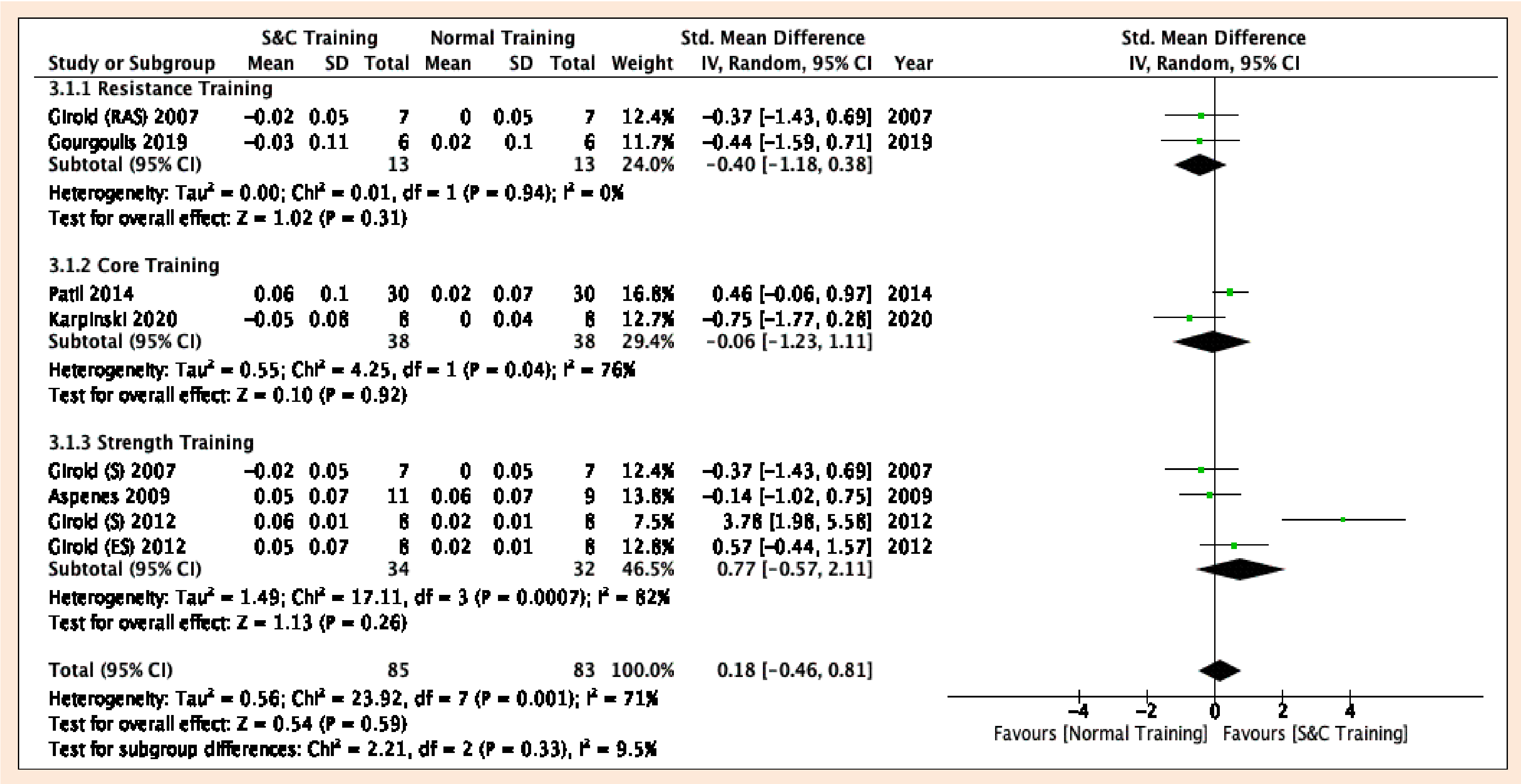

Figure 4. Forest Plot of Stroke Length. CI: Confidence Interval; ES: Electrical Stimulation Training; I^2: I-squared (Heterogeneity); RAS: Resisted & Assisted Training; S: Strength Training; S&C: Strength and Conditioning; Sets & Reps: Sets & Repetitions Training; SD: Standard Deviation; SMD: Standard Mean Difference; Z: Z-value.

Stroke and swimming biomechanics

Most of the studies measured the effects of trainings on stroke biomechanics through measuring SL and SR. For the effects on SL, the results showed S&C training programs favor the improvement in SL with non-significant effects (pool SMD: 0.18; 95%CI: -0.46, 0.81; Z = 0.54, p = 0.33) (Figure 4). However, inconsistence and debatable results were found, after separating analysis by different types of training. Only strength training showed non-significant effects on improving the SL (pool SMD: 0.77; 95%CI: -0.57, 2.11; Z = 1.13, p = 0.26), while both resistance training and core training did not favor the improvement of SL (Resistance: pool SMD: -0.40; 95%CI: -1.18, 0.38; Z = 1.02, p = 0.31; Core: pool SMD: -0.06; 95%CI: -1.23, 1.11; Z = 0.10, p = 0.92), but no significant difference was found between 3 types of trainings (p = 0.33). The I^2 test also showed there was heterogeneity among studies as I^2 value was larger than 50% ($I^2 = 71\%$). Also, there was no significant publication bias in SL analysis with p = 0.80.

Regarding the effects on SR (Figure 5), significant effects were demonstrated that S&C trainings favor the improvement on SR (pool SMD: 0.37; 95%CI: 0.02, 0.71; Z = 2.09, p = 0.04) and the result also proved the homogeneity of those studies with I^2 value was smaller than 50% (I^2 = 30%). Regarding the publication bias, however, there was significant result was found after running the Egger's regression asymmetric test (p = 0.05). Resistance training showed significant and larger effects among 3 types of training (pool SMD: 0.79; 95%CI: 0.30, 1.27; Z = 3.18, p = 0.001), and strength training showed non-significant effects on improving SR (pool SMD: 0.23; 95%CI: -0.26, 0.73; Z = 0.93, p = 0.35), while core trainings did not demonstrate any favorable effects on SR (pool SMD: -0.07; 95%CI: -0.53 7, 0.38; Z = 0.32, p = 0.75).

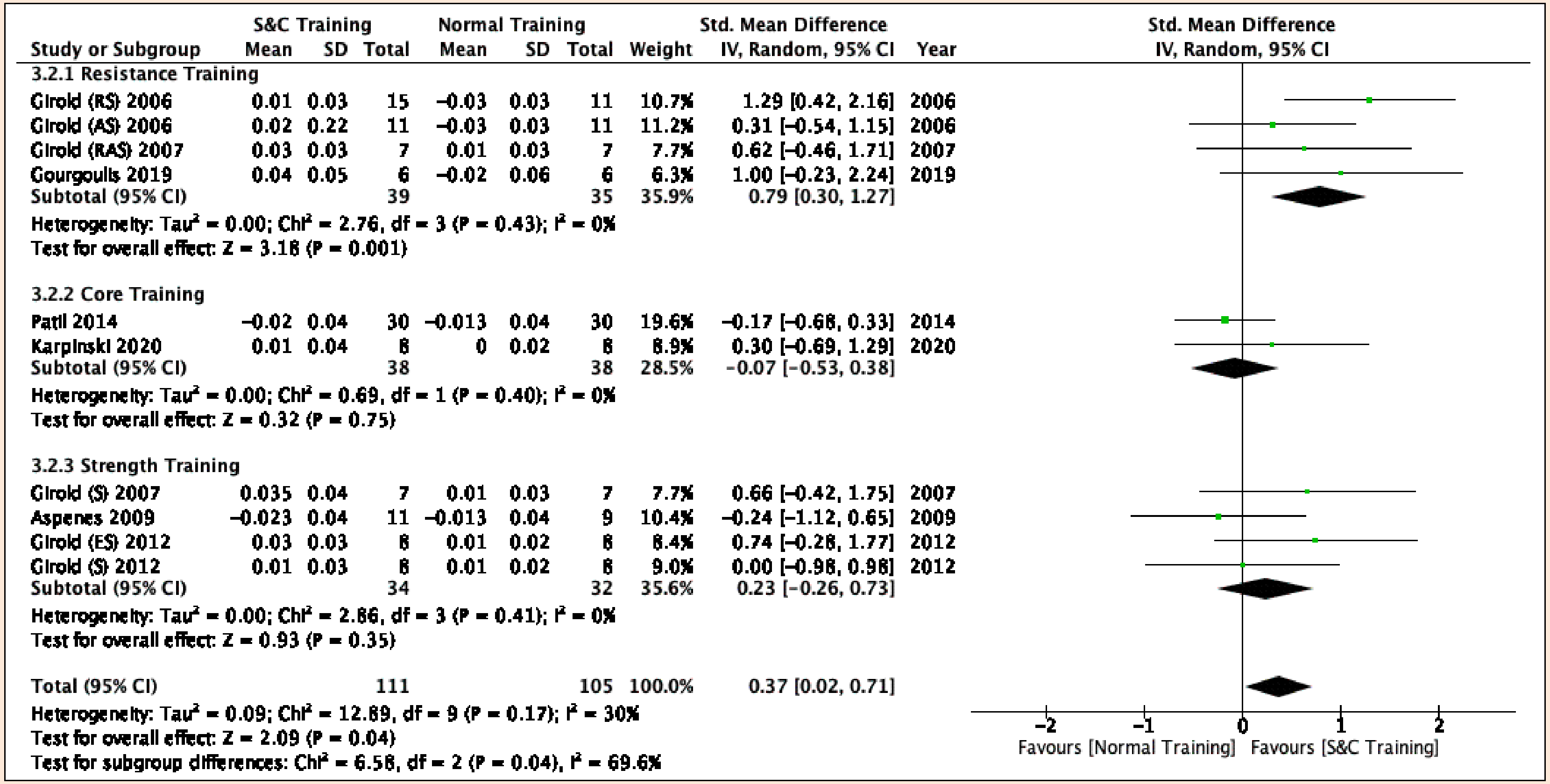

Figure 5. Forest Plot of Stroke Rate. CI: Confidence Interval; ES: Electrical Stimulation Training; I^2: I-squared (Heterogeneity); RAS: Resisted & Assisted Training; S: Strength Training; S&C: Strength and Conditioning; Sets & Reps: Sets & Repetitions Training; SD: Standard Deviation; SMD: Standard Mean Difference; Z: Z-value.

Apart from SL and SR as monitoring stroke parameters, some studies recorded the swimming velocity (SV) and distance per stroke as outcome measures (Gourgoulis et al., 2019, Morais et al., 2018, Patil et al., 2014, Sadowski et al., 2012). Significant improvement in SV were found in experimental groups ($p < 0.01$-0.05) (Gourgoulis et al., 2019; Morais et al., 2018; Patil et al., 2014), only Aspenes' study presented non-significant change result in maximum SV after training (Aspenes et al., 2009), while significant difference in distance per stroke were found between experimental and control groups after 6-week training ($p < 0.001$) (Sadowski et al., 2012).

In addition to the stroke biomechanics, one study has investigated and monitored the performance change in active drag force and drag coefficients after strength training (Garrido et al., 2010b). However, there was no significant change in both outcomes, after 8-week training in both groups ($p > 0.05$).

Muscle strength

In addition, some studies followed the changes in swimmers' muscle strength after trainings. Consistent results were found in muscle strength performance tests in several studies, as studies adopted different outcomes measurement, statistical comparison could not be processed. Most of the experimental groups presented significant results (Table 3). For ball throwing, the performance was significantly improved after weeks of strength and resistance trainings ($p < 0.001$-0.05) (Amaro et al., 2017; Garrido et al., 2010b; Morais et al., 2018), from moderate to large ES (Amaro et al., 2017; Morais et al., 2018), while one study (Amaro et al., 2017) measured the vertical jump performance and demonstrated significant improvement in experimental groups with moderate ES ($p < 0.05$, ES: 0.487-0.617). To assess the upper and lower limbs strength, 6RM bench press and leg extensions were also tested in Garrido's study (Garrido et al., 2010b), and both were significantly improved in both experimental and control groups, but the swimmers in the experimental group showed more improvement in both tests.

Apart from the performance measurement, several studies (Girold et al., 2006; 2007; 2012) used peak torque to indicate the change in muscle strength of upper limbs, in isometric, concentric or eccentric conditions. Significant changes were found, mostly were the isometric and concentric conditions in experimental groups ($p < 0.05$), and rarely showed significant changes in control groups. Moreover, two research (Aspenes et al., 2009, Sadowski et al., 2012) also monitor the changes in tethered swimming force performance after the trainings by using the tethered swimming test (TST), and both experimental groups demonstrated significant improvement, with $p < 0.01$ and $p < 0.02$ respectively.

Start performance

5 studies investigated the effects on start performance and different parameters have been measured (Table 5), thus only qualitative evaluation was performed. Among 5 studies, only 1 study did not show with significant improvement in start performance after strength training (Born et al., 2020), with non-significant change in start time in both experimental group ($p > 0.05$), but only peak resultant horizontal force had significant change with medium ES, after 6-week vertical jump training ($p < 0.05$, ES = 0.23).

Another 4 studies showed significant improvement in different parameters after plyometric (Bishop et al., 2009, Rebutini et al., 2016, Rejman et al., 2017) or core trainings (Karpiński et al., 2020). For the core training, the entry velocity ($p = 0.021$. ES = 0.36), reaction time ($p = 0.001$, ES = 2.87) have significant improvement with small to very large ES, but no significant change in entry distance, time in the air and dive angle ($p > 0.05$). Whilst for the plyometric trainings, Bishop et al. (2009) found that all parameters presented significant improvement in experimental groups ($p < 0.05$), and some showed significant differences with control groups (Swim time of 5.5m, velocity of take-off to contact, distance to head contact ($p < 0.01$) and time to head contact ($p = 0.023$)). Another study also found that start and glide time ($p < 0.05$), glide angle ($p < 0.01$) and all velocities ($p < 0.05$) have significant changed (Rejman et al., 2017), while Rebutini et al. (2016) found that most of the kinematic and kinetic parameters have significant improvement ($p < 0.05$) after plyometric long jump training, and only no significant change in Peak vertical force ($p = 0.069$) and Take-off vertical velocity ($p = 0.091$).

Turn performance

Only 1 study (Karpiński et al., 2020) has investigated the effect on turn performance and demonstrated an encouraging result (Table 5). There were significant improvements within group in time to 5m after turn ($p < 0.001$, ES = 1.51) and average velocity in 5m after turn ($p = 0.001$, ES = 1.54), showed with large ES and significant differences between groups ($p < 0.05$).

Discussion

The aim of this study was to summarize the evidence on the effectiveness of S&C trainings on performance and on relevant biomechanical parameters of swimming, starts and turns. In this review study, the results showed different S&C trainings were effective to improve swimming performance and also some relevant biomechanical parameters significantly, i.e., increased in SR and faster time performance in sprint swimming.

Quality assessment

The quality of the included studies were low with high risk of bias, and this result was similar with another review study (Costa et al., 2012). However, these were mainly caused by different constraints and restrictions to conduct this kind of intervention study to swimming athletes. The main difficulty faced by authors would be subject recruitment, i.e., random sampling from the whole swimming population. Because specific characteristics of swimmers were required for investigations, the number of eligible swimmers was limited for recruitment, and only convenience sample could be approached. Moreover, this kind of intervention required familiarization process to reduce the learning effect, no blinding was allowed, thus further lower the scores.

Table 5. **Results of Included Studies studying starts and turns performance (n=5).**

Author	Intervention	Start / Turn Performance	Biomechanical Parameters	Other Outcomes
Born et al (2020)	**Maximal strength or vertical jump trainings (6-week)** EG1: Maximal Strength Training EG2: Vertical Jump Training CG: N/A	**Start Time to 5m (s):** EG1: 1.60±0.14; 1.60±0.12 EG2: 1.62±0.07; 1.61±0.07 No sig. change in both EGs (p>0.05)	**Peak resultant horizontal force (x body mass) (N):** EG1: 1.15±0.19; 1.18±0.18 EG2: 1.30±0.18; 1.34±0.19 - Sig change in EG2 only with moderate ES (p<0.05, ES: 0.23) no sig changed in other parameters (p>0.05)	**Swim Time to 5m (s):** EG1: 1.72±0.07; 1.68±0.09 EG2: 1.66±0.06; 1.64±0.07 Sig. improved in EG1 (p=0.03) for U17 Swimmers
Karpinski et al (2020)	**Core strengthening training (6-week)** EG: Core Strengthening Training CG: Normal Training	Start Performance: **Reaction Time (s):** EG: 0.80±0.03; 0.71±0.03 CG: 0.83±0.05; 0.79±0.04 - Sig. improve in EG with very large ES (p=0.001, ES: 2.87) - Sig. diff. between group after training (p<0.001) **Time in the air (Flight time) (s):** - No sig. change in both groups (p>0.05) **Dive angle (degree):** - No sig. change in both groups (p>0.05) **Entry Distance (m):** - No sig. change in EG (p>0.05) Sig. change in CG (p=0.013) Turn Performance: **Time 5m after flip turn (s):** EG: 0.43±0.06; 0.34±0.06 CG: 0.50±0.11; 0.44±0.08 - Sig. change in EG with lager ES (p<0.001; ES: 1.51) Sig. diff. between 2 groups after training (p<0.001)	Start Performance: **Entry velocity (m/s):** EG: 12.77±1.65; 13.34±1.47 CG: 13.99±2.87; 13.53±2.81 - Sig improve in EG with small ES (p=0.021, ES=0.36) Turn Performance: **Average velocity after the flip (m/s):** EG: 11.77±1.68; 15.34±2.810 CG: 10.37±2.14; 11.58±2.11 - Sig. change in both EG (p<0.001; ES: 1.54) & CG (p=0.026, ES: 0.57), with small or large ES Sig. diff. between 2 groups after training (p<0.001)	**N/A**
Rejman et al (2017)	**Plyometric training (6-week)** EG: Plyometric training CG: N/A	**Temporal Parameters:** - Sig. improved in start & glide time (p<0.05) - No sig. changes in Take-off & flight time (p>0.05) **Spatial Parameters:** - Sig. change in Glide angle (p<0.01) No sig. changes in take-off, entry angles (p>0.05)	**Average & Instantaneous Velocities:** Sig. decreased in Take-off, Flight & Glide average & instantaneous velocities (p<0.05)	**N/A**

Unit – degree/s: degree per second; m: metre; m/s: metre per second; N: Newton; Nm: Newton metre; Nm/s: Newton metre per second; Ns: Newton second; s: second. CG: Control group; EG: Experimental group.

Table 5. Continued…

Author	Intervention	Start / Turn Performance	Biomechanical Parameters	Other Outcomes
Rebutini et al (2016)	**Plyometric long jump training (9-week)** EG: Plyometric long jump training CG: N/A	**N/A**	Kinematic Parameters **Displacement of Centre of Mass (m):** Horizontal: 2.56±0.21; 2.74±0.4 Vertical: 1.49±0.05; 1.44±0.07 - Sig change in both horizontal (p=0.032) & vertical axis (p=0.040) **Take-off Velocity (m/s):** Horizontal: 1.84±0.19; 2.14±0.21 Vertical: 0.39±0.46; 0.34±0.42 Resultant:1.93±0.18; 2.13±0.28 - Sig. improved in horizontal (p=0.012) & resultant velocities (p=0.020) - No sig. improvement in vertical axis (p=0.091) **Entry Velocity (m/s):** 1.84±0.30; 2.24±0.29 - Sig. change in horizontal axis (p=0.010) **Peak of Joint Angular Velocity (degree/s)** Right Knee: 523.56±137.56; 600.82±181.17 Left Knee:558.23±120.18; 603.59±162.44 Left Hip: 421.71±78.55; 490.90±97.50 Sig. change in left (p=0.040) & right (p=0.022) knees & left hip (p=0.023) **Rate of Torque Development (Nm/s):** Knee: 427.45±116.86; 604.43±240.42 Hip: 585.66±220.07; 1217.27±512.28 - Sig change in knee (p=0.021) & hip (p=0.010) **Peak Torque (Nm)** Knee: 148.71±44.43; 185.19±71.91 Hip: 266.08±75.64; 393.44±124.53 - Sig change in both knee (p=0.042) & hip (p=0.010) **Peak Force (N)** Horizontal: 209.20±37.60; 223.70±33.80 Vertical: 837.00±152.50; 847.33±164.23 Resultant: 890.00±154.92; 920.90±176.90 - Sig. change in horizontal axis (p=0.047) & resultant force (p=0.040) - No sig. change in vertical axis (p=0.069) **Impulse (Ns):** 221.90±61.60; 242.50±60.90 - Sig change after training (p=0.037) **Angle of resultant force (Degree)** 27.30±7.80; 22.20±10.30 Sig decrease after training (p=0.012)	**N/A**

Unit – degree/s: degree per second; m: metre; m/s: metre per second; N: Newton; Nm: Newton metre; Nm/s: Newton metre per second; Ns: Newton second; s: second. CG: Control group; EG: Experimental group.

Table 5. Continued…

Author	Intervention	Start / Turn Performance	Biomechanical Parameters	Other Outcomes
Bishop et al (2009)	**Plyometric training (8-week)** EG: Plyometric training CG: Normal Training	**Swim time to 5.5m (s):** EG: 3.88±0.48; 3.29±0.47 CG: 3.94±0.39; 3.82±0.38 **Flight Distance (Distance to head contact) (m):** EG: 1.70±0.19; 1.83±0.19 CG: 1.57±0.13; 1.50±0.17 **Flight time (s):** EG: 1.32±0.09; 1.24±0.06 CG: 1.35±0.10; 1.38±0.20 - Sig improve in EG ($p<0.05$) - Sig diff. between EG & CG after training ($p<0.05$) **Dive Angle (Degree):** EG: 26.7±7.10;34.5±6.43 CG: 23.2±7.10; 27.6±7.29 - Sig. improve in EGs ($p<0.001$) **Entry Angle (Degree)** EG: 42.3±7.33; 47.5±3.95 CG: 45.6±5.71; 48.0±7.49 Sig. improve in EGs ($p<0.05$)	**Velocity from Take-off to head contact (m/s):** EG: 1.29±0.18; 1.48±0.15 CG: 1.17±0.10; 1.10±0.16 - Sig. change in EG ($p<0.001$) Sig. diff. between EG and CG ($p<0.001$)	**Correlation** - Sig. and strengthened correlations in EG with swim time to 5.5m after training - Velocity of take-off to contact (r=-0.66 → -0.91) distance to head contact (r=0.82 → 0.88)

Unit – degree/s: degree per second; m: metre; m/s: metre per second; N: Newton; Nm: Newton metre; Nm/s: Newton metre per second; Ns: Newton second; s: second. CG: Control group; EG: Experimental group.

Swimming performance

Paramount of studies have investigated the roles of SL and SR on swimming performance in FC, and these biomechanical factors were confirmed to be important factors that linked with swimming velocity, that demonstrated positive contribution to performance (Morais et al., 2014), i.e. either through increasing SL or SR (Girold et al., 2006, Wakayoshi et al., 1995), as swimming velocity is the product of SL and SR (Craig and Pendergast, 1979). Non-uniform results were found in the effects on stroke biomechanics by evaluating the studies independently. In Girold's study (Girold et al., 2012), SL showed significant improvement after strength training, and while only showed the trend of increase in SL in other two studies with resistance or core trainings (Morais et al., 2018; Patil et al., 2014). However, after evaluating the effects according to different types of studies, strength trainings presented with positive and the largest effects (pool SMD: 0.77) on improving SL. These might be due to higher demand to swimmers' muscle strength is required for increasing SL, in order to exert larger force to overcome the resistance force from water (Toussaint, 1990; Toussaint and Vervoorn, 1990). Therefore, muscle strength of swimmers was improved after weeks of strength training, thus, positive improvement on the SL were demonstrated. Whilst core training might promote the efficiency of the kinetic chain from core to upper or lower limbs, thus swimmers would be more effective to stabilize the pelvic to overcome the water resistance and drag force from strengthened core muscles.

Oppositely, we observed that improvement in SR would present a decrease in SL but FC still improved in some studies. For example, significant increase in SR was found after 12-week resisted and assisted training in regional or national level swimmers (Girold et al., 2007), while other three studies demonstrated trend of improvement in SR with decreased SL (Girold et al., 2007; Gourgoulis et al., 2019; Karpiński et al., 2020) after strength or resistance trainings. Strength and resistance trainings might require swimmers to overcome the resistance and perform exercises with their maximal effort, thus propulsive force would be increased for each stroke and muscle strength would be increased, whilst core training promoted the stability and trunk position control, ultimately, attribute to better coordination and performance in each stroke, therefore swimmers can perform with a faster SR and thus faster swimming velocity in sprinting time trials.

Regarding to the results, most of the trainings showed benefits to SR more than to SL in overall perspective that SR showed with larger and significant effects after weeks of S&C trainings. These might indicate that SR would be better parameter for swimming performance enhancement. SR was found to have more significant change and effects after trainings, especially after resistance training (pool SMD: 0.79), as mentioned before, higher demand to swimmers' muscle strength is required for increasing SL, faster SR was performed instead, to increase the swimming velocity. This observation in our study is aligned with the results in another review study (Crowley et al., 2017) that stroke rate is the most significant factor at maximal velocity (Craig et al., 1985; Wakayoshi et al., 1995), and how to optimize the SL and SR to achieve better swimming performance still need more investigations to figure out in future. One more point should be noted that the research trend is focused on FC swimming, and the main reason might be FC have a larger proportion in competitions, with varied distance, and with higher velocity and efficiency than other three swimming strokes.

According to previous studies, scholars proved that muscle strength also a good predictor of swimming performance, i.e., strength of upper and lower limbs and core is strongly related to sprint swim performance (Aspenes et al., 2009; Garrido et al., 2010a; Hawley et al., 1992; Keiner et al., 2015; 2019; Morais et al., 2020a). Different measurement method of muscle strength was adopted to evaluate the strength of upper limbs and core, and all measurement showed positive and significant improvement after the implementation of weeks of S&C trainings to swimmers, such as, Flexor/Extensor peak torque measurement, ball throwing velocity or distance tests, and functional core strength tests. These encouraging results might be due to the effects from the gain in muscle strength and favor the swimmers to exert larger force in the water. From the studies of Girold et al. (2006; 2007; 2012), those studies showed significant improvement in the measurements of peak torque of the arms in different conditions and most of the results presented that there was larger gain in concentric condition, these might be due to the similarity of the arm movement in gliding and pushing phases. As after strength and resistance trainings, muscle strength in enhanced, thus swimmers would have greater force and power to against the drag force and propel themselves with a longer distance in each stroke, especially during high velocity sprint.

Furthermore, a study established a model that demonstrated muscle strength parameters would have a significant direct effect on stroke biomechanics and swimming performance (Morais et al., 2018). This model showed that stroke biomechanics (i.e., SL and Stroke Frequency (SF)) played a mediating role between muscle strength and swimming performance. After weeks of training, muscle strength was improved and the gain in muscle strength enhanced the SL and SF, thus ultimately, the swimming performance was enhanced. Similar results were observed in other studies (Girold et al., 2006; 2007; 2012) the peak torque measurements had significant changed, while SL and SR also showed significant changes or trend of improvement after strength or resistance trainings. Thus, seems that the increase in muscle strength would exert certain effects on stroke biomechanics, and with the product effect of improvement in SL and SR, the swimming velocity is proportionally increased, and thus swimming performance was enhanced. However, more investigations on lower limbs are suggested, despite upper limb contributed around 65% in FC swimming, legs also give contribution to overall FC performance, around 35% according to recent research (Morouço et al., 2015). Moreover, nowadays, most of the measurement of muscle strength was performed in the laboratory, instead of measuring the swimming force directly during swimming, these might affect the accuracy of the measurement, thus, another measurement methods to collect force data in a more natural environment are suggested, i.e. using force sensors or tethered swimming equipment that adopted in recent studies (Morais et al., 2020b; Morouço et al., 2015).

Besides upper limb strength, not much attention or focus has been put in investigating the effectiveness of core training on swimming performance, most of the studies implemented strength or resistance trainings to enhance the muscle strength and power and to achieve better swimming performance. With implementing core trainings to swimmers, different dynamic exercises of core were performed, which might help to promote the control of different muscles with efficiency in swimmers, and also improve the stability of the trunk. Also, with stronger core muscles, such as external oblique, latissimus dorsi and multifidus, might assist swimmers to hold the trunk and pelvic in a better position, thus reduce the drag force and more force would be used for propelling swimmers themselves forward. Not only moderate to strong correlations were found between strength of trunk and swimming performance (Keiner et al., 2015), but also demonstrated the positive effects of core trainings was transferred to faster swimming performance in different intervention studies that included in our review (Karpiński et al., 2020; Patil et al., 2014) which showed similar results with previous study (Weston et al., 2015), that there was moderate to large improvement in muscle activities of core and this might explain that there was an increase in neural adaptation in cores after 12-week core training, that athletes able to recruit specific core muscles to perform particular movements and better coordination during swimming.

Strength and Resistance trainings proved to have positive effects for improving swimming performance, through promoting changes in muscle strength and stroke biomechanics, especially on upper limbs. Nevertheless, with evidence showed that core muscles might also play an important role in swimming performance, more investigations on the effects of core training are recommended, since stronger core muscle might also be beneficial to swimming performance, and more proves should be provided to confirm its important role.

Start performance

Recently, plyometric trainings are commonly adopted in swimming trainings, as evidence proved that these trainings have positive influences on maximal strength and power (De Villarreal et al., 2010; Fowler et al., 1995) especially on the lower limbs. In our review, three studies investigated the effects of plyometric trainings and demonstrated a significant improvement in start performance (Bishop et al., 2009; Rebutini et al., 2016; Rejman et al., 2017). Plyometric trainings involved fast muscle contraction of the lower body within a short duration, and high velocity of eccentric contraction and then rapid concentric contraction. After weeks of training, neural adaptations were promoted in swimmers and thus presented with significant improvements in the kinetic and kinematic parameters of start performance, such as higher take-off velocity, faster rate of torque development around hips and knees, and larger force production, hence faster swim time to 5m and 5.5m were performed. Moreover, with evidence showed that dive distance was strongly correlated with force production (Calderbank et al., 2020), improvement in force production after plyometric trainings might bring beneficial effects on flight distance in experimental group (Bishop et al., 2009). These might also explain why there was improvement in overall start performance, as starts involved forceful actions for taking off from the block, improved muscle strength, could allow swimmers to exert larger force to the blocks, with higher peak torque, and faster rate of torque development around hips and knees were found in Rebutini's study (Rebutini et al., 2016) and also higher velocity of take-off (Bishop et al., 2009; Rebutini et al., 2016; Rejman et al., 2017), and longer flight distance (Bishop et al., 2009), hence better start performance were concluded in those studies. These results indicate that plyometric trainings are suggested to implement to promote improvement in start performance, however, we should notice that there was inconsistency in the measurement methodology among four studies.

Turn performance

Positive result is found on turn performance in FC swim. After 6-week core training, strengthened core muscles might assist swimmers to exert force from trunk flexion to extension after flip turn, and also would help lower limbs to exert force effectively against the wall. Larger force propelled and thus shorten the time required to reach 5m with higher velocity was found after turn. Despite encouraging result was found in study, only one study investigated the effects of core training to turn performance. This indicates that insufficient studies and difficult to evaluate effectiveness of core training on turn performance, only the correlation of between turn performance and the strength of lower limb were found (Keiner et al., 2019), due to the complexity of a turn that involving multiple planes of motions. Nevertheless, turn also play a crucial role that contribute to overall performance as mentioned. Therefore, more investigations are recommended to evaluate the effects to provide a more concrete evidence for supporting the effects of trainings on turn performance.

Conclusion

The current literature shows that positive effects of S&C trainings on FC swim, through improvement in stroke biomechanics and muscle strength, neural adaptations of upper and lower limbs and increase trunk stability. Strength training favor the improvement in SL, while resistance training favored improvement in SR and plyometric trainings are effective in improving start performance. S&C trainings are suggested to be part of the training for swimmers, instead of high volume of swimming training alone, to prevent or reduce the chance of getting overuse injuries. In order to identify optimal training regimes, further investigations to explore the suitable types, duration, and intensity of trainings for swimmers are recommended. Moreover, a more direct and natural for measuring force or muscle strength is suggested, in order to enhance the reliability and accuracy of the results we collected.

However, in future studies, authors should address the limitations that were found in our study. As various measurement methods were adopted in different studies, i.e., measurement of muscle strength and parameters used for evaluating star performance, no specific measurements are available and to reduce the variations among studies, development of a standardized measurement will favor statistics analysis and evaluation in future. Moreover, future studies should pay more attention on the quality of the research, which aimed to reduce the discrepancy on result interpretation and increase reliability and validity, which promote study generalizability. In order to deal with this issue, alternatives should be developed, for providing a better instrument to evaluate the quality of study that evaluating sports performance. Lastly, all included studies in this review evaluated the performance change in FC swim only, as FC account for large proportion in different competitions, and the competitiveness between swimmers in FC swim is much intense and higher. However, investigation of the effects of S&C trainings on other swimming strokes are rare, and thus more research should be conducted and recommended, to extend the positive influence on other stroke styles for achieving better performance in competitions.

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Key points

- Strength and Conditioning training programs are beneficial to both swimming sprinting performance and stroke biomechanics.
- Strength and conditioning training programs are recommended to implement as regular practice along with swimming training instead of swimming training alone.
- Start performance was improved after weeks of plyometric trainings.
- Resistance training was found to be beneficial to stroke rate.

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