Relationships Between Dry-land Resistance Training and Swim Start Performance and Effects of Such Training on the Swim Start: A Systematic Review

Thng, Shiqi; Pearson, Simon; Keogh, Justin W L

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The Effects and Relationships Between Dry-land Resistance Training On Swim Start Performance: A Systematic Review

Running head: resistance training and swimming

Shiqi Thng[1,2], Simon Pearson[2], Justin W.L. Keogh[1,3,4,5]

[1] Faculty of Health Sciences and Medicine, Bond University, Gold Coast, QLD, Australia

[2] Queensland Academy of Sport, Nathan, QLD, Australia

[3] Sports Performance Research Centre New Zealand, AUT University, Auckland, New Zealand

[4] Cluster for Health Improvement, Faculty of Science, Health, Education and Engineering, University of the Sunshine Coast, Australia

[5] Kasturba Medical College, Mangalore, Manipal Academy of Higher Education, Manipal, Karnataka, India

Corresponding Author

Shiqi Thng

Bond University, Faculty of Health Science and Medicine, Gold Coast, Australia

Ph. +61 7 5595 4489

E: sthng@bond.edu.au

ORCID: 0000-0002-3215-1458

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Abstract

Background: The swim start requires an explosive muscular response of the lower body musculature to effectively initiate movement off the starting blocks. There are currently key gaps in the literature evaluating the relationships between, and the effects of dry-land resistance training, on swim start performance, as assessed by the time to 5, 10 or 15 m.

Objective: The aims of this systematic review are to critically appraise the current literature on (1) the acute relationship between dry-land resistance training and swim start performance; (2) the acute and chronic effects of dry-land resistance training on swim start performance.

Methods: An electronic search using AusportMed, Embase, Medline (Ovid), SPORTDiscus and Web of Science was performed. The methodological quality of the studies was evaluated using the Newcastle-Ottawa Quality Assessment (NOS) scale (cross-sectional studies) and the Physiotherapy Evidence Database (PEDro) scale (intervention studies).

Results: Sixteen studies met the eligibility criteria, although the majority did not utilise the starting blocks or technique currently used in elite swimming. Swim start performance was near perfectly related ($r > 0.90$) to vertical bodyweight jumps and jump height. Post-activation potentiation and plyometrics were found to produce significant improvements in acute and chronic swim start performance, respectively.

Conclusion: While there appears to be strong evidence supporting the use of plyometric exercises such as vertical jumps for monitoring and improving swim start performance, future studies need to replicate these findings using current starting blocks and techniques and compare the chronic effects of a variety of resistance training programs.

Key Points

- Performance in a range of lower body strength and power exercises are highly correlated to swim start performance with correlations appearing greatest when utilising body weight vertical jumping exercises
- Post-activation potentiation can produce significant acute improvements in swim start performance
- Plyometrics as a form of dry-land training can produce significant chronic improvements in swim start performance

1 Introduction

A competitive swimming event can be divided into four components: the start, free swimming, turn (except for a 50 m event) and finish [1]. The swim start is a separate skill compared to the free swim portion of a race, as swimmers initiate the movement on the starting block above the water for all strokes, except those competing in the backstroke event [2, 3]. Swim start is defined as the time from the starting signal to when the swimmer crosses the 15 m mark in a race [4], with 15 m being the maximum distance that a swimmer can travel underwater before their head is required to break the surface of the water in all strokes except for breaststroke [5]. Depending on the stroke and distances of the events, swim starts have been estimated to account for 0.8% to 26.1% of the overall race time, with the latter representing the percentage in a 50 m sprint front crawl (freestyle) event [6, 7].

Three primary phases contribute towards the overall start time: the block phase, flight phase and underwater phase [6, 8]. A pictorial representation of the contribution of these phases, their biomechanical and anthropometric determinants is presented in Figure 1. The block phase requires a quick reaction to the starting signal and a large take-off velocity that is primarily horizontal in direction. The block phase is followed by the flight phase, which is the projectile motion phase in which the swimmer becomes airborne and finishes when they make contact with the water [8, 9]. The underwater phase comes next, in which swimmers attempt to maintain a streamlined position through undulatory (butterfly) leg kicks with their arms outstretched in front of the head to minimise velocity loss until their head resurfaces just before the 15 m mark [2]. The average velocity in the start phase has been shown to be more than twice the velocity of the subsequent free swim phase [10, 11]. As a result, it is imperative for swimmers to maximise their velocity off the starting blocks and to maintain as much of this velocity throughout the 15 m start phase and into the remainder of the race. Key parameters from each phase that have been previously investigated as potential correlates or predictors of starting performance include: time on the start block, the force the swimmer produces during the block phase, take-off velocity, angle of entry into the water, velocity at entry, time spent underwater and underwater velocity [6, 12, 13].

Insert Fig. 1 about here

Biomechanical research on swim start has been conducted to identify the most effective block start technique for performance. Such research has focused on comparing a number of alternative block start techniques in an attempt to improve start performance. Prior to 2008, two styles of on-block swim start techniques were most commonly used: the grab, and the track start. The primary difference between these start techniques are the foot placement on the blocks. In the grab start, both feet are positioned parallel to the front of the starting block, with the toes curled over the front edge of the starting block [14]. In the track start, one foot is placed on the front of the starting block while the other foot is placed behind [15]. The OSB11 start block (OMEGA, Zurich, Switzerland), which was introduced in 2010, features an adjustable kick plate slanted at a fixed angle of 30° that can be moved to five different positions, each at a set distance of 35 mm [8]. A kick start technique was adopted by swimmers as a result of the addition of the adjustable kick plate, where the rear foot is elevated on the angled kick plate compared to the track start technique used previously [12]. The rationale for this design was that the additional kick plate may allow for an increased duration of effective force application (i.e. greater horizontal force component) on the blocks, which in turn increases horizontal impulse and the horizontal velocity at take-off [16].

The swim start requires an explosive muscular response, especially of the lower body musculature, with swimmers having to apply large forces rapidly on the start block to increase net impulse and maximise take-off velocity in the desired direction [17]. Dry-land resistance training is commonly implemented with swim training to increase lower body strength and power output. The greater the impulse (force multiplied by time of force application) produced on the start block, the greater the change in the momentum (mass multiplied by velocity) of the swimmer. Based on this relationship, the swimmer has two distinct challenges. First, is to maximise the resultant impulse while ensuring the time spent on the start block is not exceedingly long. Secondly, any increase in the force production capacity of the swimmer needs to be achieved with some minimisation of the hypertrophic response, as an increase in body mass will reduce the take-off velocity at a given impulse off the start block (Fig. 1).

There are key gaps in the literature evaluating the relationship between dry-land resistance training and its effects on swim start performance. A recently published systematic review examined 14 studies on resistance training in swimming, but only addressed the effects on the free swim portion of a race [18]. Gaining a clearer understanding of which kinematic and/or kinetic outputs from a variety of dry-land resistance training exercises are most related to swim start performance, as well as what dry-land resistance training programs are most effective in improving swim start performance, may have major implications for high-performance swim programs. Thus, the aim of this systematic review was to critically appraise the current peer-reviewed literature on 1) the acute relationship between dry-land physical performance measures and swim start performance; 2) the acute effects of dry-land resistance training on swim start performance; and 3) the chronic effects of dry-land resistance training on swim start performance.

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2 Methods

2.1 Search strategy

This systematic review followed the guidelines provided in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [19]. A comprehensive search of five electronic databases (AusportMed, Embase, Medline (Ovid), SPORTDiscus and Web of Science) was conducted in 02 August 2018. The University Faculty librarian assisted in the development of the search strategy. A combination of the following search terms were used: “swimming”, “start”, “strength”, “power” and “resistance training”. A comprehensive database search strategy is provided in the Electronic Supplementary Material Appendix S1.

2.2 Selection Criteria

After removal of duplicate studies, all study titles and abstracts were screened by two independent reviewers. Eligible articles were retrieved in full-text and evaluated for eligibility by the same two reviewers using the following criteria: (1) articles published in peer-reviewed journals, (2) journal articles with outcome measures related to the swim start. Exclusion criteria were: (1) studies that were not written in English, (2) studies that were not available in full text, (3) not an original research study, (4) a conference abstract or presentation, (5) not swimming athletes (e.g. water polo, diving, triathlon), (6) study did not measure the swim start, (7) exercises not performed on land (8) swim start not performed on the starting block (i.e. backstroke start). Reference lists of these articles were also scanned for potentially relevant articles that were not identified in the initial database search.

2.3 Quality assessment and data extraction

The quality of studies included in the review was evaluated by two independent reviewers, with differences resolved by consensus or through a third reviewer if required.

For the cross-sectional studies, the quality of studies was assessed using a modification of the Newcastle-Ottawa Quality Assessment scale (NOS) for cohort studies [20]. This scale has been utilised in systematic reviews of athletes [21-23] and has been recommended by the Cochrane Handbook for Systematic Reviews of Interventions for assessing methodological quality or risk of bias in non-randomised studies [24]. As follow-up for cross-sectional studies in our review was not required (item 8 on the NOS scale), we omitted that criterion in the third category and had a maximum score of 4, 2 and 2 allocated for each respective category for a total possible score of 8. The threshold used to qualitatively assess the correlations in the cross-sectional studies was based on Hopkins

[25] using the following criteria: < 0.1, trivial; 0.1-0.3, small; 0.3-0.5, moderate; 0.5-0.7, large; 0.7-0.9 very large, > 0.9, nearly perfect.

For intervention studies, the Physiotherapy Evidence Database (PEDro) scale [26] was applied to assess the methodological quality of the literature. The PEDro scale is an 11-item scale that rates randomised controlled trials from 0 to 10, with 1 point given if the study satisfies the criteria and 0 points if not. Studies scoring 9-10 on the PEDro scale are considered methodologically excellent, 6-8 are considered good quality, 4-5 are considered fair and those studies scoring < 4 are considered methodologically poor.

3 Results

3.1 Study characteristics and methodology

A total of 3369 articles were retrieved from database searches. Of the 65 studies retained for full-text screening, sixteen studies were identified for review. Out of the sixteen studies, eight were cross-sectional studies and eight were intervention studies. Of the intervention studies, four examined acute and four examined chronic outcomes. The results of the search process are illustrated in a flowchart shown in Fig. 2.

Insert Fig. 2 about here

3.2 Cross-sectional studies

Results from the NOS are shown in Table 1, with each study having a score between 4 and 8 of a possible 8. Table 2 summarises the number of participants, sex, age, anthropometric characteristics, dry-land and swim start tests performed and primary kinematic/kinetic swim start outcomes in each cross-sectional study. Out of the eight studies, four studies reported using the front crawl technique [4, 27-29], while the other studies did not report the swimming stroke used in the study.

Insert Table 1 and Table 2 about here

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Among the kinematic or kinetic outputs derived from the lower body strength/power tests, it appears that jump height and the take-off velocity obtained in the bodyweight (BW) CMJ and SJ had the greatest correlation with time to 5 m [28] and time to 15 m [29] out of all eight studies (Table 3). Pupišová & Pupiš [30] included both grab and track starts and reported a moderate (r = 0.59) and large correlation (r = 0.78) of the vertical take-off velocity in the vertical jump to swim start time to 7 m and 9 m respectively. It was unclear in the methodology of the study if any arm swing or countermovement was performed during the vertical jump.

Insert Table 3 about here

Several studies have also examined the relationship between loaded vertical jumps and swim start performance. Peak bar velocities and jump heights from loaded SJ at four loads (25%, 50%, 75% and 100% BW) had large to very large correlation with start times to 5 m, 10 m and 15 m for international female [27] and male swimmers [31]. As for lower body maximal and submaximal strength assessments, a very large relationship existed for the two studies that included the back squat to aspects of swim start performance [4, 29] (Table 3).

3.3 Intervention Studies

PEDro scores for the eight intervention studies ranged from 4 to 6 out of a maximum 11 (Table 4). Table 5 provides an overview of the acute training interventions, which includes trunk activation exercises [32] and post-activation potentiation (PAP) [33-35], while Table 6 provides an overview of the chronic training interventions, which includes plyometric training [17, 36, 37] and lower body resistance training exercises [38]. Out of the eight intervention studies identified, only one study [36] utilised a controlled trial design with an intervention and control group; the remaining seven studies utilised an uncontrolled pre- and post-test design (Table 5 and 6). The two main statistical methods used in the included intervention studies were a repeated measures ANOVA and paired T-test.

Insert Table 4, Table 5 and Table 6 about here

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Seven of the eight studies demonstrated that the participants showed within-group improvements in a number of kinematic and kinetic characteristics of swim start performance (Table 5 and 6, respectively). Iizuka et al. [32] observed a 2.3% improvement in swim time to 5 m and a 5.6% improvement in the average velocity from 0-5 m as a result of an acute trunk exercises that sought to activate deep trunk muscles such as the transverse abdominis and the internal obliques on swim start performance in 9 elite level swimmers (Table 5). All three studies that investigated the acute effects of PAP on swim start performance [33-35] demonstrated significant improvements in swim start performance (Table 5).

In the four chronic intervention studies, a number of significant improvements in swim start performance were observed in all three studies involving plyometric training (Table 6). All three studies demonstrated within group improvements in take-off velocity [17, 36, 37] and horizontal take-off velocity [17]. Likewise with swim start kinematic measures, Rejman et al. [37] and Bishop et al. [36] reported a quicker swim start time to 5 m and 5.5 m (-7.5% and -15.2% respectively) post plyometric training intervention (Table 6). In contrast, Garcia-Ramos et al. [38] observed decrements in 13 international level swimmers' swim start performance (time to 10 m: +2.3%; time to 15 m: +3.9% respectively) after a three-week sea level training camp prior to an altitude training camp. Although the study's primary aim was to quantify the effects of an altitude training camp on swimming start performance, the participants performed a sea level training camp for three weeks prior to the altitude training camp. To allow a more direct comparison of the study by Garcia-Ramos et al. [38] with the current literature, the data presented in this section relate to their sea level training camp.

4 Discussion

The main findings from the cross sectional studies included in this review are that swim start performance, as assessed by the time taken to reach predetermined set distances of 5, 10 and 15 m, was more highly related to (1) vertical SJ and CMJ than measures of maximal muscle strength, (2) body weight than loaded vertical jumps and (3) jump height than other jump kinetic or kinematic measures. The primary findings from the intervention studies included in this review were: (1) post-activation potentiation is an effective training strategy to acutely improve swim start performance, (2) plyometrics can significantly improve swim start performance in as little as six weeks.

4.1 Relationship between dry land exercises and swim start performance

A number of outputs from a variety of lower body exercises have been examined within the literature to determine their relationships to swim start performance. As the outputs of many of these lower body exercises exhibited

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nearly perfect (*r* = > 0.9), very large (*r* = 0.7-0.9) or large (*r* = 0.5-0.7) correlations with swim start performance across a variety of levels of swimmer, the results of this systematic review confirmed the importance of lower body power and strength for optimising swim start performance. The strongest relationships with swim start performance were observed for bodyweight vertical jumping exercises (CMJ and SJ), which demonstrated nearly perfect correlations [28, 29]. Large to very large correlations were observed between the time required to complete distances of between 5-15 m and performance in loaded SJ at four different loads [27, 31]. Traditional strength exercises and measures of maximal muscle strength of the lower body also had a very large correlation with time to 15 m. These results suggest that a range of outputs from a variety of lower body dry-land resistance training exercises can be used to determine the lower body strength and power capacities of swimmers required for the swim start. This may reflect the requirement for high levels of force and power to be developed across the ankle, knee and hip joints and for these to be coordinated effectively with those of the upper body to maximise take-off velocity.

The different swim start techniques used in the studies identified in this systematic review may have some implications in the comparison of the results between studies. For example, even though both Benjanuvatra et al. [28] and Garcia-Ramos et al. [27] included bodyweight CMJ and SJ in their studies, there is a discrepancy between the results obtained in both studies. Benjanuvatra et al. [28] reported a nearly perfect relationship between the take-off velocity of both bodyweight CMJ and SJ with time to 5 m, whereas Garcia-Ramos et al. [27] reported a moderate to large relationship between the take-off velocity in the bodyweight CMJ with time to 10 m and 5 m, and a large relationship between the take-off velocity of the bodyweight SJ and time to 5 m. These discrepancies may be explained by the swim start technique used in each study. Benjanuvatra et al. [28] utilised the grab start, while Garcia-Ramos et al. [27] utilised the track start, with the difference between these two start techniques being the foot placement on the blocks. Pupišová & Pupiš [30] who assessed swim start performance in both grab and track start conditions, reported a small correlation in the flight phase of the track start and a very large correlation in the flight phase of the grab start with the vertical jump. Unfortunately, no clear details were provided on whether this was a concentric only squat jump or a countermovement jump [30]. Furthermore, this study also had a very small sample size of seven swimmers and other important aspects of the methodology were somewhat unclear or did not reflect what is typically performed in the swim start. Notably, Pupišová & Pupiš [30] stated in their methodology that the swim start was performed without any underwater kicks and had swimmers glide to 7 m and 9 m. This does not represent the typical action of a swimmer of the underwater phase in the swim start, where undulatory kicks are used to maintain as much entry velocity as possible [39].

4.2 Acute changes in swim start performance after dry-land resistance training intervention

PAP can be described as a training method to improve muscle contractility, strength and speed in sporting performance by performing a small number of repetitions at maximal or near maximal effort, also referred to as conditioning activity (CA) [40], several minutes before an explosive activity [41, 42]. The use of PAP in the field of strength and conditioning has grown rapidly, with performance enhancement effects of PAP demonstrated in athletic movements such as jumping and sprinting [41]. The CA is able to potentiate the neuromuscular system, thereby allowing acute improvements in performance to be observed several minutes later as the acute fatigue from the CA diminishes [43]. Several mechanisms have been suggested for the acute PAP phenomenon, including greater recruitment of higher order motor units, increase in pennation angle and the phosphorylation of myosin regulatory light chains [44].

Four studies were identified that have examined the potential acute benefits of resistance training prior to swimming start performance, with three of these studies utilising a PAP approach [33-35]. Cuenca-Fernández et al. [35] demonstrated a positive PAP effect with respect to the time required to cover a distance of 5 m and 15 m. It was also observed that a greater reduction in these times to 5 m and 15 m was observed after the use of the split stance lunge on the flywheel inertial device at maximal voluntary contraction than the split stance lunge at 85% 1RM on the Smith machine. These results are consistent with the later study by Cuenca-Fernández et al. [34], who included the arm strokes, with one PAP protocol consisting of one set of three lunge and three arm stroke repetitions on the Smith machine at 85% of 1RM , while the other protocol comprised one set of four repetitions of both the upper and lower limb on a flywheel inertial device at maximum voluntary contraction. Both PAP protocols [34] demonstrated a shorter time to 5 m in comparison to a standard warm-up, however, there was no difference in the time to 5 m between those two interventions. Conversely, Kilduff and colleagues [33], who assessed the acute effects of one set of three repetitions of heavy, 87% of 1RM back squat on start performance, did not observe any significant reduction in the only time they recorded, i.e. the time to 15 m, but reported significant improvements in peak horizontal and peak vertical forces post PAP intervention.

Within the PAP literature, the kinematic and kinetic similarity between the CA and the subsequent movement has been reported to be an important factor, with studies in the sprint literature indicating greater PAP effects when movement patterns of the CA are followed by a biomechanically similar explosive activity [45, 46]. Thus, the utilisation of a split stance rather than traditional squat may further increase this PAP effect due to the PAP protocols being more biomechanically similar to the foot position and direction/timing of force application in the kick start technique on the OSB11 start block. The significant improvements in time to 5 m [34, 35] and 15 m [35] and peak horizontal and peak vertical forces [33] observed post PAP intervention suggest some benefits of using PAP as a pre-race warm-up to enhance a swimmer's swim start performance. However, the duration over which the potentiation effect lasts may be too short to be utilised as a component of pre-competition warm-ups in swimming competitions. A meta-analysis by Gouvêa et al. [40] of PAP on jumping performance has shown that an optimal PAP effect was found with a recovery period of 8 to 12 minutes after the preceding CA, with the PAP effect dissipating after a recovery period of 16 minutes or more. Specifically, Cuenca-Fernández et al. [34] utilised a rest period of 6 mins and Cuenca-Fernández et al. [35] and Kilduff et al. [33] utilised a rest period of 8 mins between the CA and the explosive activity i.e. swim start. During competitions, swimmers may have to wait in marshalling areas for a period of up to 20 minutes after they complete their warm-up until they compete in their specific events. This could pose some current challenges as to how a PAP stimulus may be used to enhance swim start performance as a pre-competition warm-up strategy, especially as the successful PAP interventions identified in the current review have utilised heavy resistance training devices that would not be available in the marshalling areas.

In addition to using PAP to achieve short term performance enhancement, it has been suggested that PAP can be manipulated to enhance the training stimulus of explosive strength exercises to induce greater chronic training-related adaptations than traditional resistance training exercises. The manipulation of PAP within a resistance training program is also known as complex training [47]. Complex training combines heavier resistance training exercise with a lighter load power-oriented exercise in an attempt to transfer gains in strength to power [47]. The rationale for this complex pairing of exercises was that the heavy resistance strength-oriented set would provide an enhanced neural drive, which would then carry over to the lifting of the lighter resistance explosive exercise, resulting in a greater power output in the explosive exercise than would occur without the prior heavy resistance set [48]. PAP may be a viable training method when incorporated into a swimmers' regular dry-land resistance training program and possibly contribute to enhanced swim start performance after several months of training. However, due to the lack of any such chronic PAP studies involving swimmers, future studies are required to document whether significant chronic adaptations in physical capacities and swim start performance can be observed after a PAP training program.

Trunk stability is an important component in swimming as it allows for an efficient transfer of forces between the trunk and the upper and lower extremities to propel the body through the water and off the start blocks [49]. Weston et al. [50] have demonstrated chronic improvements in swimmers' core function and 50 m front crawl swim time with the implementation of a 12-week isolated trunk training program. Within the scope of this review, Iizuka et al. [32] demonstrated significant acute improvements in swim start performance as a result of acute resistance training exercises for the trunk. The authors suggested that the trunk stabilisation exercises provided enhanced trunk stability which led to an immediate improvement in time to 5 m and average velocity over 5 m.

4.3 Changes in swim start performance after dry-land resistance training intervention

The combined use of dry-land resistance training and swim training is a common practice in competitive swimming [18, 51]. By overloading the muscles required for swimming with external resistances, a dry-land resistance training program aims to increase the strength and power production of muscles that play important roles in competitive swimming events [52, 53]. Dry-land resistance training modalities can include ballistic training such as Olympic style lifts e.g. cleans and their variations as well as plyometric activities, while non-ballistic training includes the use of free weight, bodyweight and/or machine based exercises [18, 54]. Plyometric training refers to the performance of stretch-shortening cycle (SSC) movements involving a short duration, high velocity eccentric contraction followed by a rapid concentric contraction [55]. Athletes who can effectively use the SSC can produce significantly greater concentric force, velocity and power compared to what is possible in concentric only muscular contractions. The mechanisms contributing to this effect reflects specific neural adaptations of the SSC, the storage and utilisation of elastic strain energy, the stretch reflex and/or an increase in the active state of the muscle [56, 57]. Engaging in a plyometric training program that requires fast muscular contraction of the lower body has been demonstrated to significantly improve swim start performance in all three studies identified in this systematic review [17, 36, 37], with significant improvements in key swim start parameters, such as time to 5 m and 5.5 m, take-off velocity and horizontal forces and impulse observed. As the swim start is a predominantly concentric movement, these specific training adaptations from the plyometric training studies would appear to be a direct results of the swimmers' ability to utilise the neural benefits of the SSC and rapidly develop concentric force rather than their ability to utilise the SSC as a result of improvements in the athletes' eccentric strength capacity [55, 58]. In the study conducted by Rebutini et al. [17], the authors hypothesised that the long jumps performed in the training program would be effective in improving the kinetics of the swim starts because they required the production of horizontal forces at similar velocities to the actual swim start. Such a hypothesis was consistent with the results of these studies, with significant increases in swim start horizontal take-off velocity, peak horizontal forces and/or horizontal impulse observed by Rebutini et al. [17], and time to 5 m and take-off velocity by Rejman et al. [37].

The available evidence on dry-land resistance training with free weights is limited. In this systematic review, we only found one study [38] that included resistance training exercises such as variations of the squat, deadlift, hip

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thrust, leg flexion and extension exercises, although such exercises appear to be commonly used by competitive swimmers. Results indicated no significant difference in swim start performance after the three-week dry-land resistance training program that was performed prior to the altitude training camp. When comparing results of this study involving resistance training exercises [38] to the three studies involving plyometric training [17, 36, 42], it was apparent that the three weeks of traditional resistance training was of substantially shorter duration than six to nine weeks of plyometric training [17, 36, 37]. Furthermore, the swimmers were performing two swim sessions and one dry-land (some combination of resistance, cardiovascular and flexibility) session six days per week [38]. This three-week resistance training program involved a substantially greater weekly training load than the three plyometric studies. Due to these differences between the one traditional resistance training and three plyometric studies, it is difficult to determine on the basis of the current evidence whether plyometric, traditional resistance training or a combined approach may be most useful for improving swim start performance. Beyond the differences in training duration and weekly loads, it is also possible that the specificity principle may also underlie the potentially greater adaptations currently found for plyometric than traditional resistance training for improving swim start performance. Specifically, the more specific a training exercise is to a competitive movement, including the velocity, direction and time of force application, the greater the likely transfer of the training effect to performance [59, 60]. The studies by Rebutini et al. [17] and Rejman et al. [37] shared a key feature in their plyometric training programs, which is an emphasis on the horizontal direction in the plyometric exercises performed. Rebutini et al. [17] included long jumps in their plyometric training intervention and Rejman et al. [37] modified the starting position of the plyometric exercises to better simulate the swimming start and to emphasise a greater horizontal direction of take-off. The improvements in swim start performance observed with all three plyometric studies [17, 36, 37] appear to be indicative of the potential for different forms of plyometric training to elicit significant improvements in swimming start performance with as little as six to nine weeks of training.

4.4 Methodological considerations

4.4.1 Measurement of the swim start

Of the eight cross-sectional and eight intervention studies included in this systematic review, only four studies [31, 32, 35, 38] utilised the kick start technique and the OSB11 start block that is currently used in competitive swimming. Even though the track start utilised in four [27, 30, 37, 61] out of the 16 studies included in this systematic review may have some similarities to the kick start technique currently used in competitive swimming,

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Honda et al. [16] have identified that the additional kick plate on the OSB11 start block is capable of significantly improving both time to 5 m and 7.5 m, with a further 0.04s improvement obtained in the kick start compared to the track start technique at both distances. This is attributed to an increase in horizontal force production that is able to be produced by the rear leg on the kick plate of the OSB11 starting block, which ultimately increases horizontal take-off velocity [16].

The eight cross-sectional studies included in the review exhibited some degree of inconsistency with the measurement of the swim start performance kinematic measures, such as the time to set distances of 5, 10 and/ or 15 m. The majority of the studies [4, 27, 28, 31] measured swim start time when the head crossed the specified distances in their study. Two studies [61, 62] measured swim start time when the fingertips crossed 10 m, with the two other studies [29, 30] not specifying how the start time to 15 m was measured. For the intervention studies, four intervention studies [17, 34, 35, 38] measured the time to set distances when the head crossed the specified distance, while Iizuka et al. [32] measured the time to 5 m when the fingertips crossing 5 m. Despite reporting the same measure of the time to distances of 5 m and 5.5 m, there appears to be a discrepancy in the values reported between the training intervention study by Rejman et al. [37] and Bishop et al. [36]. This is due to the difference in how the swim start was quantified in both studies. Rejman et al. [37] quantified time to 5 m from the time from the final shift of centre of mass from the edge of the starting block to a distance of 5 m, whereas Bishop et al. [36] recorded time to 5.5 m using the time from starting stimulus to the point in time at which the head made contact with the water surface.

There also appear to be some differences in the nature of the swim task performed across these studies. Within this review, the majority of the studies tested the swimmers under competition rules [4, 17, 27-29, 33-36, 61, 62]. In contrast, some studies included a dive and glide test [30, 37] while Garcia-Ramos [31] had swimmers perform undulatory kicks till 15 m. Therefore, it is possible that variety of swim start methodologies performed may have significant implication in the comparison of results between studies.

4.4.2 Strength diagnostics

Tests of muscular strength and/or power qualities are commonly performed to assess training-induced changes and the efficacy of a strength and conditioning program in many athletic populations [63]. For sports requiring high to very high levels of muscular strength, maximal and submaximal strength assessments or isometric assessments such as the isometric mid-thigh pull are commonly used [63]. For dynamic performance qualities,

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vertical lower body jumping exercises are common measurement tools of athletic lower body force and power ability [64].

The majority of the cross-sectional [4, 27-31, 62] and one intervention study [38] identified in this systematic review utilised dynamic lower body exercises such as the CMJ and SJ as a measurement of lower body power. Only two of eight cross-sectional studies [4, 29] and four of eight intervention studies [17, 33-35] included any maximal strength assessments. The relative lack of maximal strength assessments compared to explosive total body jumping exercises in this systematic review may reflect the task demands of the swim start whereby high levels of lower body power rather than maximal muscle strength are required to enhance swim start performance.

4.4.3 Study population

The magnitude of difference in strength characteristics and response to a resistance training program can be affected by sex, age and training status [65]. Majority of the studies reviewed generally consisted of a small sample size and a potentially greater bias towards male compared to female participants. Only two of the cross-sectional studies had all female swimmers and the four studies that had a mix of females and males had an uneven split of both sexes, with a greater number of male participants compared to females. In addition, the majority of studies did not provide any clear description of the resistance training experience or the baseline levels of lower body muscular strength of their participants. Specifically, only two [4, 29] out of the eight cross-sectional and three acute intervention studies [33-35] included any details regarding the baseline strength level of the swimmers. As such, it is difficult to determine how sex, age and training status may influence the relationship and/or training response between dry-land jump performance to swim start performance.

4.4.4 Study design

With respect to the intervention studies, one factor for potential bias could be the research design and statistical analyses used in the studies. Only one [36] out of the eight intervention studies identified utilised a controlled trial design with an intervention and control group, with the remainder of the studies using a within group pre-post test statistical comparison using ANOVA or paired T-tests.

The lack of control groups and the use of a within group statistical analysis approach in the intervention studies make it difficult to determine whether the improvements in swim start performance were a result of the dry-land resistance training intervention, or whether they were related to the overall swim training program. One possible

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reason for the lack of randomised controlled trials may reflect the relatively limited sample size of high performance swimming squads.

5 Conclusion

Within the limits of the review, the current literature indicates that a range of lower body strength and power measures are highly correlated with swim start performance, with these correlations appear greatest when utilising body weight vertical jumping exercises. These findings would suggest that assessing vertical jump performance would be a better diagnostic tool to assess lower body power capabilities than traditional strength assessments for swim start performance. Significant acute and chronic swim start performance benefits can be obtained using a PAP training protocol and lower body plyometric exercises that are primarily horizontal in direction, respectively. Despite the relative homogeneity of participants in the studies included in this review, the results across intervention studies suggest that significant improvements in swim start performance can be obtained from both a PAP training protocol and plyometric exercises independent of skill level.

Due to the relative lack of research with the currently used OSB11 starting block and kick start technique, future cross-sectional and intervention studies should utilise the current start block and start technique to confirm that the findings highlighted in this review applies to current practices in competitive swimming. Given that swimmers simultaneously integrate swim training and dry-land resistance training within a periodised program to develop muscular strength and power capabilities [18, 54], additional research should also compare the potential benefits of different dry-land resistance training approaches to provide a better understanding of the development of strength and conditioning programs more conducive to improving swim start performance.

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Compliance with Ethical Standards

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Conflict of interest Shiqi Thng, Simon Pearson and Justin Keogh declare that they have no conflict of interest with the content of this article.

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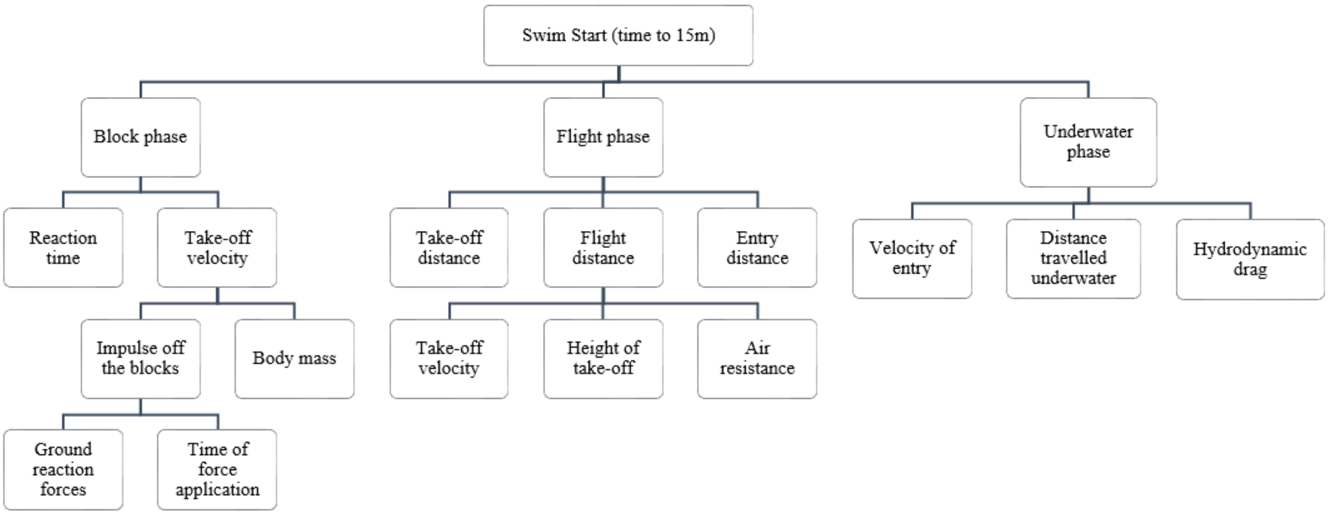

Fig. 1 Deterministic model of the swim start

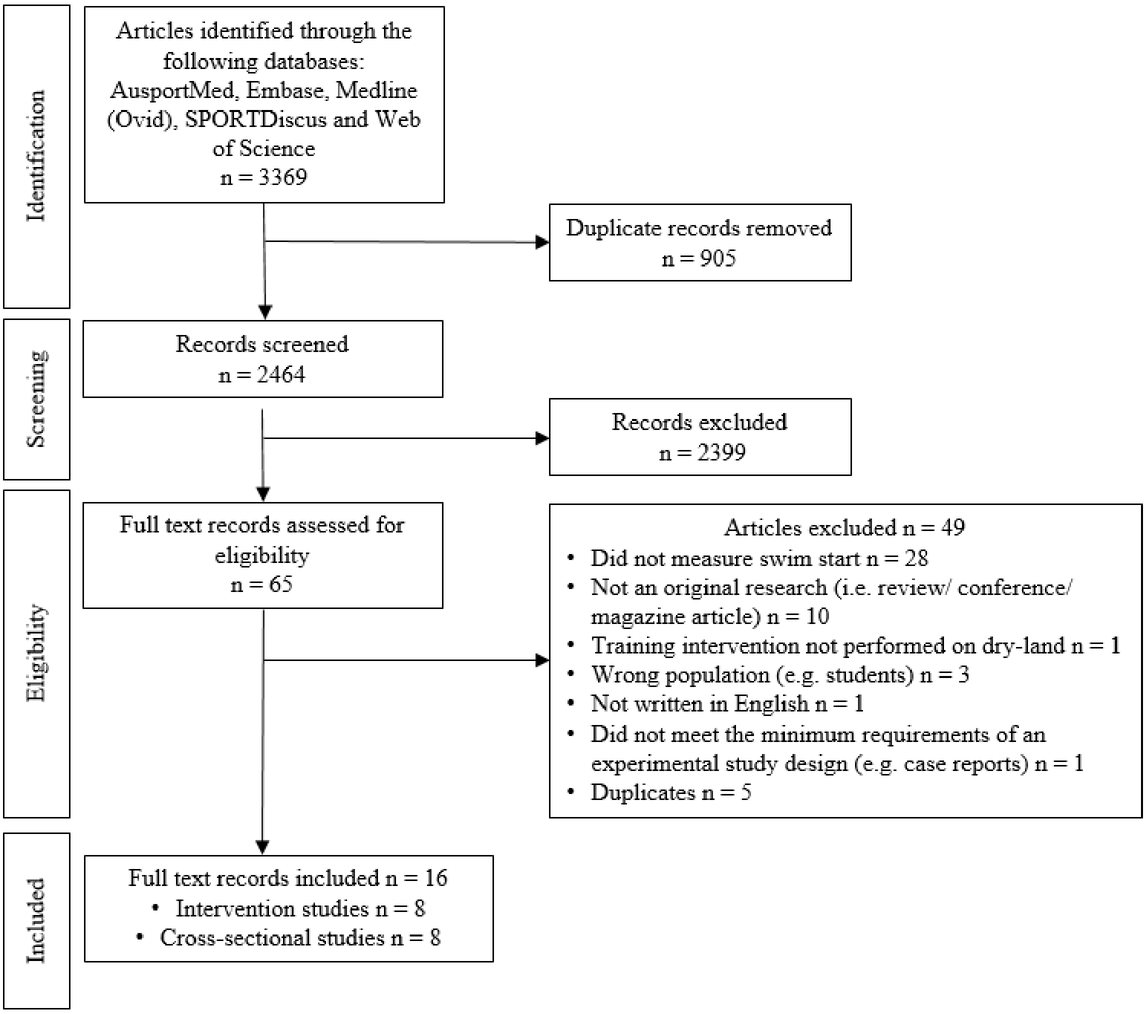

Fig. 2 Flowchart illustrating the search process according to the PRISMA guidelines

Table 1 Quality of the reviewed studies according to the Newcastle Ottawa Scale (NOS) for cohort studies

Reference	NOS score								
	Selection				Comparability	Outcome			Total score (out of 8)
	Item 1	Item 2	Item 3	Item 4	Item 5[a]	Item 6	Item 7	Item 8	
Benjanuvatra et al. [28]	1	1	1	1	2	0	N/A	1	7
Beretic et al. [61]	1	1	1	1	2	0	N/A	1	7
Garcia-Ramos et al. [27]	1	1	1	1	2	1	N/A	1	8
Pupišová & Pupiš [30]	1	1	0	0	1	0	N/A	1	4
Garcia-Ramos et al. [31]	1	1	1	0	2	1	N/A	1	7
Đurović et al. [62]	1	1	1	1	2	0	N/A	1	7
Keiner et al. [29]	1	1	1	0	1	0	N/A	1	5
West et al. [4]	1	1	1	0	2	0	N/A	1	6
Mean									6

Notes: 0 = no; 1 = yes; Item 1: representativeness of the exposed cohort; Item 2: selection of the non-exposed cohort; Item 3: ascertainment of exposure; Item 4: demonstration that outcome of interest was not present at start of study; Item 5: comparability of cohorts on the basis of the design or analysis; Item 6: assessment of outcome; Item 7: was follow-up long enough for outcomes to occur; Item 8: adequacy of follow up of cohorts; N/A = not applicable

[a]Maximum of 2 points can be given to item 5

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Table 2 Summary of participant background and methodology used in the included cross-sectional studies

Reference	Participants Sex	Age (years) Anthropometrics (mean ± SD)	Dry-land exercises tested	Swim start test	Measured swim start key performance variables (units)
Grab start					
Benjanuvatra et al. [28]	9 elite and 7 recreational level swimmers (F)	Elite: 19 ± 1.3 yrs 1.67 ± 0.06 m 65.5 ± 10.4 kg Recreational: 22 ± 3.1 yrs 1.69 ± 0.07 m 57.5 ± 5.9 kg	CMJ: 6 x vertical CMJ, 6 x horizontal CMJ SJ: 6 x vertical SJ, 6 x horizontal SJ	1 x maximal effort swim to 25 m	T5 m, T10 m (s) TOV (m/s) Reaction time (s) Movement time (s) Total time spent on blocks (s) hIMP, vIMP (N/kg)
Track start					
Beretic et al. [61]	27 international level swimmers (M)	21.1 ± 4.3 yrs 1.89 ± 10.3 m 81.6 ± 8.4 kg	2 x 5s leg extension MVIC at 1000 Hz	Best of 3 x swim starts to 10 m	T10 m (s)
Garcia-Ramos et al. [27]	20 international level swimmers (F)	15.3 ± 1.6 yrs 1.67 ± 0.06 m 57.2 ± 7.4 kg	3 x CMJ 3 x SJ 2 x loaded SJ 25, 50, 75, 100% BW each on Smith machine 2 x progressive and 2 x explosive leg extension and flexion MVIC	1 x swim start to distance slightly further than 15 m under competition rules	T5 m, T10 m, T15 m (s)
Kick start					
Garcia-Ramos et al. [31][a]	15 national and international level swimmers (M)	17.1 ± 0.8 yrs 1.81 ± 0.07 m 74.1 ± 8.0 kg	2 x unloaded SJ with 0.5kg bar Loaded SJ at 25, 50, 75, 100% BW on Smith machine	1 x swim start, using only undulatory kicks to distance slightly further than 15 m	T5 m, T10 m, T15 m (s)
Đurović et al. [62]	27 national level swimmers (M)	20.1 ± 3.4 yrs 1.82 ± 0.06 m 73.5 ± 7.3 kg	5 x SJ	Best of 2 x swim starts to 10 m	T10 m (s)
Keiner et al. [29]	21 regional level swimmers (12 M, 9 F)	17.5 ± 2.0 yrs 1.77 ± 0.10 m 69.5 ± 11.4 kg	SJ CMJ 1RM back squat 1RM deadlift	1 x maximal effort swim to 25 m under competition rules	T15 m (s)
West et al. [4]	11 international level swimmers (M)	21.3 ± 1.7 yrs 1.80 ± 0.10 m 78.1 ± 11.2 kg	3 x CMJ 3RM back squat	2 x swim start to distance slightly further than 15 m under competition rules	T15 m (s) hSPF (N), vSPF (N)

1RM = one repetition maximum; 3RM = three repetition maximum; BW = bodyweight; CMJ = countermovement jump; F = females; hIMP = horizontal impulse; hSPF = starting peak horizontal forces; M = males; MVIC = maximum voluntary isometric contraction; SJ = squat jump; T5 m = Time to 5 metres; T10 m = Time to 10 metres; T15 m = Time to 15 metres; TOV = take-off velocity; vIMP = vertical impulse; vSPF = starting peak vertical forces; vTOV = vertical take-off velocity; [a]Only sea level data were included

Table 3 Summary of the results indicating the relationship between dry-land exercises and swim start performance

Reference	Correlated dry-land exercises	Correlated dry-land key performance variables (units)	Dry-land exercise correlation to swim start performance measures				
			T5m	T10m	T15m	sPFh	sPFv
Grab start							
Benjanuvatra et al. [28]	VCMJ	VCMJ-JH (cm)	r = -0.96**				
T5m: (recreational only)		VCMJ-TOV (m/s)	r = -0.95**				
T15m: (elite only)	VSJ	VSJ-JH (cm)	r = -0.92**				
		VSJ-TOV (m/s)	r = -0.91**				
	HCMJ	HCMJ-TOV (m/s)	r = -0.86*				
	HSJ	HSJ-TOV (m/s)	r = -0.86*				
		HSJ-JD (cm)			r = -0.72*		
Track start							
Beretic et al. [61]	Leg extension MVIC	F_{rel} (N/kg)		r = -0.73***			
		F_{max} (N)		r = - 0.56*			
Garcia-Ramos et al. [27]	BW-CMJ	CMJ-TOV (m/s)	r = -0.62**	r = -0.49*			
	BW-CMJ	CMJ- PP_{rel} (W/kg)	r= -0.61**	r= -0.55*			
	BW-SJ	SJ-TOV (m/s)	r= -0.56*				
	BW-SJ	SJ-PP_{rel} (W/kg)	r= -0.57**				
	L-SJ at 25, 50, 75, 100% BW	BV (m/s)	BV at 50% BW r = -0.72**	BV at 75% BW r= -0.59**	BV at 75%BW r= -0.68**		
			BV at 25%BW r = -0.66**	BV at 25% BW r = -0.57**	BV at 100%BW r= -0.64**		
			BV at 75%BW r= -0.63**	BV at 50% BW r = -0.57**	BV at 25%BW r = -0.63**		
			BV at 100%BW r= -0.57*	BV at 100% BW r= -0.50*	BV at 50%BW r = -0.63**		
		PP_{rel} (W/kg)	PP_{rel} at 50%BW r = -0.63**	PP_{rel} at 25%BW r = -0.55*	PP_{rel} at 75% BW r= -0.64**		
			PP_{rel} at 25%BW r = -0.62**	PP_{rel} at 75%BW r= -0.54*	PP_{rel} at 100%BW r= -0.64**		
			PP_{rel} at 75%BW r= -0.57**	PP_{rel} at 50%BW r = -0.51*	PP_{rel} at 25%BW r = -0.57**		
			PP_{rel} at 100%BW r= -0.54*	PP_{rel} at 100%BW r= -0.47*	PP_{rel} at 50%BW r = -0.54*		
		PP (W)		PP at 25%BW r = -0.49*	PP at 25% BW r = -0.49*		
Kick start							
Garcia-Ramos et al. [31][a]	UL-SJ with 0.5 kg bar	JH (cm)	UL-JH r = -0.55*	UL-JH r = -0.77**	JH at 75% BW r= -0.72**		
	L-SJ at 25, 50, 75, 100% BW		JH at 50% BW r = -0.53*	JH at 75% BW r= -0.73**	JH at 100% BW r= -0.70**		
			JH at 25% BW r = -0.52*	JH at 25% BW r = -0.68**	UL-JH r = -0.67**		
				JH at 100% BW r= -0.68**	JH at 25% BW r = -0.58*		
				JH at 50% BW r = -0.65**			
Start technique not stated							
Đurović et al. [62]	BW-SJ	PP (W)		r = -0.39*			
		P_{avg} (W)		r = -0.43*			
		F_{max} (N)		r = -0.42*			
		PP_{rel} (W/kg)		r = -0.55*			
		PP_{avgrel} (W/kg)		r = -0.59*			
		F_{rel} (N/kg)		r = -0.64**			

Keiner et al. [29]	BW-SJ	JH (cm)	r = -0.94*		
	BW-CMJ	JH (cm)	r = -0.92*		
	1RM back squat	1RM back squat (kg)	r = -0.76*		
	1RM deadlift	1RM deadlift (kg)	r = -0.68*		
West et al. [4]	BW-CMJ	PP (W)	r = -0.85**	r = 0.87**	
		JH (cm)	r = -0.69*	r = 0.73*	r = 0.78**
		PP_{rel} (W/kg)	r = -0.66*	r = 0.78**	r = 0.79**
	3RM back squat	Estimated 1RM back squat (kg)	r = -0.74**	r = 0.71*	r = 0.62*

1RM = one repetition maximum; 3RM = three repetition maximum; BV = bar velocity; BW = bodyweight; CMJ = countermovement jump; F_{max} = leg extensor maximum voluntary force; F_{rel} = leg extensor relative maximum voluntary force; JD = jump distance; HCMJ = horizontal countermovement jump; HSJ = horizontal squat jump; JH = jump height; L = loaded; MVIC = maximum voluntary isometric contraction; P_{avg} = average power; PP_{avgrel} = average relative power; PP = peak power; PP_{rel} = relative peak power; SJ = squat jump; sPFh = starting peak horizontal forces; sPFv = starting peak vertical forces; TOV = take-off velocity; UL = unloaded; VCMJ = vertical countermovement jump; VSJ = vertical squat jump; $p < 0.05$*; $p < 0.01$**; $p < 0.001$***

[a]Only sea level data were included; values for each study are listed from highest to lowest correlation

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Table 4 Quality of the included intervention studies as assessed on the Physiotherapy evidence database (PEDro) scale

Reference	PEDro scores										
	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8	Item 9	Item 10	Item 11	Total score (out of 11)
Acute interventions												
Iizuka et al. [32]	0	0	0	0	0	0	0	1	1	1	1	4
Cuenca-Fernandez et al. [35]	1	1	0	0	0	0	0	1	1	1	0	5
Cuenca-Fernandez et al. [34]	1	1	0	0	0	0	0	1	1	1	1	6
Kilduff et al. [33]	1	1	0	0	0	0	0	1	1	1	0	5
Chronic interventions												
Bishop et al. [36]	1	1	0	0	0	0	0	1	1	1	0	5
Garcia-Ramos et al. [38]	0	0	0	0	0	0	0	1	1	1	1	4
Rebutini et al. [17]	1	0	0	0	0	0	0	1	1	1	0	4
Rejman et al. [37]	1	0	0	0	0	0	0	1	1	1	0	4
Mean												5

Notes: 0 = item not satisfied; 1 = item is satisfied; Item 1 = eligibility criteria were specified; Item 2: subjects were randomly allocated to groups; Item 3: allocation was concealed; Item 4: the groups were similar at baseline regarding the most important prognostic indicators; Item 5: there was blinding of all subjects; Item 6: there was blinding of all therapists who administered the therapy; Item 7: there was blinding of all assessors who measured at least one key outcome; Item 8: measures of at least one key outcome were obtained from more than 85% of the subjects initially allocated to groups; Item 9: all subjects for whom outcome measures were available received the treatment or control condition as allocated or, where this was not the case, data for at least one key outcome was analysed by "intention to treat"; Item 10: the results of between-group statistical comparisons are reported for at least one key outcome; Item 11: the study provides both point measures and measures of variability for at least one key outcome

Table 5 Summary of participant background, methodology and results of acute dry-land training intervention programs on swim start performance

Reference	Participants Sex Age (years) Anthropometrics (mean ± SD)	Dry-land training intervention protocol	Start technique	Swim test	Swim start key performance measures (units) Kinematics	 Kinetics	Results		
Trunk activation exercises									
Iizuka et al. [32]	9 elite level swimmers	Three trunk stabilisation	Kick start	1 x swim start to 5 m			Pre	Post	
	(M)	exercises			T5m (s)		0.83 ± 0.04	0.81 ± 0.04*	
	20.2 ± 1.0 yrs				V5m (m/s)		4.61 ± 0.46	4.87 ± 0.35*	
	1.74 ± 0.04 m; 68.9 ± 4.1 kg								
Post-activation potentiation									
Cuenca-Fernandez et al.	14 recreational swimmers	LWU: 1 x 3 each leg @	Kick start	1 x maximal effort			SWU	LWU	YWU
[35][a]	(10 M, 4 F)	85% 1RM		swim start to 15 m	T5m (s)		1.75 ± 0.05	1.71 ± 0.05*	1.65 ± 0.04*
	17 to 23 yrs	YWU: 1 x 4 each leg @		under competition	T15m (s)		7.54 ± 0.23	7.40 ± 0.21	7.36 ± 0.22*
	1.76 ± 0.09 m; 69 ± 11.4 kg	MVC		rules					
Cuenca-Fernandez et al.	17 national level swimmers	RMWU: 1 x 3 each arm + 1	Unspecified	1 x maximal effort 50			SWU	RMWU	EWU
[34][b]	(M)	x 3 each leg @ 85% 1RM		m race under	T5m (s)		1.57 ± 0.11	1.52 ± 0.13*	1.52 ± 0.13*
	18.4 ± 1.4 yrs	EWU: 1 x 4 each arm +		competition rules	V5m (m/s)		3.12 ± 0.28	3.27 ± 0.29*	3.28 ± 0.27*
	1.81 ± 0.02 m; 73.7 ± 9.0 kg	1 x 4 each leg @ MVC			V10m (m/s)		1.79 ± 0.17	1.83 ± 0.15*	1.84 ± 0.16*
Kilduff et al. [33][a]	9 international level sprint	Barbell back squat	Unspecified	1 x swim start to 15 m			Pre	Post	
	swimmers	1 x 3 @ 87% 1RM		under 50 m FS race		sPFv (N)	1462 ± 280	1518 ± 311*	
	(7 M, 2 F)			conditions		sPFh (N)	770 ± 228	814 ± 263*	
	22 ± 2 yrs								
	1.79 ± 0.14 m; 77.9 ± 11.2 kg								

1RM = one repetition maximum; EWU = arm stroke and split stance lunge on flywheel inertial device; F = females; FS = freestyle; LWU = split stance lunge on Smith machine; M = males; MVC = maximum voluntary contraction; RMWU = arm stroke and split stance lunge on Smith machine; sPFh = starting peak horizontal forces; sPFv = starting peak vertical forces; SWU = standard warm-up; T5m = time to 5 metres; T15m = time to 15 metres; V5m = average velocity at 5m; V10m = average velocity from 5m to 10m; YWU = YoYo split stance lunge on flywheel inertial device; $p < 0.05$*
[a]8 minutes' rest in between post-activation potentiation stimulus and swim start; [b]6 minutes' rest in between post-activation potentiation stimulus and swim start

Table 6 Summary of participant background, methodology and results of chronic dry-land training intervention programs on swim start performance

Reference	Participant Sex Age (years) Anthropometrics (mean ± SD)	Dry-land training Intervention protocol Intervention duration	Start technique	Swim test	Swim start key performance measures (units)		Results	
					Kinematics	Kinetics		
Plyometric exercises								
Bishop et al. [36]	22 adolescent swimmers	2 x 60 minutes/ week	Preferred technique	1 x swim start to			Pre	Post
	(not stated)	consisting of skips, hops		5.5 m	T5.5m (s)		Control: 3.94 ± 0.39	Control: 3.82 ± 0.38
	PT: 13.1 ± 1.4 yrs; control: 12.6 ± 1.9 yrs	and jumps for lower					PT: 3.88 ± 0.48	PT: 3.29 ± 0.47
	PT: 1.63 ± 0.12 m; control: 1.58 ± 0.12 m	body						PT vs control***
	PT: 50.6 ± 12.3 kg; control: 43.3 ± 11.6 kg	8 weeks			TOV(m/s)		Control: 1.17 ± 0.10	Control: 1.10 ± 0.16
							PT: 1.29 ± 0.18	PT: 1.48 ± 0.15
								PT vs control***
Rebutini et al. [17]	10 national level swimmers	2x/ week long jump	Preferred technique	Best of 2 x			Pre	Post
	(7 M, 3 F)	training consisting of		maximal effort		sPFh (N)	837 ± 153	847.33 ± 164.23*
	M: 22 ± 1.4 yrs; F: 21.3 ± 7.6 yrs	maximal horizontal and		swim starts to		IMP (N/s)	221.9 ± 61.6	242.5 ± 60.9*
	M: 1.78 ± 0.06 m; 69.8 ± 4.8 kg	maximal long jumps		15 m under	TOV (m/s)		1.93 ± 0.18	2.13 ± 0.28*
	F: 1.70 ± 0.05 m; 59.9 ± 2.9 kg	9 weeks		competition rules	hTOV (m/s)		1.84 ± 0.19	2.14 ± 0.21*
Rejman et al. [37]	9 national level swimmers	2 x 60 minutes/ week	Track start	Best of 3 x swim			Pre	Post
	(M)	consisting of skips,		start to 5 m	T5m (s)		1.87	1.73***
	21.9 ± 3.4 yrs	bounds, hops and jumps			TOV (m/s)		1.88	2.14**
	1.79 ± 0.001 m; 75.1 ± 6.6 kg	6 weeks						
Resistance training								
Garcia-Ramos et al. [38][a]	13 international level swimmers	Variations of the squat,	Kick start	Best of 2 x swim			Pre	Post
	(5 M, 8 F)	deadlift, hip thrust, leg		starts to distance	T10m (s)		4.37 ± 0.42	4.47 ± 0.39*
	18.1 ± 3.4 yrs	flexion and extension		slightly further	T15m (s)		7.26 ± 0.51	7.54 ± 0.61*
	1.72 ± 0.08 m; 62.6 ± 8.5 kg	exercises		than 15 m				
		3 weeks						

F = females; hTOV = horizontal take-off velocity; IMP = impulse; M = males; PT = plyometric training; sPFh = starting peak horizontal forces; T5m = time to 5 metres; T5.5m = time to 5.5 metres; T10m = time to 10 metres; T15m = time to 15 metres; TOV = take-off velocity; $p < 0.05$*; $p < 0.01$**; $p < 0.001$***

[a]Only sea level data was included