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Research article

Comparing The Effects of Maximal Strength Training, Plyometric Training, and Muscular Endurance Training on Swimming-Specific Performance Measures: A Randomized Parallel Controlled Study in Young Swimmers

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Abstract

The aim of this study was to compare the effects of maximal strength training (MST), plyometric training (PT), and muscular endurance training (MET) on starting performance and swimming performance at 25- and 50-meters freestyle. A randomized parallel controlled study was conducted involving twenty-seven high-level university swimmers (Tier 2), both men and women (age: 20.2 ± 1.1 years). The training interventions lasted six weeks, with each training group participating twice a week. MST involved resistance training at 80-95% of one maximum repetition, while PT included maximal eccentric-concentric quick movements. MET, considered as a control group, consisted of free-weight exercises or light loads performed multiple times. The swimmers were assessed before, during (in the 3rd week), and after the interventions by measuring their start performance based on takeoff distance and time at the 15-meter mark. Swimming performance was assessed through the following tests: 25-meter freestyle kicking (without stroking), 25-meter freestyle stroke (without kicking), and 25-meter and 50-meter freestyle sprints. The mixed ANCOVA, using pre-evaluation scores as covariates, revealed that after the intervention, MST was significantly better than MET in start flight distance ($p = 0.021$), 15-meter start time ($p < 0.001$), 25-meter freestyle kick ($p < 0.001$), 25-meter freestyle stroke ($p < 0.001$), 25-meter freestyle ($p = 0.004$), and 50-meter freestyle ($p < 0.001$). PT was also significantly better than MET in 15-meter start time ($p = 0.004$), 25-meter freestyle kick ($p = 0.011$), 25-meter freestyle stroke ($p < 0.001$), and 50-meter freestyle ($p = 0.014$). After the intervention, no significant differences were found between MST and PT, although some differences were observed during the mid-evaluation. The conclusions reveal that, although all groups showed significant improvement in performance, MST and PT exhibited significantly better results compared to MET in enhancing sprint freestyle performance overall.

Key words: Swimming; sports training; resistance training; sports performance; dry-land strength training.

Introduction

Swimming sprint events, particularly the 50-meter freestyle, place considerable physiological and muscular demands on athletes. These events require a highly developed anaerobic system (Nagle Zera et al., 2021), combined with exceptional muscular power (West et al., 2011) applied through proper stroke technique (Morais et al., 2023). Research also shows that lower and upper body and core muscle power (West et al., 2011; Keiner et al., 2015) are essential for achieving explosive starts and rapid strokes, which are characteristic of sprinting. Key factors influencing performance in these events include stroke technique, which optimizes propulsion while minimizing drag (Morais et al., 2022), as well as reaction time (Papic et al., 2019) and power at the start (Keiner et al., 2021), both of which impact overall race times. Furthermore, the ability to maintain high stroke rates with minimal energy expenditure is critical, as elite sprinters typically exhibit superior biomechanical efficiency (Morris et al., 2016). Thus, in addition to regular swim training, a strength and conditioning program that enhances muscular strength and power is crucial for maximizing performance in the 50-meter freestyle (Bishop et al., 2013).

Among the various forms of resistance training, maximal strength training (MST), plyometric training (PT) each may offer different benefits for sprint swimmers (Crowley et al., 2017). MST focuses on increasing the peak force a muscle or muscle group can generate, typically through low-repetition, high-resistance exercises (Keiner et al., 2021). For sprint swimmers, this can enhance their ability to execute powerful strokes and explosive starts—both crucial in short, high-intensity races like the 50-meter freestyle (Keiner et al., 2021). PT, which involves explosive movements that utilize the stretch-shortening cycle and potentiation with relatively low resistance, may improve neuromuscular efficiency by increasing the rate of force development for instance (Huang et al., 2023). This may translate to faster stroke rates and quicker starts, both key for sprint swimming success (Fone and van den Tillaar, 2022).

Considering the impact of MST on the 25-meter freestyle, a previous experimental study reported improved performance (Amara et al., 2021), while another found no overall change except for enhanced sprint start performance (Born et al., 2020). For shorter distances ranging from 5 to 15 meters, only Schumann et al. (Schumann et al., 2020) observed significant improvements in swimming speeds over 10 meters. Regarding PT, a previous study demonstrated its significant effectiveness in improving block start performance in swimming (Bishop et al., 2009), while another (Sammoud et al., 2019) found it to significantly enhance the 25-meter kick without push-off and the 25-meter front crawl, proving more effective than standard swimming training alone for improving jump performance and sport-specific swimming skills. A previous study also

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found that PT effectively enhanced 50-meter sprint swimming performance following the training intervention (Potdevin et al., 2011).

Recommendations for strength training in swimmers highlight the importance of incorporating various training methods to enhance performance (Bishop et al., 2013). To optimize training schedule and athletic performance, it is essential to explore the differences between resistance training methods. A recent systematic review (Crowley et al., 2017) suggests that specific, low-volume, high-velocity/force resistance training programs are ideal for maximizing transfer to performance. In particular, stroke length appears to benefit most from low-repetition, high-velocity/force training, while resisted swims are considered the most effective for enhancing stroke rate (Crowley et al., 2017). However, despite these theoretical distinctions, there is still no clear consensus on which strength training method is most advantageous for swimming performance, as emphasized in a recent systematic review (Fone and van den Tillaar, 2022). This highlights the need for further research to identify the most effective approaches, as there is a noticeable lack of studies comparing different training methods, particularly in specific MST and PT. This may help coaches make informed methodological decisions and optimize their available time to enhance swimmers' performance.

Given the reasons outlined above and the existing research gap in exploring the differences between resistance training methodologies for enhancing swimming sprint performance, this study aims to compare the effects of MST, PT, and muscular endurance training (MET) on starting performance and swimming performance in the 25- and 50-meter freestyle distances. It is hypothesized that both MST and PT will significantly improve starting performance compared to MET, as MST enhances maximal strength, which supports powerful push-offs and rapid acceleration (Schumann et al., 2020), while PT focuses on explosive movements that improve neuromuscular coordination and power, leading to quicker and more forceful starts (Bishop et al., 2009). Furthermore, MST and PT are expected to significantly outperform MET in enhancing 25- and 50-meter freestyle performance. MST increases maximal strength and power, which may contribute to better stroke mechanics and faster speeds during sprints (Amara et al., 2021). PT, by improving explosive power and neuromuscular efficiency (Potdevin et al., 2011), may help athletes maintain high-intensity efforts, translating into faster times in short-distance races.

Methods

Design

The study utilized a randomized controlled design, incorporating two experimental intervention groups (MST, PT) alongside an active control group (MET) that continued regular dry-land muscular endurance training. Participants were drawn from an university swimming team using convenience sampling. To ensure specific swimming training did not affect the results, the swimmers within each sex were randomly assigned to one of the three groups. The randomization, using a 1:1 allocation ration, was carried out through simple randomization using opaque envelopes distributed to the swimmers prior to their initial assessment, giving each swimmer an equal opportunity to be placed in any group. This method ensured allocation concealment.

The randomization process was overseen by a researcher who had no role in the subsequent evaluations, guaranteeing the blinding procedure. Independent researchers, unaware of both the group assignments and the intervention protocols, conducted assessments one week before the intervention started, at the third week of interventions and again after the sixth week of training. The swimmers and the coaches implementing the training interventions, however, were not blinded.

Ethical standards

The study received approval from the Ethics Committee of Chengdu Institute of Physical Education, with the protocol registered under code number 120-20240913. Participants were fully informed about the study's objectives and procedures before involvement. Swimmers voluntarily provided consent by signing an informed consent form. Adhering to ethical standards outlined in the Declaration of Helsinki, the research ensured that all participation was completely voluntary.

Participants

To achieve a statistical power of 0.95 and a significance level of 0.05 for the F tests -specifically focusing on the repeated measures ANOVA within-between interaction- a total sample size of 6 participants was recommended by the G*Power software (version 3.1.9, Universität Düsseldorf, Germany). This calculation was grounded in an effect size of 2.38, utilizing a partial eta squared value of 0.85 from prior research comparing plyometric training in swimming in the variable of 25-m front crawl (Sammoud et al., 2019). Once the necessary sample size was established, the recruitment phase began by reaching out directly to local university swimming team, engaging with coaches and team directors. The research team outlined the study's design and invited swimmers to participate on a voluntary basis. Interested swimmers were then evaluated against specific inclusion criteria.

The criteria for inclusion included the following: (i) attendance at the three evaluation points, (ii) a minimum of five years of swimming experience was required to avoid the learning curve associated with the primary movement proposed, ensuring the training targets the desired outcomes without exposing participants to poor posture or an increased risk of injury, (iii) attendance of at least 90% of intervention training sessions, (iv) absence of any injury or illness during the experiment and in the month leading up to it, (v) no involvement in any additional strength and conditioning programs, and (vi) experience in resistance training of at least 2 years. Conversely, exclusion criteria were also established: (i) non-attendance at any evaluation moments or tests, and (ii) the use of any drugs or illegal substances that might affect the adaptations being examined. The criteria match was verified by two researchers, each holding a PhD in sports science and with over five years of experience in strength and conditioning training for athletes. After initial recruitment, thirty swimmers were recruited. Throughout the experiment, three participants were removed from the study due to unrelated injuries sustained during non-intervention training activities (Figure 1).

Twenty-seven university-level swimmers (10 women and 17 men) participated in the study. The men had an average training experience of 9.2 ± 1.3 years, while the women had an average of 9.0 ± 1.9 years. The men averaged 182.7 ± 6.3 cm in height, and the women averaged 169.6 ± 7.5 cm. The men weighed 72.9 ± 10.8 kg, while the women weighed 59.1 ± 6.0 kg. The men had a body mass index of 21.8 ± 2.8 kg/m², and the women had a BMI of 20.5 ± 1.0 kg/m². Additional information about the specific characteristics of each group and overall is provided in Table 1. The overall competitive level of the swimmers is classified as Tier 2 (trained/developmental) according to the Participant's Classification Framework (McKay et al., 2022). This classification is based on their participation in regional-level competitions, an average of 3 training sessions per week, and an average total swimming training time of 03h:30min per week. The swimming training was the sole responsibility of the coaches, with no interference from the research team.

Training interventions

All groups participated in regular swimming training, which was exclusively designed by the coaches without input from the researchers. The training routine often included warm-up exercises, technique drills, and conditioning training in form of high-intensity interval training or sprint sets, followed by cooldown.

In addition to their regular training, the experimental groups (MST, PT and MET) engaged in resistance-based training interventions. During the training period, swimmers participated in 12 resistance training sessions (6 weeks with two sessions a week) that focused on three distinct training modalities: MST (involving bench presses, back squats, and deadlifts at 80% to 95% of their one-repetition maximum), PT (including explosive push-ups, medicine ball throws, and non-weight jumping exercises), and MET training (e.g. push-ups, squatting up, pull-up, dumbbell-flying birds). Each session was conducted twice a week for 50 to 60 minutes, incorporating 10 to 15 minutes of preparatory activities, and took place on Mondays and

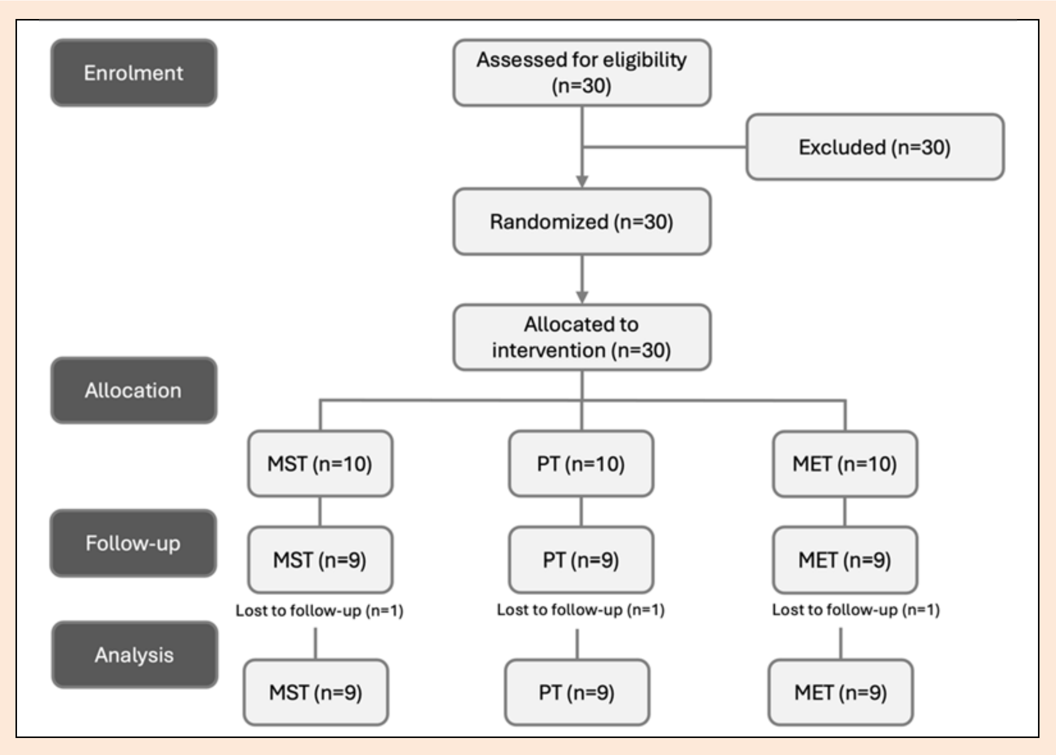


Figure 1. Overview of participant enrollment, allocation, and analysis across the various phases of the study.

Table 1. Summary statistics (mean and standard deviation values) for participant characteristics across all groups.

	MST (n=9)	PT (n=9)	MET (n=9)	Overall (n=27)
Women	3	4	3	10
Men	6	5	6	17
Age (years)	20.0±1.0	20.4±1.3	20.2±1.0	20.2±1.1
Experience (years)	9.1±1.7	9.2±1.5	8.9±1.5	9.1±1.5
Stature (cm)	180.3±6.6	176.2±9.8	177.1±10.7	177.9±9.0
Body mass (kg)	75.0±16.0	66.2±11.1	68.3±13.7	69.9±13.7
Body mass index (kg/m^2)	23.0±4.6	21.2±2.2	21.7±2.7	22.0±3.3
50-m freestyle (best times, s)	27.2±1.6	28.0±2.0	28.5±1.9	27.9±1.8

MST: maximal strength training; PT: plyometric training; MET: muscular endurance training

Table 2. Description of the six-week maximal strength training group plan.

	First session of the week	Second session of the week
Week 1	Bench press (4 sets, 6-8 reps, 80-85% 1-RM) Deadlifts (4 sets, 6-8 reps, 80-85% 1-RM)	Bench press (4 sets, 6-8 reps, 80-85% 1-RM) Back squat (4 sets, 6-8 reps, 80-85% 1-RM)
Week 2	Bench press (3 sets, 4-6 reps, 85-90% 1-RM) Deadlifts (3 sets, 4-6 reps, 85-90% 1-RM)	Bench press (3 sets, 4-6 reps, 85-90% 1-RM) Back squat (3 sets, 4-6 reps, 85-90% 1-RM)
Week 3	Bench press (3 sets, 4-6 reps, 85-90% 1-RM) Deadlifts (3 sets, 4-6 reps, 85-90% 1-RM)	Bench press (3 sets, 4-6 reps, 85-90% 1-RM) Back squat (3 sets, 4-6 reps, 85-90% 1-RM)
Week 4	Bench press (3 sets, 2-4 reps, 90-95% 1-RM) Deadlifts (3 sets, 2-4 reps, 90-95% 1-RM)	Bench press (3 sets, 2-4 reps, 90-95% 1-RM) Back squat (3 sets, 2-4 reps, 90-95% 1-RM)
Week 5	Bench press (3 sets, 2-4 reps, 90-95% 1-RM) Deadlifts (3 sets, 2-4 reps, 90-95% 1-RM)	Bench press (3 sets, 2-4 reps, 90-95% 1-RM) Back squat (3 sets, 2-4 reps, 90-95% 1-RM)
Week 6	Bench press (2 sets, 4-6 reps, 85-90% 1-RM) Deadlifts (2 sets, 4-6 reps, 85-90% 1-RM)	Bench press (2 sets, 4-6 reps, 85-90% 1-RM) Back squat (2 sets, 4-6 reps, 85-90% 1-RM)

1-RM: one repetition maximum; reps: repetitions

Thursdays from 14:00 to 15:00, allowing for a 72-hour recovery period between sessions to optimize performance and muscle adaptation. The randomization process for assigning swimmers to groups was conducted within performance clusters. This method ensured that athletes within each cluster were randomly assigned, eliminating any potential interference from differing performance levels in their adaptation. Additionally, all athletes within a given cluster followed the same swimming training plan, while still being allowed to pursue individual goals based on their own swimming paces. Despite these individualized goals, the training methodology was standardized across the group. The only difference occurred in dry-land strength training, where each swimmer performed the specific resistance exercises assigned to their group, with the training designed and supervised by the coaches.

Resistance training and swimming-specific training were deliberately separated to maximize recovery and performance; the training load was systematically increased from weeks 1 to 5, followed by a reduction in intensity during week 6 to promote recovery and adaptation. Each resistance training session started with a standard warm-up routine that included 5 minutes of running, followed by 10 minutes of dynamic stretching targeting both the upper and lower limbs.

Table 2 presents a detailed overview of the MST training regimen. MST involved a regimen that included exercises such as the bench press, back squat, and deadlifts, often performed in alternating combinations. The training utilized both maximum and submaximal loads, with the following progression: Week 1 focused on 6-8 repetitions at 80-85% of 1-RM; Weeks 2-3 involved 4-6 repetitions at 85-90% of 1-RM; Weeks 4-5 targeted 2-4 repetitions at 90-95% of 1-RM; and Week 6 emphasized 4-6 repetitions at 85-90% of 1-RM. Rest intervals between sets lasted 3 to 4 minutes. Barbell weights were selected to ensure muscle failure occurred within the last two repetitions of the target range while maintaining high-quality technique. If an athlete consistently reached the upper limit of the target repetition range, the weight for the subsequent set was increased by 2.5 kg. Training sessions were supervised by a professional strength and fitness coach. During the bench press, athletes were instructed to maintain a five-point contact posture, ensuring that their head, shoulders, buttocks, and both feet were in contact with the bench at all times. They were also instructed to avoid any bouncing of the bar off the chest during the eccentric-concentric transition. The elbows were kept at a 45° angle during the eccentric phase of the lift. For the back squat, a high bar position was used, and all movements targeted a knee flexion angle of less than 90°. The eccentric phase was performed at a controlled speed, with an immediate reversal of direction at the lowest knee flexion angle. The concentric phase was executed as quickly as possible under high loads. Hard pulls - referring to explosive, high-intensity pulling exercises, such as deadlifts- were incorporated into the training program to enhance the neuromuscular recruitment patterns needed for an effective swim start, mimicking the explosive power and speed required during the initial phase of a swim race.

The PT program is detailed in Table 3. The upper limb movements in the training program included front hand raises with 3 kg weights and explosive push-ups. Since the power direction of the body tended to be more horizontal, the lower limbs were engaged in a variety of jumping movements in five mixed directions: alternating leg jumps with arm swings, explosive mat jumps, longitudinal hurdles, continuous jumps, and one-legged jumps. Additionally, three vertical jumping movements were incorporated: alternating leg kicks, squat jumps, and various types of leg jumps. Each training session comprised five exercises, consisting of two upper limb movements, two mixed-direction movements, and one vertical movement. Split squats were also included to replicate the neuromuscular recruitment patterns used during swimming starts.

All movements required maximal intent and maximal speed execution. During weeks 1 to 5, the number of touchdowns was progressively increased by one each week, reaching a total of 64 to 108 touchdowns. In week 6, this number was slightly reduced to 72. Rest periods of 1 to 2 minutes were provided between sets and also between exercises. Movements performed during the warm-up or ground contact times were not counted in the training plan.

The details of the MET program are presented in Table 4. MET involved five commonly used strength exercises: push-ups (no weight), standing sleepers (no weight), dumbbell bird raises (3 kg), squats (no weight), and men pull-ups/women oblique pulls (no weight). These exercises were performed at a controlled pace, with 2 to 3 minutes of rest between sets, and each exercise was completed for 4 sets of 15 repetitions.

For the pull-ups, participants grasped the bar with both hands at shoulder width, maintaining approximately a 90-degree angle between the arms and torso. The body

Table 3. Description of the six-week plyometric training group plan.

Body region		Exercise	Training week					
			1		2		3	
			Group oneself times		Group oneself times		Group oneself times	
			First session	Second session	First session	Second session	First session	Second session
Upper limbs		① Outbreak type push-ups / medium	3×12	3×12	3×14	3×14	3×16	3×16
		② Throw the medicine ball in front of both hands / low	3×12	3×12	3×14	3×14	3×16	3×16
		Total number of upper limbs	72	72	84	84	96	96
Lower limbs	Mixed direction	① Exchange leg jump-both arms swing / middle	4×6	4×6	——	——	——	——
		② Explosive pad jump / low	4×6	4×6	——	——	——	——
		③ Longitudinal obstacle continuous jump / medium	——	——	5×5	5×5	5×6	5×6
		④ single leg jump / high	——	——	——	——	——	——
	Vertical direction	⑤ Legs continuous jump / middle	——	——	5×5	5×5	5×6	5×6
		⑥ Exchange leg kick / low	4×4	4×4	——	——	——	——
		⑦ Squat and jump in split legs / middle	——	——	——	——	5×5	5×5
		⑧ Leg longitudinal jump / low	——	——	5×5	5×5	——	——
		The total number of foot touches	64 (16)	60(20)	75 (25)	75 (25)	85 (25)	85 (25)
Body region		**Exercise**	**Training week**					
			4		**5**		**6**	
			Group oneself times		**Group oneself times**		**Group oneself times**	
			First session	**Second session**	**First session**	**Second session**	**First session**	**Second session**
Upper limb		① Outbreak type push-ups / medium	3×18	3×18	3×18	3×18	2×16	2×16
		② Throw the medicine ball in front of both hands / low	3×18	3×18	3×18	3×18	2×16	2×16
		Total number of upper limbs	108	108	108	108	64	64
Lower limbs	Mixed direction	① Exchange leg jump-both arms swing / middle	5×6	5×6	——	——	——	——
		② Explosive pad jump / low	——	——	6×6	6×6	——	——
		③ Longitudinal obstacle continuous jump / medium	——	——	——	——	4×6	4×6
		④ single leg jump / high	5×6	5×6	5×6	5×6	——	——
	Vertical direction	⑤ Legs continuous jump / middle	——	——	——	——	4×6	4×6
		⑥ Exchange leg kick / low	5×6	5×6	——	——	——	——
		⑦ Squat and jump in split legs / middle	——	——	6×6	6×6	——	——
		⑧ Leg longitudinal jump / low	——	——	——	——	4×6	4×6
		The total number of foot touches	90 (30)	90 (30)	108 (36)	108 (36)	72 (24)	72 (24)

Note: The number in parentheses indicates the total number of vertical foot touches per week.

angle relative to the ground was less than 45 degrees, with the legs aligned horizontally with the torso. During the exercise, participants pulled themselves up until their chin touched or surpassed the bar, and then lowered their bodies back to the starting position to complete the repetition.

To promote effective training techniques and maximize swimmers' performance, each group was paired with a dedicated researcher or assistant who had a minimum of three years' experience in strength and conditioning coaching. The coaching groups were responsible for delivering the program to the swimmers, offering constructive feedback, and ensuring that every exercise was executed with full intensity to enhance the training effect. Swimmers received clear instructions to exert their utmost effort during each repetition, and verbal motivation was provided throughout the workouts to foster dedication and engagement among the participants.

Testing procedures

The testing procedures were conducted during three distinct time points: the week prior to the start of the intervention, the third week of the intervention, and the week following its completion. The testing days and procedures were consistent across all assessment periods to minimize potential biases that could influence the results. To ensure proper recovery, a 48-hour rest period was observed before each evaluation, which took place before the swimmers' first session of the week.

All evaluations were conducted in the morning, beginning in a climate-controlled room set to 22ºC and 55% relative humidity. In this setting, demographic data, anthropometric measurements, and strength levels were assessed (the strength assessments were used exclusively for adjusting the strength training). Approximately 30 minutes after completing the strength evaluations, participants moved to a 50-meter swimming pool with a water temperature of 26.6ºC for the swimming performance tests.

Before the swimming tests, the athletes performed a specific dry-land warm-up that included a standardized dynamic stretching routine for both the upper and lower

Table 4. **Description of the six-week muscular endurance training group plan.**

	First session of the week	Second session of the week
Week 1	Push-ups (4 sets, 12 reps) Standing sleeper support (4 sets, 12 reps) By dumbbell-flying birds (4 sets, 12 reps) Squatting up (4 sets, 12 reps) Pull-up <men> / oblique led ked <women> (4 sets, 12 reps)	Push-ups (4 sets, 12 reps) Standing sleeper support (4 sets, 12 reps) By dumbbell-flying birds (4 sets, 12 reps) Squatting up (4 sets, 12 reps) Pull-up <men> / oblique led ked <women> (4 sets, 12 reps)
Week 2	Push-ups (4 sets, 15 reps) Standing sleeper support (4 sets, 15 reps) By dumbbell-flying birds (4 sets, 15 reps) Squatting up (4 sets, 15 reps) Pull-up <men> / oblique led ked <women> (4 sets, 15 reps)	Push-ups (4 sets, 15 reps) Standing sleeper support (4 sets, 15 reps) By dumbbell-flying birds (4 sets, 15 reps) Squatting up (4 sets, 15 reps) Pull-up <men> / oblique led ked <women> (4 sets, 15 reps)
Week 3	Push-ups (4 sets, 15 reps) Standing sleeper support (4 sets, 15 reps) By dumbbell-flying birds (4 sets, 15 reps) Squatting up (4 sets, 15 reps) Pull-up <men> / oblique led ked <women> (4 sets, 15 reps)	Push-ups (4 sets, 15 reps) Standing sleeper support (4 sets, 15 reps) By dumbbell-flying birds (4 sets, 15 reps) Squatting up (4 sets, 15 reps) Pull-up <men> / oblique led ked <women> (4 sets, 15 reps)
Week 4	Push-ups (5 sets, 15 reps) Standing sleeper support (5 sets, 15 reps) By dumbbell-flying birds (5 sets, 15 reps) Squatting up (5 sets, 15 reps) Pull-up <men> / oblique led ked <women> (5 sets, 15 reps)	Push-ups (5 sets, 15 reps) Standing sleeper support (5 sets, 15 reps) By dumbbell-flying birds (5 sets, 15 reps) Squatting up (5 sets, 15 reps) Pull-up <men> / oblique led ked <women> (5 sets, 15 reps)
Week 5	Push-ups (5 sets, 15 reps) Standing sleeper support (5 sets, 15 reps) By dumbbell-flying birds (5 sets, 15 reps) Squatting up (5 sets, 15 reps) Pull-up <men> / oblique led ked <women> (5 sets, 15 reps)	Push-ups (5 sets, 15 reps) Standing sleeper support (5 sets, 15 reps) By dumbbell-flying birds (5 sets, 15 reps) Squatting up (5 sets, 15 reps) Pull-up <men> / oblique led ked <women> (5 sets, 15 reps)
Week 6	Push-ups (4 sets, 15 reps) Standing sleeper support (4 sets, 15 reps) By dumbbell-flying birds (4 sets, 15 reps) Squatting up (4 sets, 15 reps) Pull-up <men> / oblique led ked <women> (4 sets, 15 reps)	Push-ups (4 sets, 15 reps) Standing sleeper support (4 sets, 15 reps) By dumbbell-flying birds (4 sets, 15 reps) Squatting up (4 sets, 15 reps) Pull-up <men> / oblique led ked <women> (4 sets, 15 reps)

Reps: repetitions

limbs (~5 minutes). This was followed by a 600-meter freestyle swim and three 50-meter freestyle accelerations at low to medium intensity. Three minutes after completing the warm-up, the swimmers began the performance tests.

The swimming tests were always performed in the same sequence to ensure consistency. The selected tests were proposed to differentiate the key phases of performance in competitive freestyle swimming: the start phase and the freestyle swimming phase (Marinho et al., 2021). The 15-meter start performance from the platform emphasized explosive power and maximal acceleration (West et al., 2011), utilizing the kick-start technique with back foot tilt to standardize the start across all athletes. This was followed by a 25-meter freestyle swim, selected to assess the transition to stroke efficiency and quality (Kováčová and Broďáni, 2019). The subsequent 25-meter and 50-meter freestyle sprints were included to evaluate sprinting endurance and peak velocity, with a 10-minute rest between each to ensure full recovery.

Testing was conducted with the 15-meter start individually to allow full focus on the athlete's performance, while the remaining tests were performed in pairs for efficiency and comparative analysis. Verbal encouragement was provided throughout to maximize effort, ensuring consistency in performance across all trials.

Starting performance

The starting performance assessment included both flight distance and platform-to-15m time. A previous study found that the first 15 meters of a 50-meter sprint can account significantly for the overall race performance (Seifert et al., 2010). Flight distance referred to the horizontal distance between the point where the athlete's fingertips entered the water (Maglischo, 2003) and the starting wall. The platform-to-15m time was measured from the moment the starting signal was given until the athlete's head reached the 15m mark (West et al., 2011).

To measure flight distance, an iPhone 14 (recording at 1080p HD / 30 fps) was used as the test instrument (Figure 2). The device was positioned 3.5 meters from the pool, parallel to the swimming lane, at a height of 130 cm. The lower edge of the video frame was aligned with the waterline of the swimming lane. The video captured the athlete from the start until their entire body entered the water.

Flight distance was determined using Kinovea (version 0.9.5-x64), a two-dimensional motion analysis software. The camera was calibrated using a series of poles with fixed lengths, positioned at a vertical offset of 40 cm between the leading edge of the pool and the starting wall, which was accounted for in the video recording. This procedure aligns with previous studies employing calibration

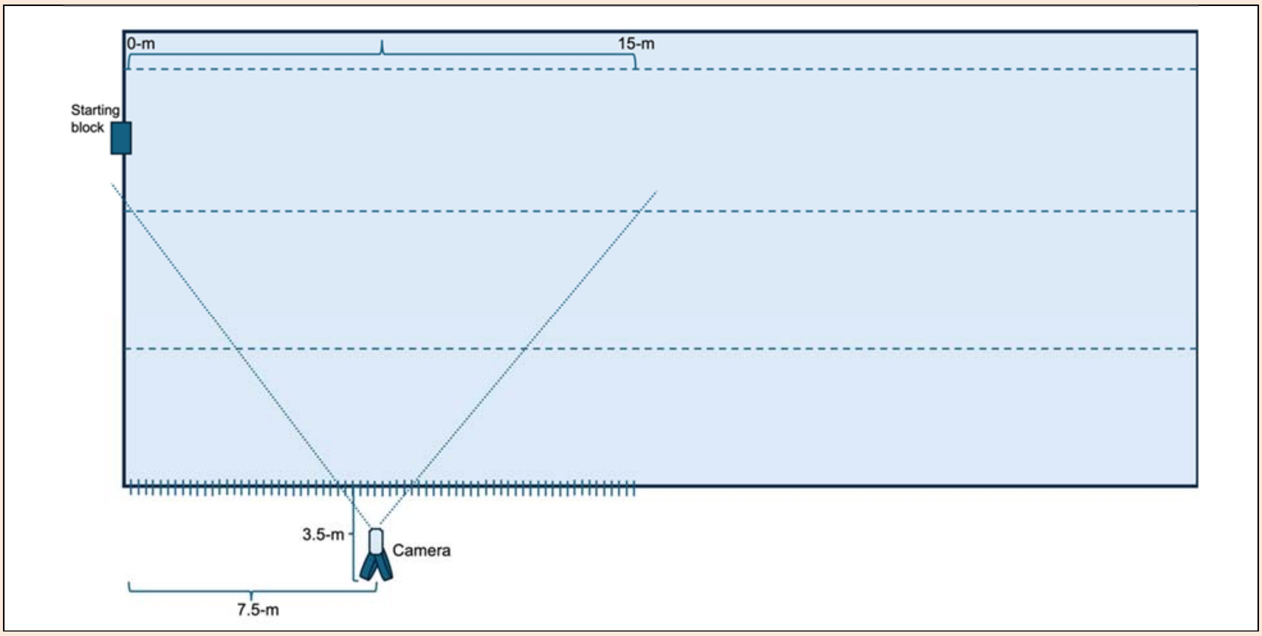


Figure 2. **Setup for measuring flight distance.**

techniques for analyzing the aerial phase in swimming (Hermosilla et al., 2022). The parameters used in the analysis included both the flight distance and the time taken from platform departure to the 15m mark.

Swimming performance assessment

The swimming specific performance assessment included four key test indicators to evaluate the athlete's performance in different swimming scenarios (Ruiz-Navarro et al., 2024). These indicators were: (i) 25m Freestyle Kick without stroking: measured from the moment the starting signal is given until the athlete's head reaches the 25m mark. The purpose of this test was to isolate the contribution of the legs in the swimming performance by excluding the use of the arms. By focusing on the kick, we aimed to assess the impact of maximal leg strength on short-distance propulsion; (ii) 25m Freestyle Arm Stroke without kicking: measured from the starting signal until the athlete's head reaches the 25m mark. This test aimed to isolate the contribution of the arms by removing the propulsion of the legs. It aimed to measure the swimmer's ability to generate speed with upper-body strength, highlighting the relationship between maximal arm strength and swimming performance; (iii) 25m Freestyle: measured from the starting signal until the athlete's head reaches the 25m mark. By combining both the legs and arms, this test aimed to evaluate the swimmer's overall efficiency and speed when all muscle groups are engaged; and (iv) 50m Freestyle: measured from the starting signal until the athlete's fingertips touch the wall at 50m. This test involves a longer distance and incorporates both the legs and arms, making it a more comprehensive measure of sustained performance. It aimed to assess how the swimmer's strength translates into endurance, power output, and speed over a slightly longer duration.

The pool was marked at the 15m, 25m, and 50m points to ensure consistent measurements during each test. Additionally, the distances for the 25m freestyle, 25m freestyle kicking, and 25m freestyle stroke (i.e., kicking without stroking and stroking without kicking) were clearly indicated at the bottom of the pool. This method provided a standardized approach to measure swimming-specific performance across different techniques and distances.

In all tests, the start was initiated from the 15-meter mark, with the referee providing the starting signal. Each swimmer completed the test once, and times (measured in seconds) were first measured using an electronic stopwatch (LI-NING 019-1, China). The evaluations were consistently conducted by the same researcher, who is a former swimmer, current coach, and also a judge in swimming tournaments. Prior to the experiments, the researcher was tested in a pilot study, where the results were compared with those obtained through video camera analysis. The pilot study included data from 30 swimmer attempts during an experiment, and the intra-class correlation test, comparing the researcher's results with those from the video analysis, revealed a value of 0.93, showing excellent reliability (Koo and Li, 2016). Additionally, the entire performance was captured on video using an iPhone 14 (recorded in 1080p HD at 30 fps) to verify the time marks. The video was synchronized with the starting signal using a small light trigger that illuminated immediately when the signal mark appeared. A specialized evaluator analyzed the videos using a software designed for competitive swimming race analysis (SwimWatch Race Analyzer, NatriSoft, The Netherlands). The final result, known as the swimming special score, was calculated as the average of the recorded times.

Statistical procedures

Before proceeding with inferential analyses, the normality of the sample distribution was evaluated using the Shapiro-Smirnov test, which yielded a p-value greater than 0.05. To assess the assumption of homogeneity, Levene's test was also conducted, with results showing p > 0.05. A mixed ANCOVA (time * group) was then conducted, using the pre-evaluation scores as a covariate. This analysis incorporated the calculation of partial eta squared (η_p^2) to gauge effect sizes (ES), along with Cohen's d for comparisons between pre- and post-test results. ES were interpreted according to predefined categories (Hopkins et al., 2009): trivial (<0.2), small (0.2 - 0.6), moderate (0.6 - 1.2), large (1.2 - 2.0), very large (2.0 - 4.0), and nearly perfect (>4.0). For post-hoc comparisons, the Bonferroni test was employed. All statistical analyses were conducted using JASP software (version 0.18.3, University of Amsterdam, The Netherlands), with a significance level established at p < 0.05.

Results

Significant interactions between time and group were observed in the starting flight distance ($F = 5.375$; $p = 0.009$; $\eta_p^2 = 0.319$), 15-m starting time ($F = 14.437$; $p < 0.001$; $\eta_p^2 = 0.557$), 25-m freestyle kick ($F = 12.010$; $p < 0.001$; $\eta_p^2 = 0.511$), 25-m freestyle stroke ($F = 75.442$; $p < 0.001$; $\eta_p^2 = 0.868$), 25-m freestyle ($F = 5.386$; $p = 0.006$; $\eta_p^2 = 0.319$), and 50-m freestyle ($F = 9.606$; $p < 0.001$; $\eta_p^2 = 0.455$).

Table 5 describe the statistics or the swimming performance variables across groups. No significant differences between groups were observed in the pre-intervention evaluations (p > 0.05).

Significant differences were observed between groups in middle evaluation for the starting flight distance ($F = 6.282$; $p = 0.007$; $\eta_p^2 = 0.353$), 15-m starting time ($F = 12.055$; $p < 0.001$; $\eta_p^2 = 0.512$), 25-m freestyle kick ($F = 23.454$; $p < 0.001$; $\eta_p^2 = 0.671$), 25-m freestyle stroke ($F = 52.304$; $p < 0.001$; $\eta_p^2 = 0.820$), 25-m freestyle ($F = 10.049$; $p < 0.001$; $\eta_p^2 = 0.466$), and 50-m freestyle ($F = 26.484$; $p < 0.001$; $\eta_p^2 = 0.697$).

Significant differences were observed between groups in post-intervention evaluation for the starting flight distance ($F = 5.075$; $p = 0.015$; $\eta_p^2 = 0.306$), 15-m starting time ($F = 13.557$; $p < 0.001$; $\eta_p^2 = 0.541$), 25-m freestyle kick ($F = 10.317$; $p < 0.001$; $\eta_p^2 = 0.473$), 25-m freestyle stroke ($F = 90.748$; $p < 0.001$; $\eta_p^2 = 0.888$), 25-m freestyle ($F = 6.729$; $p = 0.005$; $\eta_p^2 = 0.369$), and 50-m freestyle ($F = 11.658$; $p < 0.001$; $\eta_p^2 = 0.503$).

Figure 3 exhibits the within-group variations in starting performance, including flight distance and 15-m start time, across different evaluation periods for MST, PT, and MET. When considering the starting flight distance, PT performed significantly better than MET in the mid-evaluation ($p = 0.005$; ES = 0.117, trivial), while MST was better than MET in the post-intervention evaluation ($p = 0.021$; ES = 0.290, small). In regards the starting 15-m

Table 5. Descriptive statistics (mean ± standard deviation) for the swimming performance variables across groups.

		MST (n=9)	PT (n=9)	MET (n=9)
Start – flight distance (cm)	Pre	298.1±23.3*,$	296.6±39.4*,$	296.6±31.0*,$
	Middle	302.9±24.3#,$	303.2±39.0c,#,$	299.1±31.2b, #,$
	Post	310.1±25.5c,#,*	307.5±38.9#,*	301.9±31.1a,#,*
	Post-pre difference (%)	+4.0	+3.7	+1.8
	Post-pre ES (d)	0.492, small	0.278, small	0.171, trivial
Start 15m (s)	Pre	7.38±0.62*,$	7.44±0.69*,$	7.42±0.89*,$
	Middle	7.26±0.61#,$	7.27±0.66c,#,$	7.35±0.90b,#,$
	Post	7.06±0.64c,#,*	7.17±0.64c,#,*	7.27±0.89^a,b,#,*
	Post-pre difference (%)	–4.3	–3.6	–2.0
	Post-pre ES (d)	–0.508, small	–0.406, small	–0.169, trivial
25-m Freestyle kick (s)	Pre	21.47±1.22*,$	21.42±1.38*,$	21.45±1.80*,$
	Middle	21.26±1.25b,c,#,$	21.11±1.40^a,c,#,$	21.33±1.79^a,b,#,$
	Post	20.94±1.30c,#,*	20.96±1.37c,#,*	21.22±1.78^a,b,#,*
	Post-pre difference (%)	–2.5	–2.1	–1.1
	Post-pre ES (d)	–0.421, small	–0.335, small	–0.128, trivial
25-m Freestyle stroke (s)	Pre	15.62±0.89*,$	16.22±1.88*,$	16.38±1.80*,$
	Middle	15.24±0.86 b,c,#,$	15.97±1.87^a,c,#,$	16.26±1.81^a,b,#,$
	Post	15.03±0.84 c,#,*	15.67±1.86 c,#,*	16.17±1.80^a,b,#,*
	Post-pre difference (%)	–3.8	–3.4	–1.3
	Post-pre ES (d)	–0.682, moderate	–0.294, small	–0.117, trivial
25-m Freestyle (s)	Pre	13.55±0.83*,$	13.91±1.00*,$	14.15±0.87*,$
	Middle	13.35±0.78b,c,#,$	13.80±0.99a,#,$	14.06±0.87^a,#
	Post	13.19±0.75c,#,*	13.65±0.96#,*	13.99±0.89a,#
	Post-pre difference (%)	–2.7	–1.9	–1.1
	Post-pre ES (d)	–0.456, small	–0.265, small	–0.182, trivial
50-m Freestyle (s)	Pre	28.26±1.68*,$	29.05±2.09*,$	29.62±1.94*,$
	Middle	27.85±1.59 b,c,#,$	28.82±2.04^a,c,#,$	29.47±1.94^a,b,#
	Post	27.58±1.57 c,#,*	28.53±2.00 c,#,*	29.40±1.94^a,b,#
	Post-pre difference (%)	–2.4	–1.8	–0.7
	Post-pre ES (d)	–0.418, small	–0.254, small	–0.113, trivial

ES: Effect size; MST: maximal strength training group; PT: plyometric training group; MET: muscular endurance training group; a: significantly different from MST group (p<0.05); b: significantly different from PT group (p<0.05); c: significantly different from MET (p<0.05); #: significantly different from pre-intervention evaluation (p<0.05); *: significantly different from middle evaluation (p<0.05); $: significantly different from post-intervention evaluation

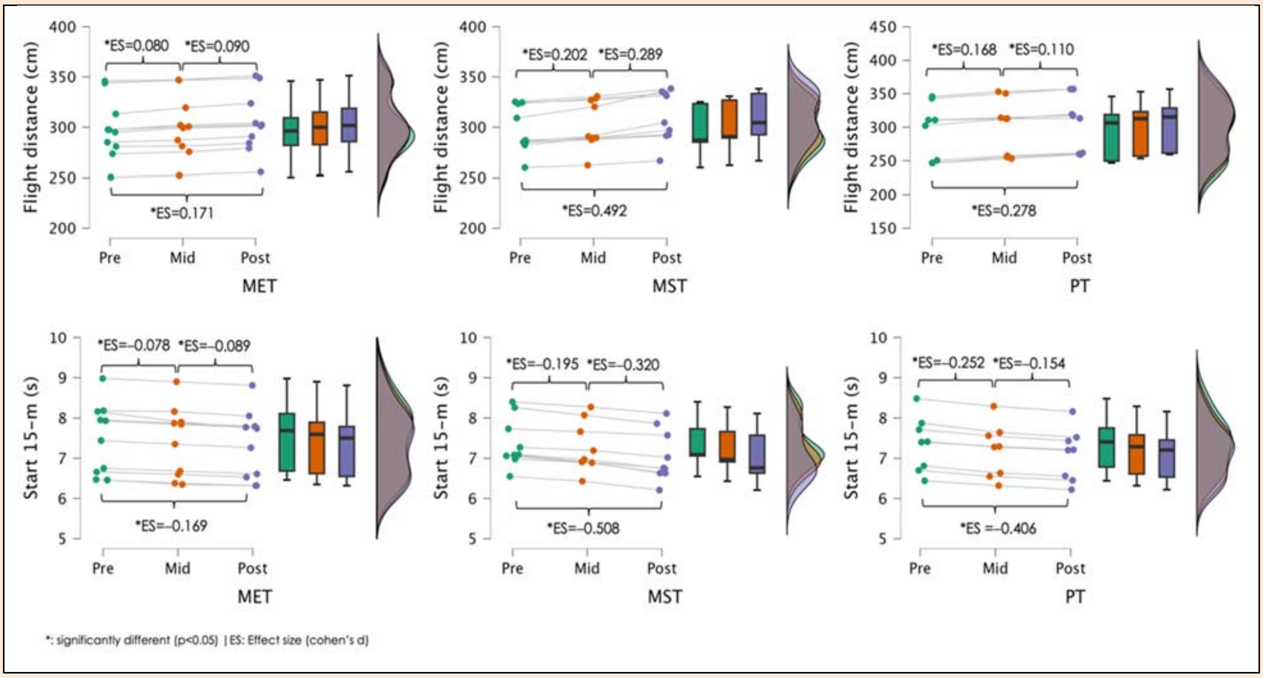


Figure 3. **Within-group variations in starting performance, including flight distance and 15-m start time, across different evaluation periods for maximal strength training (MST), plyometric training (PT), and muscular endurance training (MET).**

time, PT performed significantly better than MET in the mid-evaluation ($p < 0.001$; ES = 0.103, trivial), while MET was significantly worse than MST ($p < 0.001$; ES = 0.275, small) and PT ($p = 0.004$; ES = 0.131, trivial) in the post-intervention evaluation.

Figure 4 shows the within-group variations in 25-m freestyle kick and stroke, across different evaluation periods for MST, PT, and MET. In the 25-meter freestyle kick, during the mid-evaluation, PT significantly outperformed both MST ($p = 0.007$; ES = 0.113, trivial) and MET ($p < 0.001$; ES = 0.138, trivial), while MST was also better than MET ($p = 0.007$; ES = 0.046, trivial). However, in the post-intervention evaluation, significant differences in the 25-meter freestyle kick were only observed between MET and both MST ($p < 0.001$; ES = 0.182, trivial) and PT ($p = 0.011$; ES = 0.165, trivial), with MET performing significantly worse.

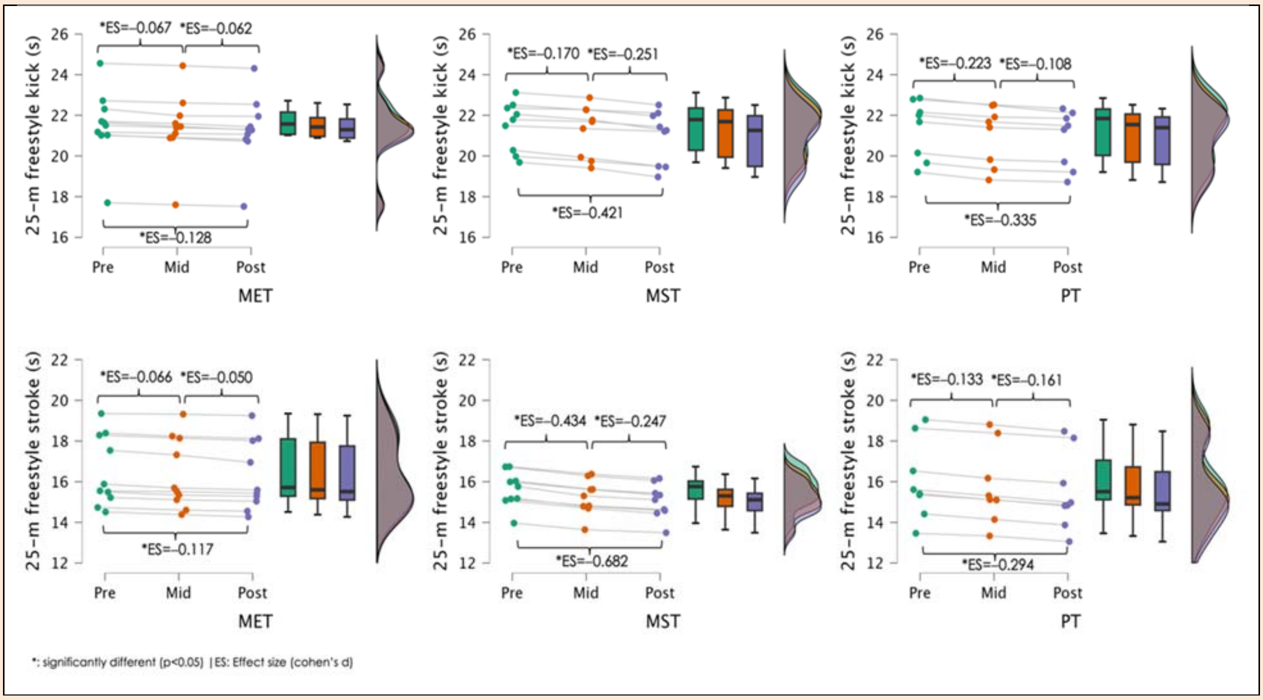
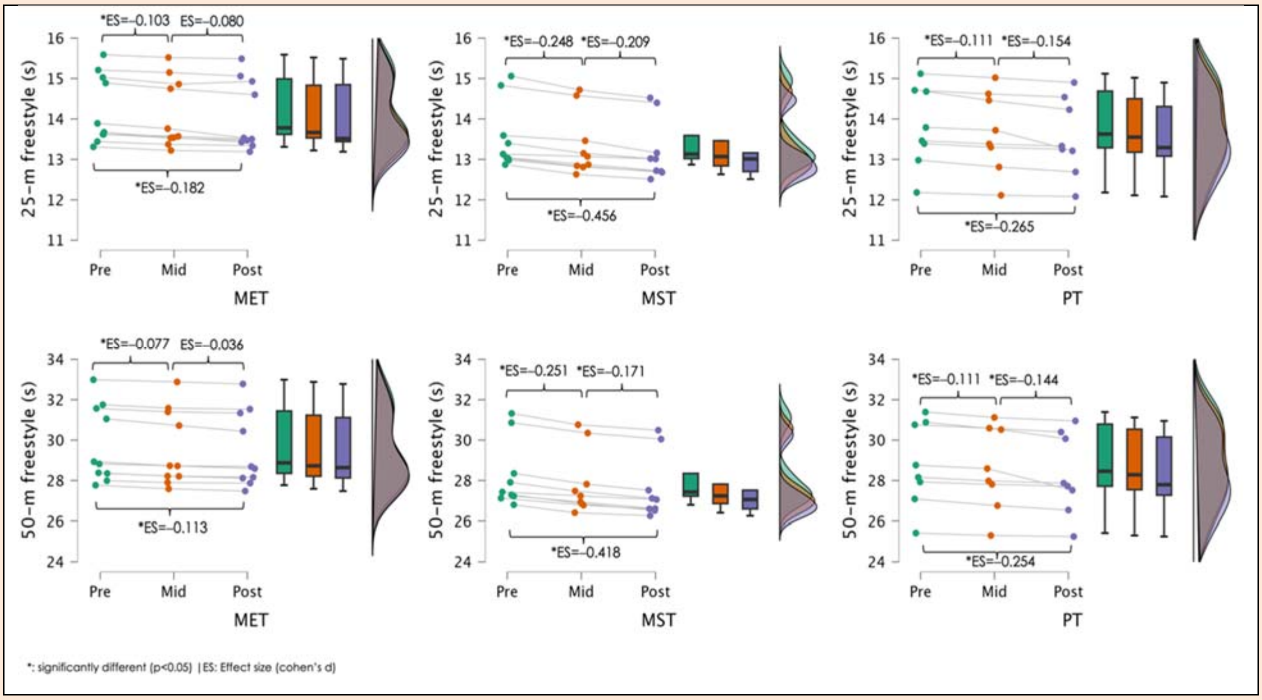


Figure 4. **Within-group variations in 25-m freestyle kick and stroke performances, across different evaluation periods for maximal strength training (MST), plyometric training (PT), and muscular endurance training (MET).**



*: significantly different (p<0.05) | ES: Effect size (cohen's d)

Figure 5. **Within-group variations in 25-m and 50-m freestyle performances, across different evaluation periods for maximal strength training (MST), plyometric training (PT), and muscular endurance training (MET).**

In the 25-meter freestyle stroke, during the mid-evaluation, MST significantly outperformed both PT ($p < 0.001$; ES = 0.535, small) and MET ($p < 0.001$; ES = 0.764, moderate), while PT was also better than MET ($p < 0.001$; ES = 0.158, trivial). However, in the post-intervention evaluation, significant differences in the 25-meter freestyle stroke were only observed between MET and both MST ($p < 0.001$; ES = 0.864, moderate) and PT ($p < 0.001$; ES = 0.273, small), with MET performing significantly worse.

Figure 5 illustrates the within-group variations in 25-m and 50-m freestyle, across different evaluation periods for MST, PT, and MET. In the 25-meter freestyle, during the mid-evaluation, MST significantly outperformed both PT ($p = 0.007$; ES = 0.508, small) and MET ($p < 0.001$; ES = 0.861, moderate). However, in the post-intervention evaluation, significant differences in the 25-meter freestyle were only observed between MST and MET ($p = 0.004$; ES = 0.976, moderate), with MST performing significantly better. No significant differences were observed between PT and MET.

In the 50-meter freestyle, during the mid-evaluation, MST significantly outperformed both PT ($p < 0.001$; ES = 0.534, small) and MET ($p < 0.001$; ES = 0.918, moderate). However, in the post-intervention evaluation, significant differences in the 50-meter freestyle were only observed between MET and both MST ($p < 0.001$; ES = 1.037, moderate) and PT ($p = 0.014$; ES = 0.442, small), with MET performing significantly worse.

Discussion

The findings of our study revealed that both groups significantly improved swimming performance following the interventions. While both MST and PT were similarly effective and significantly outperformed MET in enhancing starting performance in sprint swimming and specific drills, such as 25-m freestyle kicking and stroke alone, only MST demonstrated significantly greater improvement than MET in 25-m and 50-m freestyle swimming. PT, by contrast, showed a significant advantage over MET only in the 50-m test. Furthermore, MST resulted in faster performance improvements than PT, with significant gains observed within just three weeks, indicating quicker adaptation with MST.

Starting performance in our study was measured through 15-m starts, which allowed us to observe that both MST and PT were significantly more effective than MET in improving start flight distance and 15-m start swimming time. Interestingly, PT was the first to show significant improvement over MET after just 3 weeks of training. By the post-intervention phase (6th week), both MST and PT were significantly better than MET, with no significant difference between MST and PT at that point. Previous studies suggested that higher lower limbs and trunk strength enable a more powerful and rapid takeoff, increasing horizontal velocity, which contributes significantly to overall sprint performance (Keiner et al., 2015; Kwok et al., 2021). Additionally, greater muscular power supports faster and more efficient body positioning during the entry and streamline phases, minimizing drag and allowing for quicker transitions into the swim stroke (Crowley et al., 2017), possibly leading to better sprint times.

MST and PT lead to superior improvements in starting flight distance and 15-m sprint times in comparison to MET possibly due to their specific impact on neuromuscular adaptations. MST often allows the recruitment of high-threshold motor units and increases overall force production (Suchomel et al., 2018), enabling swimmers to generate more explosive power during the start. PT improves the rate of force development and stretch-shortening cycle efficiency, allowing for quicker, more forceful movements during push-off and flight (Thng et al., 2019). These adaptations possibly resulted in a longer and more effective flight phase and faster acceleration in the water. In contrast, MET focuses on sustaining lower-intensity efforts over time (Rodríguez González et al., 2023), which does not significantly enhance the rapid power and strength required for optimal sprint starts.

The results of our study also showed that both MST and PT significantly improved 25-m freestyle performance, whether using only kick or only stroke, compared to MET. Interestingly, at the 3-week evaluation, PT performed significantly better than MST in the 25-m kick-only test, while the opposite was observed for the 25-m stroke-only test, where MST achieved faster results than PT. However, by the post-intervention phase, no significant differences were found between MST and PT in either test. Such findings align with evidence about the relevance of muscular strength and power for optimizing stroke and kicking performance during sprint swimming possibly due to their role in generating propulsion and minimizing resistance (Keiner et al., 2021). Scientific findings show that stronger upper and lower body and core muscles allow swimmers to apply greater force during the pull phase of each stroke (Keiner et al., 2015), enhancing stroke efficiency and distance per stroke. Similarly, powerful leg muscles contribute to faster, more forceful kicks, which are critical for maintaining high velocity in the water (Argun et al., 2023). Both strength and power enable swimmers to overcome hydrodynamic drag more effectively (Takagi et al., 2023), improving propulsion and body positioning. Additionally, increased muscular power enhances the swimmer's ability to sustain high stroke rates and kick frequencies (Keiner et al., 2021), which are key to maintaining peak speed throughout the sprint.

The results observed in our study may be attributed to the hypothesis that MST enhances the recruitment of high-threshold motor units and improves muscle fiber activation (Girold et al., 2012). This, in turn, allows swimmers to generate greater force with each stroke and kick (Fone and van den Tillaar, 2022). Additionally, PT may enhance the stretch-shortening cycle, potentially contributing to both potentiation and an increased rate of force development, which may be important for fast and powerful movements in the water (Waddingham et al., 2021). These adaptations may lead to more efficient and powerful propulsion during both the stroke and kick phases, resulting in improved sprint performance (Sammoud et al., 2019). In contrast, MET may be more suitable for enhancing fatigue resistance (Rodríguez González et al., 2023), which might not significantly contribute to the rapid force and power demands of sprint swimming.

When examining ultimate performances in 25-m and 50-m freestyle sprint swimming, our results indicated that only MST exhibited significantly better performance than MET at both distances. Additionally, PT was only significantly better than MET in the 50-m sprint. MST modality often promotes greater improvements in explosive strength, leading to more powerful strokes and effective kick propulsion, crucial for short-distance sprints (Keiner et al., 2021). Additionally, the enhancements in muscle force production translate into increased acceleration off the blocks and improved overall velocity through the swim (Wirth et al., 2022). In contrast, MET primarily develops the ability to sustain submaximal efforts over longer durations (Wirth et al., 2022), which may not translate as effectively into the rapid force generation needed for optimal sprint performance in the 25-m and 50-m events. PT showed better performance than MET in the 50-m test possibly due to its ability to take advantage of the stretching shortening cycle to optimize the contractions in longer sprint distances (Rebutini et al., 2016).

An additional interesting finding revealed that MST showed faster improvement, being significantly better than both PT and MET by the third week. However, by the sixth week, no significant differences remained when compared to PT. The significant improvements observed in the MST group by the third week can be attributed to rapid neuromuscular adaptations, such as increased motor unit recruitment and firing rates (Tillin and Folland, 2014), which may translate to immediate performance benefits in sprint swimming.

Despite the promising findings of this study, several limitations warrant consideration. First, the relatively short intervention period of six weeks may not fully capture the long-term effects and sustainability of the training modalities on sprint swimming performance, nor does it account for the impact of trainability over longer durations. Future research should explore extended training periods to determine whether the observed benefits persist or evolve over time. Additionally, the sample size and context of this study may limit the generalizability of the results to broader populations, particularly those at different competitive levels. Moreover, due to time constraints, some training interventions could potentially be more robust in future research. For instance, in our study, the MST did not include a pulling exercise, which is highly relevant for swimmers. Future investigations should include diverse participant groups, specifically elite and younger swimmers, to enhance the external validity of the findings. Lastly, while we measured starting performance, future studies could incorporate additional metrics, such as biomechanical analyses, to provide a more comprehensive understanding of the underlying mechanisms driving performance improvements.

This study has some interesting practical implications. It suggests incorporating MST twice a week, as visible effects can be observed by the third week, with further enhancements in performance noted by the sixth week in short-distance sprint swimming. While PT is also recommended, its effectiveness varies depending on the context, as it shows significant improvements in shorter sprint tests but is less effective for the 50-meter distance. Coaches must consider the specific context when integrating these training modalities and adjust their introduction according to periodization. Additionally, managing appropriate training loads is essential to avoid potential negative effects on the daily water-based training process.

Conclusion

This randomized parallel study revealed that, although all groups showed significant improvements after the interventions, both MST and PT played a more substantial role in enhancing sprint swimming performance compared to MET, albeit with specific nuances. MST was significantly more effective than MET in starting performance, analytical drills (kick and stroke), and freestyle swimming at both 25-m and 50-m distances. In contrast, PT showed significant improvements over MET in starting performance, sprint swimming (kick and stroke), and 50-m freestyle, but not in 25-m freestyle. Interestingly, MST demonstrated faster, more significant adaptations in 25-m and 50-m freestyle swimming compared to PT and MET, making it preferable for shorter training periods, such as 3 weeks. These findings suggest that coaches may consider MST for quicker performance improvements, while PT may offer a better balance of adaptation over a longer period, such as 6 weeks.

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The experiments comply with the current laws of the country where they were performed. The authors have no conflict of interest to declare. The datasets generated during and/or analyzed during the current study are not publicly available but are available from the corresponding author who organized the study.

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Key points

- Maximal strength training (MST) is effective in enhancing starting and swimming performance in sprint freestyle tests.
- Plyometric training (PT) is effective for improving 50-meter freestyle swimming performance, but it does not show the same benefits for 25-meter swimming when compared to MET.
- MST tends to produce faster gains, making it the preferred option when only a short training period.

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