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Research article

The Effect of The 8-Week Core Muscle Training in Swimming Time, Swimming Force and Core Muscle Activity Among Swimmers: A Randomized Controlled Trial

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Abstract
This intervention was conducted to evaluate the effects of 8 weeks of core training on swimming performance, force performance and core muscle activation. An 8-week core training was implemented, 32 swimmers were randomly allocated to experimental group (EG) (age: 14.38-14.88) and control group (CG) (age: 15.33-17.40). The CG maintained regular in-water training, while EG performed two additional core training a week. Swimming time, stroke rate (SR), stroke length (SL) and bilateral core muscle activity were obtained through 50 m front-crawl (FC) time trials and surface electromyography (sEMG). Moreover, the tethered swimming force was measured using the Tethered Swimming Test (TST) as a kinetic parameter. All tests were performed twice (pre- and post-intervention) to examine differences in measured parameters. No between-group differences were found. Male swimmers in EG showed within group decrease in swimming time (- 0.59 s; $p < 0.05$; ES = 0.827), while female swimmers in both groups showed changes in swimming velocity (EG: + 0.03 m/s; CG: + 0.02 m/s; $p < 0.05$). EG in male and female swimmers showed more improvement in TST than CG. For the co-contraction index (CCI) of the core muscle, no differences were demonstrated in female and male groups. This study did not indicate significant effects of core training on swimmers, additional research exploring core training is recommended to confirm these findings.

Key words: Core training, Tethered swimming force, Co-contraction index, Front crawl.

Introduction

Strength training is often used to improve athletic performance. Research has demonstrated that plyometric training enhanced jumping and sprinting performance, while resistance training has also been shown to have a beneficial effect on muscle strength, power and sports performance, including agility and coordination (Eraslan et al., 2021; Granacher et al., 2016). Specifically for swimming, recent reviews have investigated the effectiveness of strength and conditioning (S and C) training on swimming and showed its positive effects on muscle strength and performance (Fone and van den Tillaar, 2022; Kwok et al., 2021). Core training was shown to improve swimming performance by 2 - 3% (Fone and van den Tillaar, 2022), while there was 7.5% improvement for 200 m Front Crawl (FC) swim following in-water resistance training (Gourgoulis et al., 2019).

Past research on FC has mainly looked at the arms and legs, as they contribute more to performance (Keiner et al., 2021), but the role of core muscles in FC has been overlooked. Core muscles would assist in providing stability for movement and facilitate torque transfer between the upper and lower body (Hibbs et al., 2008), which act as the kinetic link between (Kibler et al., 2006; Saeterbakken et al., 2022). Specifically, for FC, the muscle activation patterns reported by Andersen et al. (2021) suggest that the core muscles would assist in maintaining a streamlined position or providing stability, and those swimmers might adjust their swimming motions to maintain the trunk posture according to the environment.

Furthermore, higher core muscle activation ($p < 0.05$) has been found during sprinting (integrated EMG: 38.7 - 141.1 µV) compared to middle-distance events (integrated EMG: 16.7 - 86.9 µV) (Andersen et al., 2021; Andersen et al., 2019). This suggests more trunk engagement during sprinting and, training focuses on core muscles may be beneficial to the FC sprinting performance. However, only a few studies have examined the effects of core training on FC swimming time. Patil et al. (2014) and Karpiński et al. (2020) both revealed improvements in FC time. However, the characteristics of recruited participants were diverse. The research from Patil et al. (2014) and Weston et al. (2015) included both male and female swimmers, with school and club level (38 males & 22 females; Age: 13.4-14.7) and national level (10 males & 10 females; Age: 15.7-16.7) respectively. While for Karpiński et al. (2020), only male national level swimmers were recruited but not included female swimmers. Mixed samples would limit the generalizability of the result, and separate analyses by sex are recommended, as performance variations between males and females in swimming were found (Sandbakk et al., 2018). Hence, further investigation may assist the field to evaluate the effects of core training on FC performance by sex and to have a better understanding of the role of the core during FC swimming.

Previous studies (Karpiński et al., 2020; Patil et al., 2014; Weston et al., 2015) have been limited to evaluate swimming time, stroke length (SL) and stroke rate (SR), or dry-land strength test (i.e., prone bridge test and functional core muscle strength performance). Core stability is the ability to control the trunk position and motion for the

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production and transfer of force (Kibler et al., 2006). It has been argued that improved performance in core would facilitate force production by limbs (Shinkle et al., 2012) and could enhance propulsion. Some investigations have evaluated the effects of S and C training on kinetics and showed improvements in tethered swimming force (e.g., Aspenes et al., 2009), which was measured by tethered swimming tests (TST). TST is a reliable method (Amaro et al., 2014) with small and acceptable errors (Psycharakis et al., 2011), and has been adopted in previous research (Morouço et al., 2018; Santos et al., 2016). A study (Morouço et al., 2018) found the tethered force performance could explain over 80% of swimming performance, while Maximum force (Fmax) is positively correlated with swimming velocity (SV) ($r = 0.61$, $p < 0.02$) (Santos et al., 2016), in 200 m FC swim. However, there is limited evidence quantifying the effects of core training on improving arm and leg force production, which might require further investigations.

In addition, S&C training will have the potential to stimulate the neuromuscular adaptation (De Luca, 1997). Research showed that there was an increase in muscle activation by 2% ($p < 0.01$) after resistance training (Knight and Kamen, 2001). This result might suggest that increases in muscle activation would demonstrate there is neural adaptation, which will be associated with the effects on core muscle activity after core training. However, there is no study has been done and examined the effects of neuromuscular adaptation of core muscles by using electromyography during swimming.

Regarding the role of spine stabilization of core muscles in swimming, the co-contraction index (CCI) could be one of the EMG outcomes to be examined (Gabriel et al., 2006). Co-contraction refers to the agonistic and antagonistic muscles activated together to provide stability, for example, Rectus Abdominis (RA) and Erector Spinae (ES) co-contracting, for enhanced spinal stability (Faries and Greenwood, 2007; Granata and Marras, 2000). According to the findings of Matsuura et al. (2019), better core stability may have assisted swimmers to adopt a more streamlined position during FC swim, by reducing the lumbar lordosis angle (- 4.1 deg, $p < 0.01$), with flutter kick performance also improving ($p < 0.05$). CCI of the core muscles could help the evaluation of neuromuscular changes after core training intervention. Despite its potential importance in swimming performance. The CCI of the core and its response to training have not been examined in any studies.

In summary, while previous studies have reported positive relationships between the core, biomechanical parameters and FC performance, the effects of core training on these aspects remain unclear. Gaining insight into how core training can benefit swimmers' performance is important for both athletes and coaches. Therefore, the aim of this study was to evaluate the effects of dry-land core training on FC swimming performance, tethered force and core muscle CCI of swimmers. The findings may assist the coaches in deciding whether implementing additional core training would benefit FC performance more effectively.

Methods

Experimental approach to the problem

Core training was the independent variable, while the dependent variables were swimming time, stroke kinematics (SR, SL and SV), tethered force parameters, and CCI. Measurements were conducted pre- and post-intervention in a 50 m x 25 m x 2 m pool, with a water temperature between 27 - 29°C. Prior to data collection, swimmers were familiarized with the testing procedures and equipment. They refrained from other training on the days before the test sessions. Before the start of the study, all participants and parents provided written informed consent. The study was conducted according to the guidelines of the Declaration of Helsinki (HSEARS20220611001).

Participants

The inclusion criteria were: (1) competitive swimmers who had joined competitive swimming clubs with at least five training sessions per week; (2) swimmers aged 12 or above; (3) swimmers physically able to participate in the core training interventions. Participants were excluded if (1) they had any injuries in the three months leading to the study that restricted their swimming training or competitions and (2) engaged in any S&C training programs during the period of the intervention. For this study, 32 swimmers were recruited and then randomly assigned into two groups, and the minimum number of participants was achieved according to the sample size calculation (G*Power 3.1.9.2). Eight female and eight male swimmers (age: Male = 14.87 ± 1.64; Female = 14.35 ± 1.06 years old) in the experimental group (EG) and six female and 10 male swimmers (age: Male = 17.40 ± 3.92; Female = 15.33 ± 2.16 years old) in the control group (CG).

Core training intervention program

The EG completed eight weeks of core training that included two sessions/week on non-consecutive days. Each session lasted 35 to 45 minutes and was conducted poolside. The program was designed based on the literature and consultations with coaches, trainers and physiotherapists. Core exercises targeted different planes of motion to develop strength and stability through implementing unstable surfaces (i.e., Swiss ball and balance pad) to simulate swimming movements (Prieske et al., 2016). Exercises included plank, bird bod, dead bug, back extension, pallof press and squat (Mullane et al., 2021; Weston et al., 2015) (Table 1). Exercises were progressed every two weeks to overload the swimmers after muscle adaptation time (Kraemer and Ratamess, 2004; Williams et al., 2017), including increasing the number of sets, reps, or resistance, or implementing unstable surfaces and reducing the recovery time, as demonstrated in Table 1. The progression of exercises was under the supervision of coaches or regressed to a previous level if swimmers could not perform correctly (Kraemer and Ratamess, 2004).

Participants in both groups maintained their normal training of seven to nine sessions/week, a total of 35 - 50 km/week, including endurance and anaerobic training. Swimmers were asked to refrain from other S&C training beyond their normal swimming training over the course of the study.

Table 1. The details of the core training program for 8 weeks.

Exercises	Progression of Exercises							
	Variation	Intensity	Variation	Intensity	Variation	Intensity	Variation	Intensity
	Week 1-2		Week 3-4		Week 5-6		Week 7-8	
Plank	Static Plank	30s x 3sets	Alternative Arms Extension	40s x 3sets	Alternative Legs Extension, Elbows on balance pad	45s x 3sets	Alternative Arms and Legs Extension, Elbows on balance pad	60s x 3sets
Bird Dog	With Hip Extension	30s x 3 sets	With Arms Extension	30s x 3 sets	With both Arms and Hip Extension	40s x 3sets	With Arms and Hip Extensions and Arms on Balance Pad	45s x 3sets
Dead Bug	With Hands and Legs movement	30s x 3sets	With Legs extension and Hands hold with elastic bands in tension	40s x 3sets	With Legs Extension only and Hands hold with elastic bands in tension	45s x 3sets	Both Hands and Legs Movement with Elastic Band	45s x 3sets
Back Extension	Hold	30s x 3 sets	Arms Extension	40s x 3 sets	Legs Kicking	40s x 3sets	Alternative Arms and Legs Movements	45s x 3sets
Pallof Press	Pallof Press Hold with elastic band	20s x 3sets x 2 sides	Pallof Press Hold with elastic band	30s x 3sets x 2 sides	Pallof Press with Elbow Extensions	30s x 3sets x 2 sides	Pallof Press with Elbow Extensions	35s x 3sets x 2 sides
Squat	Squat with elastic band	40s x 3 sets	Squat with elastic band	45s x 3sets	Squat with arms hold with elastic band	60s x 3 sets	Overhead squat with arms extension with elastic band	60s x 3sets

Table 2. Swimmers' anthropometrics and swimming performance information (n = 32).

	Experimental Group (n = 16)	Control Group (n = 16)
Sex	M: 8; F: 8	M: 10; F: 6
Age	M: 14.87 ± 1.64 F: 14.35 ± 1.06	M: 17.40 ± 3.92 F: 15.33 ± 2.16
Height (m)	M: 1.68 ± 0.12 F: 1.62 ± 0.04	M: 1.73 ± 0.08 F: 1.64 ± 0.07
Body Mass (kg)	M: 59.36 ± 13.12 F: 53.40 ± 8.02	M: 65.76 ± 10.98 F: 51.92 ± 8.95
Arm Span (m)	M: 1.71 ± 0.11 F: 1.62 ± 0.03	M: 1.76 ± 0.10 F: 1.66 ± 0.10
Years of Experience	M: 6.38 ± 0.11 F: 7.00 ± 1.69	M: 9.90 ± 2.85 F: 7.00 ± 1.10
FINA Points	M: 436.29 ± 88.41 F: 563.00 ± 72.99	M: 581.11 ± 64.15 F: 538.33 ± 97.26

Testing procedures

Before carrying out the tests, anthropometric and personal information of each swimmer were collected, including age, body mass (kg), height (m), arm span (m), year of experience in competitive swimming and the fastest swimming time (s) in 50 m FC swim in long course within the two years before the study. The FINA points of each swimmer were calculated. Body mass (kg) was measured by the TANITA scale (InnerScan, BC-541N, TANITA). Height (m) and arm span (m) were measured by a measuring tape. Swimmers were requested to extend their elbows with forward-facing palms, and arm span was measured as the distance from the tip of the middle finger of one arm to the tip of the middle finger of another arm. All swimmers' descriptive data are presented in Table 2.

Two 50 m freestyle swim time trials were conducted for each swimmer pre- and post-intervention. During the trials, the following variables were concurrently measured and recorded: swimming time (s) by stopwatches, stroke biomechanics (SR, SL, and SV), and core muscle activity via surface electromyography (sEMG). The same testing protocol was followed before and after the 8-week core training program to assess any changes in performance.

The fastest time trial was chosen for further analysis. The SR (cycle/min) over five stroke cycles during the mid-section of the pool was recorded by the same experienced coach with a stopwatch (SEIKO SVAS009, S141 Stopwatch, Japan) for each trial. SV (m/s) was calculated by diving 50 m by the time taken to complete it. SL (m/stroke) was then calculated by dividing SV by SR.

Prior to time trials, swimmers completed a 1000 m warm-up at moderate intensity as previously documented (Morouço et al., 2014), including 400 m swim, 100 m pull and kick respectively, 4 x 50 m at an increasing pace, and 200 m easy swim. Between trials, 10 to 15 minutes of active and passive recovery were provided to prevent fatigue influencing subsequent performances (Amaro et al., 2017).

A 50 m in-water start was used to minimize the effects of diving on EMG outcomes. Muscle activity of core muscles during front FC swimming was measured using wireless sEMG. A 16-channel, 2000 Hz Mini Wave Waterproof sEMG system (Cosmeta, Milan, Italy) was connected to the software (Ver. 6.0.4.0 Cometa) during the 50 m FC time trials. Bilateral muscle activity of the rectus abdominis (RA), external oblique (EO), internal oblique (IO), and erector spinae of the lumbar part (LES) were measured with reference to previous research (Andersen et al., 2021; Andersen et al., 2019) and then used to calculate CCI

(Matsuura et al., 2019). The skin was prepared for electrode placement, and body hair was shaved from electrode sites, which were then cleaned with alcohol pads according to SENIAM guidelines (Hermens et al., 2000). 3M™ Tegaderm™ Transparent Film Roll 16004 was applied over the electrodes to reduce the water noise during recording. To minimize variability of electrodes' position, and in addition to adhering to SENIAM guidelines, photos were taken for each participant for the pre-evaluation and then served as references for the positioning of the electrodes during post-evaluation.

To evaluate changes in force production capability as another key performance outcome, swimmers performed a TST before and after intervention. To avoid any influence on performance, TST was conducted on a separate day from the 50 m FC time trial. The set-up of TST was shown in Figure 1, which included (1) A belt with a 3.5 m inelastic cable wear on swimmers' waists, (2) Load cell (Futex Model LRF350, Irvine, CA, USA) fixated on the handlebar of starting block, (3) data acquisition system (MonoDAQ-U-X, Dewesoft, Slovenia), and (4) Portable Computer with an installed software for the execution of data collection. Before the start of TST, swimmers performed the same warm up as that for the maximal FC trials. They then completed three randomized 30 seconds trials for each TST: whole-body (WB), arms-only stroking (AS), and legs-only kicking (LK). For those AS and LK tests, floating devices were used to restrict the arms or legs' actions during the tests. An elastic band was also placed around the ankles when swimmers were performing AS, to restrict kicking action. Swimmers were instructed to give 100% effort with verbal encouragement during testing. At least 10 minutes of active recovery with low intensity is provided between each test to avoid fatigue influencing subsequent performances.

Due to the small angle of the setup (Figure 1), the horizontal force results were computed from the raw data and then also processed using MATLAB (The MathWorks, Inc, Natick, MA; Version 2021) with a low-pass fourth-order Butterworth filter with a 5 Hz cutoff frequency (Morouço et al., 2014). Mean force (Fmean) was the average force over 30 seconds. The sum of the impulse of force (IMPsum) integrated the area under the force-time curve per stroke and is summed across all strokes. Mean IMP (IMPmean) was produced by dividing the IMPsum by the number of strokes performed during WB and AS conditions.

For the muscle activity, the EMG data have been processed through the band-pass filter with cutoff frequency ranging from 20 to 300 Hz, full-wave rectified and smoothed with root mean square (RMS) by the software (MATLAB 2020a). CCI was calculated for the agonist and antagonist muscle pairs. In this study, two possible muscle pairs were evaluated: the right side of RA and LES (RRA-RLES), and the left side of RA and LES (LRA-LLES). CCI% was calculated according to the formula below (Matsuda et al., 2016):

$$CCI\% = (2*(Musclelowact)/(Musclehighact + Musclelowact)) *100$$

Where Musclelowact was representing muscle with a lower % mV value and Musclehighact was representing a higher % mV value in the muscle pairs.

Descriptive data were presented as mean and standard deviation (SD). The results of each outcome measure were presented along with the changes from pre-intervention and post-intervention (by subtracting post-intervention data from pre-intervention one). Normality was checked using Shapiro-Wilk's test and homogeneity via Levene's test. Parametric tests were used as the data met the assumptions. Two-way repeated measures ANOVA (Time x Group) evaluated interaction effects. Independent and paired t-tests examined between- and within-group differences, respectively. Pearson's correlations identified relationships between changes over time.

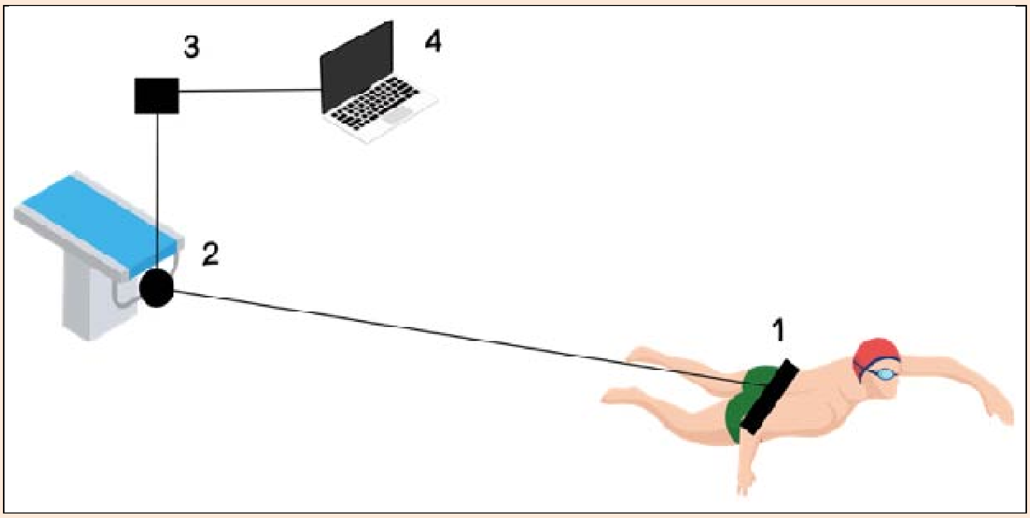

Figure 1. This illustrated the set-up of Tethered Swimming Test (TST). The angle between the cable and swimmer is 5.7°. (1) A belt with a 3.5 m inelastic cable wear on swimmers' waists, (2) Load cell fixated on the handlebar of starting block, (3) Data Acquisition System, and (4) Portable Computer with installed software.

Statistical significance was set at p ≤ 0.05, and the statistical analysis was performed by SPSS (IBM Corp, Armonk, NY; Version 28). Effect sizes for t-tests were reported as Cohen's d (small = 0.2, medium = 0.5, large = 0.8) (Cohen, 1992). Partial eta squared (η2) represented ANOVA effect sizes (small = 0.01, medium = 0.06, large = 0.14) (Richardson, 2011).

Results

Of the 32 swimmers volunteering for the study, two swimmers dropped out after pre-intervention testing due to personal reasons, and follow-up data for two more swimmers (each for EG and CG) were lost. Table 3 shows the results of the swimming performance of both pre- and post-intervention of experimental and control groups and presented in mean and SD. For the baseline measurement results, there were no differences in swimming performance, tethered swimming force, and core muscle activity between EG and CG for male and female swimmer groups, respectively. No discomfort or injuries were reported by the swimmers during the core training.

For the male swimmer groups, EG and CG showed a decrease in swimming time of 0.59 s (~ 1.94%) and 0.07 s (~ 0.25%), respectively. Swimming time (p = 0.04; η2 = 0.24), SR (p = 0.03; η2 = 0.26), and SV (p = 0.04; η2 = 0.23) showed a time effect with a large ES. No time x group interaction effects were found in any swimming performance parameters. Both female groups improved their swimming time, EG by - 0.39 s (~ 1.23%) and CG by - 0.12s (~ 0.38%). No significant time, group or time x group interaction effects were observed, for swimming time, SL, SR, and SV, after 8 weeks of core training (p > 0.05). Nevertheless, within group differences with large ES were found in some parameters. An increase in SV (+ 0.02 m/s) was found in female swimmers of EG (p = 0.05, d = 0.86) and for male swimmers in EG, a decrease in swimming time (- 0.59 s; p = 0.05; d = 0.83) and increase in SV (+ 0.03 m/s; p = 0.05; d = 0.84), but no significant within group differences were shown in CG of both female and male swimmers.

Table 4 presents the force performance results in the TST, including IMPsum, IMPmean, and Fmean, for three different conditions in both groups. Overall, no substantial improvements were found in most variables, only three out of eight outcomes showed large time x group effects in male swimmers, including IMPmean of WB (p = 0.02; η2 = 0.30), IMPsum (p = 0.04; η2 = 0.24) and Fmean (p = 0.05; η2 = 0.23) of LK TST tests. For the female groups, no time x group interaction effects were observed in any outcomes in TST. The only within-group differences were observed in the IMPmean of the AS (p = 0.01; ES = 1.19) in the EG.

Table 3. Results of Swimming Time and Stroke Biomechanics (SR, SL, SV) in 50M FC time trial.

		Male Swimmers			Female Swimmers		
		Pre	Post	Changes	Pre	Post	Changes
Swimming Time (s)	EG	30.38 ± 1.38	29.79 ± 1.25	-0.59 ± 0.72*	31.54 ± 1.43	31.15 ± 1.31	-0.39 ± 0.50
	CG	28.49 ± 3.03	28.42 ± 2.85	-0.07 ± 0.53	31.71 ± 2.20	31.59 ± 2.33	-0.12 ± 0.55
Stroke Rate (stroke/min)	EG	53.23 ± 3.78	55.13± 3.53	1.90 ± 3.51	50.52 ± 2.35	51.37 ± 4.23	0.85 ± 2.53
	CG	55.46 ± 6.11	57.01 ± 4.25	1.55 ± 2.73	50.82 ± 4.03	51.52 ± 24.41	0.70 ± 2.03
Stroke Length (m/cycle)	EG	1.87 ± 0.17	1.84 ± 0.16	-0.03 ± 0.09	1.89 ± 0.12	1.89 ± 0.15	0.00 ± 0.08
	CG	1.93 ± 0.18	1.87 ± 0.16	-0.06 ± 0.09	1.88 ± 0.17	1.85 ± 0.13	0.03 ± 0.07
Swimming Velocity (m/s)	EG	1.65 ± 0.08	1.68 ± 0.07	0.03 ± 0.04*	1.59 ± 0.07	1.61 ± 0.07	0.02 ± 0.02*
	CG	1.77 ± 0.16	1.77 ± 0.16	0.00 ± 0.03	1.58 ± 0.11	1.59 ± 0.11	0.01 ± 0.03

* p < 0.05, significant within group differences. CG: Control group; EG: Experimental group.

Table 4. Results of Tethered Swimming Test in 3 conditions.

			Male Swimmers			Female Swimmers		
			Pre	Post	Changes	Pre	Post	Changes
Whole Body	EG	IMPsum	2284 ± 694	2369 ± 564	85 ± 293	1908 ± 332	1976 ± 207	68 ± 252
		IMPmean	55 ± 15	60 ± 18 †	5.3 ± 7.5	52 ± 11	52 ± 9	0.8 ± 3.4
		Fmean	83 ± 23	85 ± 20	1.3 ± 9.5	68 ± 12	71 ± 7	2.4 ± 8.9
	CG	IMPsum	2849 ± 884	2830 ± 819	-19 ± 185	1880 ± 324	1982 ± 442	102 ± 142
		IMPmean	69 ± 17	66 ± 14	-2.9 ± 5.6	47 ± 8	49 ± 10	2.0 ± 3.1
		Fmean	102 ± 32	101 ± 29	-0.7 ± 6.6	67 ± 11	71 ± 16	3.4 ± 5.4
Arms Stroking Only	EG	IMPsum	1693 ± 533	1712 ± 482	19 ± 229	1305 ± 162	1410 ± 127	105 ± 180
		IMPmean	43 ± 14	46 ± 16	2.7 ± 8.0	35 ± 5	39 ± 5	3.7 ± 3.1*
		Fmean	62 ± 19	61 ± 17	-0.9 ± 6.8	47 ± 6	50 ± 5	3.8 ± 6.4
	CG	IMPsum	2142 ± 445	2136 ± 460	-6 ± 257	1289 ± 158	1208 ± 122	-81 ± 153
		IMPmean	51 ± 12	51 ± 10	0.3 ± 6.7	34 ± 6	34 ± 8	-0.3 ± 6.0
		Fmean	77 ± 16	76 ± 16	-0.2 ± 9.2	46 ± 6	43 ± 4	-2.9 ± 5.5
Legs Kicking Only	EG	IMPsum	967 ± 339	995 ± 256 †	28 ± 111	858 ± 127	877 ± 175	19 ± 56
		Fmean	35 ± 11	36 ± 9 †	0.6 ± 3.1	31 ± 5	31 ± 6	0.7 ± 2.0
	CG	IMPsum	1269 ± 318	1139 ± 305	-130 ± 175 *	857 ± 183	901 ± 206	44 ± 33*
		Fmean	45 ± 11	41 ± 11	-4.7 ± 6.3 *	31 ± 7	32 ± 7	1.6 ± 1.2

*p <0.05, significant within group differences; † p<0.05, significant time*group effects. Abbreviations: CG: Control group; EG: Experimental group; Fmax: Maximum force; Fmean: Mean force; IMPmean: Mean of Impulse of Force; IMPsum: Sum of Impulse of Force.

For the CCI data, including RRA-RLES, LRA-LLES, the results did not show any changes, nor any interaction effects in both male and female groups. Different changes in CCI were observed between female and male swimmers. Female swimmers showed an increase in CCI, while male swimmers had shown an increase and decrease in CCI for both groups.

Discussion

The objective of this study was to investigate the effects of 8 weeks of core training on swimming performance, force performance and core muscle activity. The present study was the first to evaluate the impact of core training via TST and sEMG. There were improvements in performance in both groups, which seemed to be higher for the EG than the CG. Nevertheless, there was little evidence of change in TST or CCI variables, providing no clear indication of the effects of the intervention on swimming performance.

There were no differences in swimming performance or any interactions between EG and CG for male and female swimmers. The improvement in swimming time was similar to that in other studies, such as the 1.8%-1.9% changes reported by Karpiński et al. (2020) and Garrido et al. (2010). Also, EG showed within-group differences in swimming (except females) and SV. These results might imply that core training may impact differently according to the sex of swimmers, as there were differences in physiological responses between males and females to exercise training (Landen et al., 2023), including metabolism and hormonal effects.

The female swimmers in the EG had 1.23% improvement, which was higher than the CG (0.37%), albeit not statistically significant, perhaps because of the relatively small sample size. One study investigated the effects of strength and endurance training on female swimmers for 11 weeks, and they reported 1.90% (~0.6 s) in time improvements in the 50 m sprint (Aspenes et al., 2009). No significant result was demonstrated in female swimmers, but this might be due to the relatively small sample size, despite the sample size minimum number is achieved. A limitation of the present study is that manual timing by stopwatch was used, which might lead to some errors compared to other electronic timing devices.

Swimmers in the EG showed marginally better improvements in stroke biomechanics compared to those in the CG. Male EG swimmers increased SR (+ 1.90 vs + 1.55 stroke/min) with less decrease in SL (- 0.03 VS - 0.06 m/cycle). Female swimmers in EG had slightly higher improvement in SR than those in the CG (+ 0.85 VS + 0.70). Our results aligned with previous research (Karpiński et al., 2020) in favoring SR gains over SL, but not aligned with another study that showed more improvement in SL (Patil et al., 2014). With the increase in SR, SV would also increase, thereby improving the propulsive force generated by the hands (Tsunokawa et al., 2019). Also, significant positive correlations were previously found between changes in tethered force and changes in SR (r = 0.804 - 0.939) (Gourgoulis et al., 2019), indicating that a higher SR may be associated with greater force propulsion and potentially improved swimming performance.

Regarding the results of the force performance measured by TST, only the male WB IMPmean showed significant time x group interaction. Nonetheless, previous findings suggest core training may promote force transferring ability from core to limbs, allowing more effective force production through limb actions (Kibler et al., 2006; Saeterbakken et al., 2022; Shinkle et al., 2012). Force performance in the AS and LK conditions may also provide insight, given a stronger core's potential benefits. Better stability could allow maintenance of a more streamlined position during testing, reducing leg sinking and associated drag. As a result, swimmers may find it easier to exert higher horizontal forces (Silveira et al., 2017), potentially enhancing SV. Most parameters in the current study improved for the EG in AS and LK, suggesting enhanced core stability could transfer to force abilities, optimizing the limbs' function through the kinetic chain (Kibler et al., 2006). However, measuring leg kinematics via underwater cameras was lacking here. Future research quantifying changes in leg positioning after core training may help explain performance impacts more comprehensively.

To evaluate the effects on core muscles after training, sEMG was used for quantifying CCI of core muscle dur-ing FC swim (Gabriel et al., 2006). Female swimmers increased core CCI in post-intervention, which may be due to improved spinal stability (Faries and Greenwood, 2007; Granata and Marras, 2000), which could be ad-vantageous for swimming performance by increasing the muscle activation after core training (Knight and Kamen, 2001). Meanwhile, male swimmers showed no clear CCI changes, this may be due to males having higher muscle mass, too much co-contraction could increase energy demands without performance benefits (Moore et al., 2014). Our results align with previous research that there were different trends in co-contraction between sexes (Anders et al., 2007). Increased spinal stability through targeted co-contraction may benefit females, whereas males may prefer strategies minimizing unnecessary co-activation. One thing to note, is the measures in the pre-sent study were taken on a single day. Although it would not be unreasonable to expect that competitive swimmers would have high inter-day reliability in technique during maximal testing, as indicated in previous studies (Fulton et al., 2009; 2011), inter-day EMG variabil-ity is not often assessed and it could be measured in fu-ture studies to provide evidence specifically on EMG inter-day reliability.

Lack of significant findings may partly reflect the core's stabilizing (Martens et al., 2015) rather than prime mover role, meaning effects on metrics like force could be subtle. Sample sizes may also have been too small and the big difference in age between the male groups, as developmental factors may have confounded the performance changes observed. Therefore, future studies with larger, well-matched samples are needed. Additionally, the subtle impacts of core strength warrant sensitive testing methods able to discern fine-tuned changes in biomechanics and force generation abilities from training. Our study did not directly compare CCI between sexes; future research examining inter-sex differences in specific muscle pair co-contraction could help clarify these divergent responses and optimize training approaches for each group.

Nonetheless, these preliminary insights provide impetus for continued exploration of core musculature's role in swimming. Addressing limitations through optimized research designs can further elucidate its potential for enhancing performance.

Conclusion

In summary, significant within-group changes in swimming time and SV were found in the EG. No significant group differences were found in most variables, including tethered force and CCI. The swimmers in the EG demonstrated a trend for higher improvements in swimming time, SV, and tethered forces. The results provide insight that additional core training may enhance swimming performance beyond typical training alone. As the responses to core training may differ between sexes in terms of co-contraction in core muscles, further investigation is needed to improve our understanding of these differences.

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Key points

- Core training led to significant improvements in force measurements within the experimental group, indicating that enhanced core stability may optimize limb function through the kinetic chain.
- Analysis of the co-contraction index revealed gender-specific responses: female swimmers generally exhibited increased co-contraction, while male swimmers showed more variable changes.

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