Original Research Article

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Lower-body strength, power and sprint front crawl performance

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Abstract

Purpose: To determine the association between lower-body strength and lower-body power capacities with sprint swimming performance in adolescent competitive swimmers.

Methods: A total of 44 front crawl swimmers (27 males and 17 females) performed anthropometric assessments, lower-body strength tests (half squat maximum isometric strength, dynamic half squat with 20, 30 and 40 % of the maximum isometric strength, and knee extension maximum isometric strength) and lower-body power tests (squat jump [SJ], countermovement jump [CMJ] and Abalakov jump). Further front crawl swimming best times in 50 and 100 m were recorded from official swimming competitions and front crawl technique was assessed by an experienced coach using a visual analogue scale.

Results: Swimming performance was correlated with lower-body power variables (SJ [r=−0.573 for 50 m and −0.642 for 100 m], CMJ [r=−0.497 for 50 m and −0.544 for 100 m], and Abalakov jump [r=−0.452 for 50 m and −0.415 for 100 m]; p≤0.05) and lower-body strength (half squat maximum isometric strength [r=−0.430 for 50 m and −0.443 for 100 m]; p≤0.05) in males but not in females. Further linear regression models showed that only lower-body power predicted both 50 m (Abalakov jump; r^2=0.58; change in r^2=0.18) and 100 m (SJ; r^2=0.66; change in r^2=0.15) performance in male swimmers.

Conclusions: This study emphasizes the greater association between lower-body power and sprint front crawl performance in adolescent males compared to females. Practical tests (i.e., SJ and Abalakov jump) are shown to predict front crawl swimming performance, which may facilitate the performance control by coaches and trainers.

Keywords: front crawl swimming; testing; lower-body; dry-land strength; dry-land power; adolescence

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Introduction

A significant body of research has supported the relationship between sprint performance and measurements of strength and power in numerous sports, suggesting that muscle function has some association with sprint performance [1]. Swimming is characterized by unique demands on muscle function, taking place in a singular environment where water viscosity increases resistance to movement. This results in the application of force to propel the swimmer's body through the water and overcome such drag forces. Although previous research has demonstrated that the upper body represents about 70 % of the propulsive forces used in water during front crawl sprint swimming [2], the role of the lower extremities should not be underestimated considering its importance in the drag force by reducing the inclination of the body [3] and in the start and turn phases. A recent study by Keller et al. examined the lower and upper extremity contributions to propulsion and resistance in front crawl swimming [4]. These authors revealed a larger role of the lower-body to the maximal speed than that previously shown in the literature (~30 %), with a contribution of 43.8 % in national and international level swimmers. Ribeiro and colleagues further studied the energy demand during full and upper body extreme swimming intensity (100 m maximal front crawl swim), and observed a comparable contribution of the aerobic and anaerobic metabolism during this maximal effort of ~64 s [5]. Additionally, they concluded that the action from the lower limbs allowed the swimmers to optimise their energy availability in the swimmers' working muscles and to improve performance by ~14 %. Previous results have shown that the block start phase accounts for approximately 26.1 % of the total 50 m time [6], highlighting the importance of lower-body strength and power to sprint swimming performance. These results are in line with the work of Keiner and colleagues who highlighted the importance of training both lower and upper body strength and power to increase sprint front crawl and start performance [7]. Previous authors have focused on the importance of the swim start and its biomechanical determinant factors, also highlighting the performance differences between the track start and kick start with back plate use [8, 9]. For example, de Jesus and colleagues showed that kick start elicited faster start times by reducing block time and increasing horizontal take-off velocity [8].

The need to optimise every relevant aspect in training is evident when considering the very small winning margins. For example, a time difference of 0.01 s separated the gold medal performance of U.S. swimmer Michael Phelps from silver (and an Olympic record of 50.58 s) during the 100 m butterfly in the 2008 Beijing Olympics. Therefore, significant improvements in lower-body strength and power could translate in worthwhile gains in swimming performance.

The contribution of lower-body strength and power to block start performance (from 5 to 15 m) has been extensively studied [10–12]. However, there is a paucity of literature examining the importance of lower-body strength and power in short distances performance (from 25 to 100 m), with unclear conclusions regarding the best indicator to predict overall swimming performance [13]. While Garrido et al. reported higher contributions of lower-body strength (knee extension) to 25 and 50 m swimming performance, in comparison to lower-body power (countermovement jump; CMJ) [14], previous research has suggested that lower-body power is a better predictor of swimming performance than lower-body strength [15, 16]. Specifically in adolescents, Keiner et al. examined the influence of maximal strength of upper and lower body on sprint swimming performance in 17.5 years old swimmers [17]. They found strong correlations between both upper and lower body strength and front crawl swimming performance. It is however unknown whether younger adolescent swimmers would exhibit comparable correlations and if lower body power would potentially reveal stronger associations.

Therefore, the aim of this study was to determine the associations between lower-body strength and lower-body power with front crawl swimming performance in male and female adolescent competitive swimmers. The summary of this study is presented in Figure 1.

Methods

Participants attended our laboratory and performed the strength and power tests (vertical jumps on the force platform, isometric and dynamic half squat and knee extensors strength), anthropometric assessments and questionnaires were completed within 2 h, with the performance times data recorded on a separate day. Prior to commencement, participants warmed up by cycling at 60 W for 10 min and performed specific warm-up for each exercise.

Subjects

Forty-four trained swimmers (27 males and 17 females; age 14.6 ± 1.3 years, height 166.7 ± 10.3 cm, mass 56.3 ± 10.9 kg, Tanner Stages 2–5) took part in the present study. According to the recent performance classification by Ruiz-Navarro et al., swimmers are included in performance level 5 (<450 FINA points) [18]. Participants were included if they met the following inclusion criteria: swimmers between the ages of 12.5 and 17.5 years, Caucasian, healthy and free of injuries. All participants had swum more than 6 h a week for at least 3 years, competing in regional and national events with a mean performance of 30.0 ± 2.4 s in 50 m and 64.9 ± 4.8 s in 100 m front crawl events, corresponding to an 84 % of the Spanish record for the same age-group swimmers.

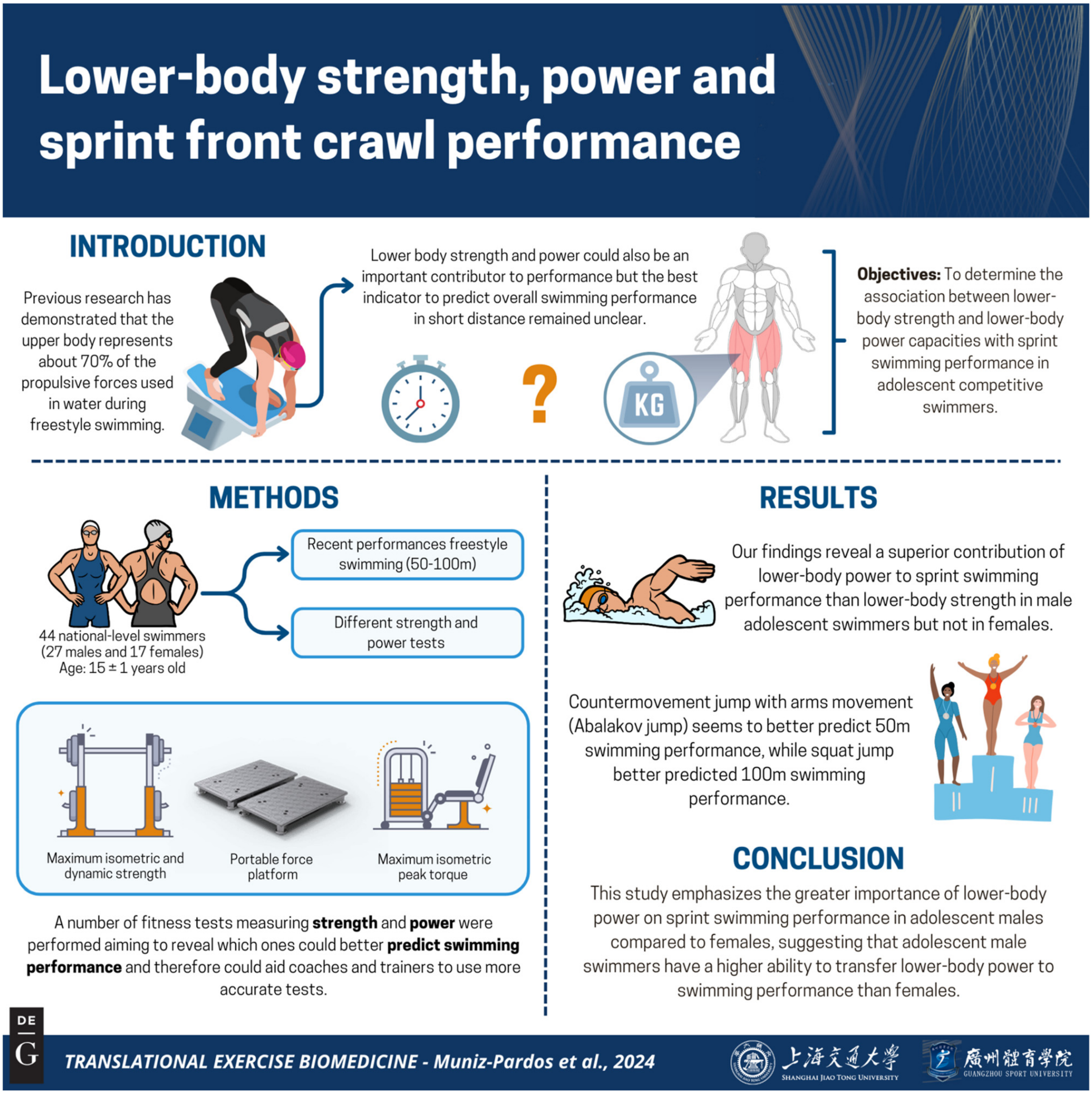

Figure 1: Graphical representation of this study. Key points: (1) greater contribution of lower-body power than lower-body strength to swimming performance in males. (2) Female swimmers did not show such a relationship. (3) Abalakov jump better predicted 50 m swimming performance while squat jump predicted 100 m swimming performance to a greater extent. Figure created with BioRender.

All procedures were approved by the Ethics Committee of Clinical Research from the Government of Aragón (C.I.PI11/0034; CEICA; SPAIN), and followed the international rules for research with humans, following the declaration of Helsinki (1964) as revised in 2013 in Fortaleza. Parents or tutors provided written consent. This study is part of a randomized controlled trial [19] which is registered in a public database (www.clinicaltrials.gov) with the following register number: NCT02380664.

Anthropometric measurements and general information

All participants had basic anthropometric measurements taken (body mass and height). Participants' height was measured while wearing minimal clothing and without shoes to the nearest 0.1 cm (SECA 225, SECA, Hamburg, Germany) and weighted to the nearest 0.1 kg (SECA 861, SECA). An ad-hoc structured questionnaire was completed by all participants which included information related to swimming experience, swimming volume, other sports practiced, in addition to medical history, previous injuries and the evaluation of sex maturity proposed by Tanner [20].

Swimming performance times and front crawl technique assessment

The most recent performances in both 50 and 100 m front crawl swimming (performed up to 15 days near to the testing sessions) were collected from official competitions, reported by the regional swimming federation. These competitions were performed in a 25 m pool. Additionally, the front crawl swimming technique of each swimmer was subjectively graded by an experienced swimming coach with over 10 years of experience. A 10-points scale was used with one for being a very poor technique and 10 for a near perfect technique.

Dry-land strength and power assessments

A strength test has been defined as a procedure to determine the ability to generate high forces against large resistances, whereas a power test has been understood as the assessments to determine the ability to produce a high work rate [1]. Hence, for the present study, those tests which aim to obtain maximum strength would be considered as strength tests, whereas those tests aiming to obtain the maximum strength at a maximum rate or speed, including actions involving the activation of the stretch-shortening cycle (explosive countermovement jumps, drop jumps or short sprints), would be considered as power tests. The methodological procedures of the tests employed during this study have been previously published in methodological research [19]. Of note, swimmers were experienced with strength training and testing and therefore we did not include an additional familiarisation session.

Dry-land strength assessments

Maximum isometric strength from the half squat position was measured using a KISTLER platform type 9260AA (Kistler instruments Ltd., Hampshire, UK). This test has been suggested to reliably reflect lower-body strength and explosiveness [21]. Participants were placed in a 90° half squat position standing on the platform, performing two maximal isometric strength repetitions against a fixed bar with a rest of ~3 min in between. The researcher encouraged the participant to push the bar as strong and quick as possible, always maintaining an adequate technique, with the best attempt recorded. For the dynamic half squat assessment, which has been widely used in the literature with swimmers [22], lower-body strength was measured from the dynamic half squat exercise performed on a Smith machine (Impulse IT Smith Machine, Midlothian, Scotland) with the 20, 30 and 40 % of the participants' maximal isometric strength loaded in the bar. Participants started the exercise from a standing position and then they were asked to perform three maximum repetitions, with ~1 s stop between them in order to avoid technique errors, assessing the maximum propulsive velocity during the concentric phase. A rotator encoder attached to the bar (T-Force dynamic measurement system, model TF-100, Ergotech consulting S.L. Murcia, Spain) was used to register mean propulsive velocity.

Furthermore, maximum isometric peak torque through knee extension was measured using a strain gauge (MuscleLab, Force Sensor, Norway). This test is also widely used with swimmers to test the strength of knee flexors and extensors [23]. The participant was sitting with an anchorage placed on the distal third of the tibia. This anchorage was connected to the strain gauge, registering force data during the 6 s that the participant performed the maximum knee extension. Two attempts were permitted for each leg, with the best performance recorded.

Dry-land power assessments

Vertical jump tests have been widely implemented in swimmers to assess their lower-body power [22]. Participants completed the squat jump (SJ), countermovement jump (CMJ) and the Abalakov jump tests on a portable force platform (Kistler instruments Ltd., Hampshire, UK). For the SJ test, participants were instructed to start from a semi-squatted position (90° knee flexion), with both arms on the hip to isolate the lower limbs action and jumped with no countermovement. For the CMJ performance, participants stood with both hands on their hips, and performed a vertical jump with an earlier fast countermovement. Finally, the Abalakov jump test incorporated the assessment of the intermuscular coordination capacity, the participant performed a CMJ but was allowed to freely coordinate the arms and trunk movements to reach the maximum height. Three attempts with a rest of ~3 min were permitted for each jump and the best performance was selected for further analysis. Peak force and rate of force development (RFD) were computed for each jump through the BioWare® Software (Kistler Group, Winterthur, Switzerland).

Statistical analyses

Mean and standard deviation (SD) were calculated for each variable. The Kolmogorov–Smirnov test was applied, showing a normal distribution for most of the variables. For non-normal variables, normality was checked with histograms and data were transformed to obtain normalized variables with mean 0 and SD 1 through the Blom's test. One-way ANOVA (sex effect) and ANCOVA (sex effect controlling the age and maturity effect) were used to examine the differences in the data, including the estimation of the 95 % CI of the differences between sexes (p≤0.05). Partial eta square (ηp^2) showed the effect size index interpreted as: (a) no effect if $0<\eta p^2\leq0.04$, (b) minimum if $0.04<\eta p^2\leq0.25$, (c) moderate if $0.25<\eta p^2\leq0.64$, and (d) strong if $\eta p^2>0.64$. Bivariate Pearson correlations were used to assess the relationship between swimming times and fitness variables, analysing males and females separately.

Those variables showing significant correlations were included in different linear regression models, for which the 50 and 100 m times were the two dependent variables. Firstly, Model one was used to examine the relative influence of age, maturity status and front crawl technique in swimming performance, so these three variables were introduced in the regression model (Enter method). The next model (Model 2) incorporated the lower-body power variables that had previously shown a correlation with swimming performance (step-wise method). Data did not present multicollinearity (as assessed with the variance inflation factor and the tolerance statistic).

In order to assess the reliability of the fitness-related tests with this specific sample, intraclass correlation coefficient (ICC; one-way random) was calculated for each fitness test. Power calculation and sample size estimations were computed based on the primary outcome which is reported in the corresponding methodological article published elsewhere [19]. The present study is based on a secondary analysis and therefore a specific power calculation was not developed for the present calculations. The Statistical Package for the Social Science 24.0 software (SPSS) was used for all analyses and p value was set at p≤0.05.

Results

Personal data and anthropometric characteristics as well as the variables for both lower-body strength and lower-body power tests, as well as 50 and 100 m front crawl swimming performances are shown in Table 1. Males presented higher values for maturity, height and body mass (Table 1) and also for half squat maximal isometric strength, knee extension maximal isometric strength, mean propulsive velocity at 20 and 30 % of the half squat maximal isometric strength, SJ_{PEAK}, CMJ_{PEAK} and Abalakov jump peak force (Table 1), than females for both unadjusted and age- and maturity-adjusted data (p≤0.05). Males presented better performance times in both 50 and 100 m when compared to females, although when these performance times were converted to FINA points, males showed 364 and 340 points for 100 and 50 m, respectively, while females 384 and 360 points for 100 and 50 m respectively. FINA points as recently stated by Ruiz-Navarro et al. [18] represent the most appropriate method to standardise swimming performance times across different techniques, distances, short/long course and to standardise between sexes. No differences were found in age, swimming experience (y), training volume (h $week^{-1}$), mean propulsive velocity at 40 % of the maximal isometric strength in half squat, SJ_{RFD}, CMJ_{RFD}, and Abalakov jump RFD, between sexes (p>0.05).

For the correlation of the lower-body power variables, three males and four females were removed for the analysis due to incorrect jumping execution during SJ (i.e., countermovement prior the concentric phase). Thus, subsequent correlation and linear regression analyses were performed with a sample of 37 swimmers when including SJ (24 males and 13 females). In males, bivariate correlations exhibited significant values between swimming performance and lower-body power variables (SJ_{PEAK}, CMJ_{PEAK}, Abalakov jump peak force and RFD for both 50 and 100 m performance; p≤0.05, Table 2). Only half squat maximal isometric strength from the lower-body strength variables correlated with swimming performance in males (p≤0.05, Table 2). In females, bivariate correlations did not find any significant relationship with swimming performance (p>0.05, Table 2).

Table 3 displays the results of the linear regression analyses between performance times and the variables that had a significant correlation with performance time in male swimmers (no correlations found for female swimmers). For 50 m performance, age, maturity and front crawl technique adjustments were firstly performed, indicating a significant predictive value of $r^2=0.40$ (p≤0.01; Model 1, Table 3). When lower-body power variables were inserted in the regression analyses, only Abalakov jump RFD significantly increased the predictive value ($r^2=0.58$, change in $r^2=0.18$, p≤0.05; Model 2, Table 3). Similarly for 100 m performance, age, maturity and front crawl technique adjustments indicated a significant predictive value of $r^2=0.51$ (p≤0.01; Model 1, Table 3). When adding the lower-body power variables that previously showed a significant correlation with 100 m performance, SJ_{PEAK} was the only variable included in the regression model (Model 2, $r^2=0.66$, change in $r^2=0.15$, p≤0.01; Table 3).

Table 1: Descriptive analysis of anthropometrics and personal data, front crawl swimming times, lower-body strength and lower-body power variables.

	All (M ± SD)	Boys (M ± SD)	Girls (M ± SD)	CI (95 %)		ANOVA			ANCOVA[c]		
	n=44	n=27	n=17	Lower	Higher	F	p-Value	ηp^2	F	p-Value	$^{d}p^2$
Anthropometrics and personal data											
Age, years	14.6 ± 1.3	14.75 ± 1.26	14.4 ± 1.4	14.2	15.0	0.668	0.418	0.016			
Tanner stage (I/II/III/IV/V)	0/3/14/22/5	0/1/7/14/5[a]	0/2/7/8/0	3.4	3.9	4.505	0.041	0.114			
Height, cm	166.5 ± 10.5	172.10 ± 8.41[a]	157.6 ± 6.5	163.3	169.7	36.78	<0.001	0.467			
Body mass, kg	56.0 ± 11.1	61.34 ± 10.12[a]	47.5 ± 6.4	52.6	59.4	25.295	<0.001	0.376			
BMI, kg m^{-2}	20.0 ± 2.4	20.63 ± 2.58[a]	19.1 ± 1.6	19.3	20.8	4.962	0.031	0.106			
Front crawl T (0–10)	6.3 ± 1.7	6.3 ± 1.8	6.3 ± 1.5	5.8	6.8	0.008	0.930	0.000			
SW Exp, y	8.2 ± 2.6	7.9 ± 2.9	8.6 ± 2.1	7.4	9.0	0.770	0.385	0.018			
Tr Vol, h/wk^{-1}	10.2 ± 2.0	10.3 ± 1.9	10.2 ± 2.2	9.6	10.8	0.012	0.913	0.000			
Swimming performance											
T-50, s	30.18 ± 2.38	28.89 ± 1.63[a]	32.22 ± 1.93	29.45	30.90	37.628	<0.001	0.473	26.495	<0.001	0.665
T-100, s	65.26 ± 4.77	62.80 ± 3.24[a]	69.16 ± 4.19	63.81	66.71	31.994	<0.001	0.432	26.537	<0.001	0.666
Lower-body strength											
MIS half squat, N	1,280.3 ± 400.5	1,460.4 ± 405.35[a]	994.1 ± 149.4	1,158.5	1,402.0	20.587	<0.001	0.329	19.108	<0.001	0.589
MIS KE, N	913.4 ± 195.8	1,005.3 ± 182.86[a]	767.5 ± 108.6	853.9	973.0	23.416	<0.001	0.358	13.034	<0.001	0.494
MPV_{20}, m s^{-1}	0.63 ± 0.08	0.66 ± 0.08[a]	0.58 ± 0.05	0.61	0.66	12.934	0.001	0.235	5.854	0.002	0.305
MPV_{30}, m s^{-1}	0.54 ± 0.08	0.57 ± 0.09[a]	0.50 ± 0.05	0.52	0.57	6.642	0.014	0.137	4.411	0.009	0.249
MPV_{40}, m s^{-1}	0.47 ± 0.09	0.46 ± 0.10	0.45 ± 0.08	0.43	0.49	0.174	0.679	0.004	1.013	0.397	0.071
Lower-body power											
SJ_{PEAK}, N[b]	1,167.1 ± 286.6	1,289.4 ± 278.12[a]	941.3 ± 114.1	1,071.5	1,262.6	18.475	<0.001	0.345	9.703	<0.001	0.469
SJ_{RFD}, N s^{-1}[b]	5,156.0 ± 2,618.2	5,649.0 ± 3,055.96	4,245.9 ± 1,132.2	4,283.1	6,029	2.524	0.121	0.067	0.970	0.418	0.081
CMJ_{PEAK}, N	1,194.6 ± 273.6	1,316.2 ± 250.37[a]	1,001.4 ± 186.0	1,111.4	1,277.8	19.892	<0.001	0.321	11.989	<0.001	0.473
CMJ_{RFD}, N s^{-1}	8,653.3 ± 5,648.4	8,787.1 ± 5,728.51	8,440.6 ± 5,686.6	6,936.0	10,370.5	0.038	0.846	0.001	0.508	0.679	0.037
ABA_{PEAK}, N	1,158.6 ± 287.9	1,285.9 ± 260.20[a]	956.5 ± 204.8	1,071.1	1,246.1	19.553	<0.001	0.318	13.268	<0.001	0.499
ABA_{RFD}, N s^{-1}	6,893.0 ± 4,178.6	7,826.6 ± 4,677.57	5,410.1 ± 2,750.3	5,622.5	8,163.4	3.709	0.061	0.081	1.372	0.265	0.093

[a]Significant differences between sexes ($p \leq 0.05$). [b]The original sample was reduced to 37 swimmers (24 males and 13 females) due to incorrect jumping execution during the SJ. [c]Sex differences following age and maturity adjustments. [d]p^2=partial eta squared; BMI, body mass index; CI, confidence interval; T-50=best performance time in 50 m; T-100=best performance time in 100 m; MIS, half squat=maximal isometric strength from half squat position; MIS KE, maximal isometric strength of the knee extensors; MPV_{20}=mean propulsive velocity in half squat at 20 %; MPV_{30}=mean propulsive velocity in half squat at 30 %; MPV_{40}=mean propulsive velocity in half squat at 40 %; SJ_{PEAK}, squat jump peak force; SJ_{RFD}, squat jump rate of force development; CMJ_{PEAK}, countermovement jump peak force; CMJ_{RFD}, countermovement jump rate of force development; ABA_{PEAK}, abalakov jump peak force; ABA_{RFD}, abalakov jump rate of force development; SW, Exp=swimming experience; Tr Vol=training volume; Front crawl T=Front crawl technique.

Supplementary Table 1 displays the ICC results for all the fitness variables. All variables presented excellent ICC (range: 0.912–0.977), indicating that the performed tests were highly reliable methods to test strength and power in this group of adolescent swimmers.

Discussion

The main findings of the present study revealed that lower-body power through vertical jumps has a superior influence on sprint swimming performance than lower-body strength, in adolescent male swimmers, and not for females. Our study also highlights the importance of lower-body power depending on the distance swam, with the coordination of the upper extremities during the jump being remarkably more important during shorter events. Our findings showed that vertical jumps explained 18 and 15 % of the variance for 50 and 100 m swimming performance, respectively, after adjustments for age, maturity status and front crawl technique. None of the lower-body strength variables explained swimming performance in this group of swimmers neither for 50 m nor 100 m performance.

Table 2: Pearson bivariate correlations in males (n=27) and females (n=17) between front crawl swimming times, lower-body strength and lower-body power.

	Males					Females				
	Lower-body strength variables and swimming performance					Lower-body strength variables and swimming performance				
	MIS KE	MIS half squat	MPV_{20}	MPV_{30}	MPV_{40}	MIS KE	MIS half squat	MPV_{20}	MPV_{30}	MPV_{40}
T-50	−0.142	−0.430[a]	−0.212	−0.008	−0.037	−0.305	−0.076	−0.246	0.018	−0.298
T-100	−0.161	−0.443[a]	−0.313	−0.120	−0.105	−0.358	−0.104	−0.124	−0.045	−0.343

	Lower-body power variables and swimming performance						Lower-body power variables and swimming performance					
	[c]SJ_{PEAK}	[c]SJ_{RFD}	CMJ_{PEAK}	CMJ_{RFD}	ABA_{PEAK}	ABA_{RFD}	[c]SJ_{PEAK}	[c]SJ_{RFD}	CMJ_{PEAK}	CMJ_{RFD}	ABA_{PEAK}	ABA_{RFD}
T-50	−0.573[b]	−0.252	−0.497[b]	−0.262	−0.503[b]	−0.452[b]	−0.082	0.037	−0.150	0.099	−0.274	−0.101
T-100	−0.642[b]	−0.322	−0.544[b]	−0.296	−0.488[b]	−0.415[a]	−0.208	0.063	−0.222	−0.062	−0.308	−0.111

[a]$p \leq 0.05$; [b]$p \leq 0.01$. [c]The sample size was reduced to 24 males and 13 females due to incorrect jumping execution during SJ. ABAPEAK=ABA, peak force; ABARFD=ABA, rate of force development; CMJPEAK=CMJ, peak force; CMJRFD=CMJ, rate of force development; MIS KE, maximal isometric strength of the knee extensors; MIS, half squat=maximal isometric strength from half squat position; MPV20=mean propulsive velocity in half squat at 20 %; MPV30=mean propulsive velocity in half squat at 30 %; MPV40=mean propulsive velocity in half squat at 40 %; SJPEAK=SJ, peak force; SJRFD=SJ, rate of force development; T-50=best performance time in 50 m; T-100=best performance time in 100 m.

Table 3: Linear regression models to predict 50 and 100 m swimming performance in male swimmers (n=24).

	SEE	r	r^2	Change in r^2	Adjusted r^2	β	Semip corre	p-Value
T-50								
Model 1	1.30	0.635	0.404	0.404	0.314			0.014[a]
Age						−0.491	−0.513	0.015[a]
Tanner						−0.096	−0.117	0.605
Front crawl T						−0.249	−0.296	0.180
Model 2	1.11	0.764	0.584	0.180	0.496			0.010[a]
ABARFD						−0.426	−0.550	0.010[a]
Age						−0.459	−0.555	0.009[a]
Tanner						−0.087	−0.126	0.586
Front crawl T						−0.253	−0.354	0.116
T-100								
Model 1	2.34	0.714	0.509	0.509	0.436			0.002[a]
Age						−0.459	−0.524	0.012[a]
Tanner						−0.069	−0.093	0.682
Front crawl T						−0.423	−0.504	0.017[a]
Model 2	2.01	0.811	0.657	0.148	0.585			0.010[a]
SJPEAK						−0.431	−0.549	0.010[a]
Age						−0.280	−0.381	0.088
Tanner						−0.090	−0.144	0.534
Front crawl T						−0.361	−0.507	0.019[a]

[a]$p \leq 0.05$. Model 1: Linear regression model introducing Age, Tanner and Front crawl technique assessment (Enter method). Model 2: Linear regression model introducing Model 1 + all the lower-body power variables that previously showed significant correlations (step-wise method). ABARFD, Abalakov jump rate of force development; β=estimated standardized regression coefficient; B=estimated non-standardized regression coefficient; Front crawl T=front crawl technique; SEE, standard error of estimation of the model; Semip corre=semi-partial correlation; SJPEAK, squat jump peak force; T-50=best performance time in 50 m; T-100=best performance time in 100 m.

In males, data showed a significant relationship between lower-body power tests and swimming performance and half squat maximal isometric strength was the only lower-body strength test that correlated with swimming performance. When lower-body strength and lower-body power variables were analysed through linear regression models, no lower-body strength variables were included in any regression model. The importance of lower-body power showed in the present study is in agreement with Garcia-Ramos et al., who only found associations between lower-body power (SJ and CMJ) and swimming start performance (time to 5, 10 and 15 m), but not with lower-body strength (maximal isometric strength of knee extension and flexion) [11]. Several cross-sectional studies reinforce the relationship between lower-body power (jumping ability) and swimming performance although this association appears arguable when the sample includes adolescent females [15, 16, 22].

The difference between sexes observed in the present study in relation to strength and power capabilities is consistent with previous longitudinal data which examined the lower-body power capacity over different maturation stages among males and females [24]. This longitudinal study showed that adolescent males improved lower-body power (vertical jumping performance) from prepubescence (Tanner stages 1–3) to postpubescence (Tanner stages 4–5), whereas adolescent girls did not. The authors suggested that the neuromuscular increase that takes place in prepubertal males naturally, may be artificially induced through neuromuscular training in females across puberty. There are other factors that might affect swimming performance in female swimmers, such as a reduced energy expenditure for staying afloat because of their higher percentage of adipose tissue [25], or a smaller frontal area in females which has shown to reduce drag values (i.e. lower resistance) [26].

Further linear regression analysis revealed that Abalakov jump RFD was the only variable predicting 50 m performance in males, whereas SJ_{PEAK} was the only variable that predicted 100 m performance. The higher contribution of Abalakov jump RFD to predict 50 m performance may be partially explained by the positive transfer of the lower-body power exerted during the jump as well as a greater influence of the intermuscular coordination using trunk and upper limbs to the specific action [27]. A superior performance in this jump not only reveals those powerful swimmers, but also those swimmers capable to efficiently coordinate both the upper and lower limbs to perform an optimal moment of inertia. This greater moment of inertia and coordination during the early phase of the concentric movement (where the RFD takes place), could be linked to a greater lower-body power exerted during the take-off phase as well as an optimal rotation during the flight phase. As previously reported, the main aim of the flight phase is not only to go as far as possible, but also to prepare the body for a streamlined entry to favour an efficient under-water phase [28]. In order to optimize the flight phase, the movement of the upper extremities seems to play a crucial role since they highly influence the angular momentum needed to enter in the water with the optimal rotation [29]. We therefore suggest that the capacities tested during Abalakov jump (i.e., lower-body power and optimal coordination to use the upper extremities) would partially explain a high performance during the start phase and thus 50 m performance in male adolescent swimmers.

Regarding the greater influence of SJ_{PEAK} to predict 100 m swimming performance shown in this study, it is worth noting that this test has been designed to isolate the lower-body power. This would avoid the influence of other factors that take place during other jumps, such as the elastic energy during CMJ, or Abalakov jump, or the coordination capacity using the trunk and upper limbs during Abalakov jump [27]. Therefore, it seems that lower-body power in isolation may play a greater role in this distance, which could be explained due to a higher number of turns (one in 50 m races vs. three in 100 m races over a 25 m pool) and thus a higher contribution of the front crawl turning performance during a longer event, when compared to a 50 m race [30]. In relation to the turning phase, it is believed that there exists a negligible countermovement of the lower limbs during the push-off phase in order to store elastic energy for a greater push-off [31]. Nevertheless, since the turn phase has a critical time element and performing a countermovement has shown to risk the swimmer´s valuable time [32], it is common that the swimmer performs little to no active eccentric phase during the push-off phase [33]. Pereira and colleagues extensively studied the kinematic, kinetic and electrical muscle activity of swimmers when performing the front crawl flip turn. These authors examined the time spent on each turning sub-phase (rolling, wall support, pushing, gliding) and reported wall support times of 0.14 s and pushing times of 0.26 s, illustrating the need to contact the wall as little as possible [34].

We therefore hypothesize that a higher jump performance without countermovement (i.e., SJ performance) might predict a shorter ground contact time during the pushing-off the wall phase, partly predicting 100 m performance. As displayed in Table 3, front crawl swimming technique significantly predicted swimming performance only for 100 m, which is in agreement with previous research highlighting biomechanical factors (e.g., stroke rate, stroke length and stroke index) contribute more to 100 and 400 m performance in adolescent swimmers, compared with physiological or anthropometric factors [35]. However, our study did not examine physiological or anthropometrical factors, which limits this comparison.

It is worth considering that the aforementioned cross-sectional data do not report a cause-effect relationship, being difficult to assess these markers as causative. Nonetheless these results agree with previous intervention studies. Bishop et al. found that 8 weeks of plyometric training improved the start phase (time to 5 m) and also the turning phases (enhancement of 2.9 %), in adolescent swimmers [36].

Potdevin et al. developed a 6-week plyometric training in adolescent swimmers and, besides an improvement in CMJ and SJ height, they observed higher improvements in 400 m performance (4.4 %), in comparison with 50 m performance (3.2 %) [30]. Considering that this latter study is the only which investigated the chronic effects of plyometrics on overall swimming performance in adolescent swimmers, definitive conclusions cannot be made. Further cross-sectional data revealed positive relationships between lower-body strength (leg extension) and sprint performance (25 and 50 m) but not with lower-body power (CMJ) [14]. Nevertheless, swimmers involved in their study [14] were prepubescents (Tanner stages 1–2) and, as reported by the authors, vertical jump performance in prepubescent swimmers could be highly dependent on skill [37]. We therefore hypothesise that the potential relationship between lower-body power and swimming performance might not reflect faster swimmers at this maturity stage yet.

Some limitations are important to consider in the interpretation of the present results. Additional muscle composition analysis through biopsies, or metabolic assessments using different biomarkers (lactate, ammonia, blood glucose) might have revealed whether the higher lower-body power contribution could have been due to either the characteristics of the lower-body power tests, or the specific swimmer's physiological profile. However, the development of this analysis was not possible for this study and we assumed that this physiological profile would be representative for this specific sample and level of performance. The performance level of the swimmers was low as aforementioned in the methods section (Level 5), which made the comparison with previous research using higher calibre swimmers challenging (Level 4 to 1). In order to obtain more precise and reliable data, a wider sample size is recommended for both male and female groups. The incapacity of some adolescent swimmers to adequately perform the SJ technique was another limitation since it partially reduced the sample size, which would require a further familiarization session in future investigations.

The method used in this study to assess SJ performance (i.e., jumping from a 90° knee flexion position) is widely used in both testing and research, although the optimal knee starting angle to maximize jumping performance has shown to be widely varied between subjects [38]. Therefore, this starting angle should be personalized for each individual in further studies. Front crawl technique was not assessed through objective biomechanical data (e.g., stroke index, stroke rate or stroke length) but rather a qualitative assessment (not validated) from an experienced coach and therefore, this assessment should be carefully interpreted. A potential solution for future studies wishing to use a qualitative assessment of front crawl technique would be to use valid observation sheets already published [39]. Swimming competitions were also performed on a short course (25 m) where turns are more common and therefore important to overall swimming performance than on long courses (50 m). This may explain the high correlations observed between lower-body power and swimming performance in males, which cannot be extrapolated to long courses. Considering the strong relationship between lower-body power and swimming performance and the lack of plyometric training interventions aiming to improve swimming performance, there is an urgent need for scientific validation of plyometric training exercises to improve swimming performance.

Practical applications

This study will aid coaches and trainers to decide which lower-body power test would be the most accurate for sprinters to predict front crawl swimming performance, depending on the distance swam. Coaches are encouraged to incorporate specific lower-body power tests through vertical jumps to assess the swimmer´s performance progression. Accordingly, Abalakov jump will be a better option to test 50 m performance while SJ jump will predict 100 m performance with more accuracy. Considering the lack of a significant relationship between lower-body power and swimming performance in female swimmers observed in our study, we encourage coaches to use different strength/power tests (to be further studied) and, if supported by intervention studies, pay more attention to lower-body power training in female adolescents to improve front crawl swimming performance.

Conclusions

Our findings reveal a superior contribution of lower-body power to sprint swimming performance than lower-body strength in male adolescent swimmers but not in females. Vertical jump assessments potentiating upper extremities coordination and lower-body power (i.e., Abalakov jump) seem to be a more representative test to predict shorter distances performance in males. The movement of the upper extremities during a jump seems to favour the prediction of 50 m performance, probably due to a positive transfer of both lower-body power and upper extremities movement to the specific sports action. In the present study, SJ peak power, in part, has shown to predict 100 m swimming performance in males, hypothesizing that the power exerted during this jump could be related to the power utilized during the push-off the wall phase. Further research is needed in female populations in an attempt to identify further performance proxies to predict sprint swimming performance.

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Informed consent: Parents or tutors provided written consent.
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