Associations and predictive value of isometric strength, isokinetic strength, and anaerobic power for 100-m freestyle performance in young swimmers

Zied Abbes[1*,A-F], Rabeh Labbadi[2,A,B,D,F], Faten Salhi[3,C,D,F]

[1] Physical Education Department, College of Education, Qatar University, Doha, Qatar
[2,3] Higher Institute of Sports and Physical Education of Kef, University of Jendouba, El Kef, Tunisia

***Corresponding author:** Zied Abbes; Physical Education Department, College of Education, Qatar University, Doha, Qatar; email: zi.abbes@qu.edu.qa

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ABSTRACT

Background: Multiple physical and physiological factors influence sprint swimming performance; however, the relative contributions of isometric strength, isokinetic strength, and anaerobic power to 100-m freestyle performance in young swimmers remain unclear.

Objectives: This study investigated the associations and predictive contributions of physical characteristics, isometric and isokinetic upper-body strength, and anaerobic power to 100-m freestyle swimming performance in young swimmers.

Methods: A cross-sectional study was conducted with 21 male swimmers aged 10–13 years, selected purposively. Eligibility criteria included a minimum of three years of structured swimming training, regular participation in 3–5 training sessions per week, and absence of musculoskeletal injuries. Upper-body strength was assessed using isometric and isokinetic dynamometry (60°/s and 180°/s), while anaerobic power was measured using the 30-s Wingate Anaerobic Test. Swimming performance was evaluated using a 100-m freestyle time trial. Pearson correlation and linear regression analyses were performed after verification of regression assumptions.

Results: Swimming speed was significantly correlated with isometric elbow flexor strength ($r = .49$, $p < .05$), isokinetic flexor strength at 60°/s ($r = .41$, $p < .05$), and Wingate peak power ($r = .37$, $p < .05$). Simple linear regression analysis identified isometric elbow flexor strength as the strongest predictor of swimming performance ($B = 0.005$, $p = .026$, $R^2 = .235$), followed by isokinetic flexor strength at 60°/s ($B = 0.004$, $p = .038$, $R^2 = .210$) and Wingate peak power ($B = 0.001$, $p = .031$, $R^2 = .198$). No significant associations were observed for isokinetic strength at 180°/s.

Conclusions: Upper-body muscular strength, particularly isometric elbow flexor strength, is a significant determinant of 100-m freestyle swimming performance in young swimmers. These findings highlight the importance of maximal force-generating capacity, alongside anaerobic power development, for sprint swimming performance.

Keywords: anaerobic power, isometric strength, isokinetic strength, swimming performance, youth youth swimmers.

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INTRODUCTION

Swimming performance, particularly in sprint events such as the 100-m freestyle, is determined by a complex interaction of physiological, biomechanical, and technical factors. Among these, the ability to generate propulsive force and sustain high-intensity effort over short durations is considered critical (Jones & Vanhatalo, 2017; Natera et al., 2020). However, despite extensive research in competitive swimming, there remains ongoing debate regarding which physical attributes most strongly influence performance in young swimmers. This issue is especially relevant given that young swimmers often exhibit variability in both physical capacity and technical proficiency, making performance determinants less predictable compared to adult athletes.

Understanding the key predictors of sprint swimming performance in young athletes is of considerable importance for both scientific and practical reasons. From a coaching perspective, identifying the most influential physical factors can help optimize training programs and improve performance outcomes (Boullosa et al., 2020; Smith, 2003). In youth populations, where training time and physical development must be carefully managed, prioritizing the most relevant components—such as strength or anaerobic power—becomes essential. Moreover, early identification of performance-related factors may contribute to long-term athlete development by guiding appropriate conditioning strategies during critical growth periods (Lloyd et al., 2015).

Previous research has highlighted the importance of upper-body strength for swimming performance, particularly in front crawl, where the upper limbs generate the majority of propulsive force. In line with this, a recent study by Abbes et al. (2023) examined the relationship between physical characteristics and 200-m swimming performance in young swimmers and reported that isometric and isokinetic elbow flexor strength were significantly associated with swimming speed, whereas anaerobic power was not. However, the role of anaerobic power in sprint swimming performance remains inconclusive. While anaerobic metabolism is considered a major contributor to events lasting approximately 60–90 seconds, previous studies have reported inconsistent findings regarding the relationship between Wingate-derived anaerobic power and swimming performance in young swimmers (Kachaunov & Petrov, 2020). Furthermore, most available studies have focused on a single physical determinant rather than evaluating the relative contribution of strength and anaerobic power within the same investigation.

In addition, other studies have demonstrated that dry-land strength and force production are significantly associated with sprint swimming velocity, as stronger swimmers generate greater propulsive force during the underwater phase (Morais et al., 2021). Isokinetic assessments have also been widely used to evaluate muscle function in swimmers, providing insight into torque production at different movement velocities (Wirth et al., 2022). Furthermore, anaerobic capacity has been considered an important contributor to short-distance swimming performance due to the high reliance on anaerobic energy systems (Gastin, 2001).

Nevertheless, existing studies have predominantly focused on middle-distance events such as the 200-m, or have examined strength and anaerobic variables separately. Sprint events, such as the 100-m freestyle, place distinct physiological and biomechanical demands on athletes, characterized by higher movement velocity, greater reliance on rapid force production, and different energy system contributions

(Price et al., 2024; Ruiz-Navarro et al., 2025). In addition, there remains limited evidence examining the combined role of isometric strength, isokinetic strength at different angular velocities, and anaerobic power within a single analytical model in young swimmers. As a result, the extent to which these variables contribute to sprint swimming performance, particularly during early developmental stages, remains unclear. To our knowledge, no previous study has simultaneously examined the associations and predictive value of isometric strength, isokinetic strength at different angular velocities, and anaerobic power for 100-m freestyle performance in young swimmers. This study, therefore, addresses an important gap by evaluating these physical determinants within the same cohort and performance context.

From a physiological perspective, 100-m freestyle performance depends on the interaction between force production capacity and short-term energy supply (Yang et al., 2026). Upper-body muscular strength contributes to the generation of propulsive force during the pull and push phases of the stroke cycle. In contrast, anaerobic power supports the maintenance of high-intensity effort throughout the race (Sandford, Laursen, & Buchheit, 2021). Isometric strength may reflect maximal force-generating capacity, while isokinetic strength provides insight into force production under movement-specific conditions. Together, these factors may influence the swimmer's ability to generate propulsion, minimize performance decline, and sustain swimming velocity during sprint events.

Therefore, this study aimed to investigate the associations and predictive value of isometric, isokinetic, and anaerobic power for 100-m freestyle performance in young swimmers. We hypothesized that upper-body strength and anaerobic power would be positively associated with swimming performance, with isometric strength showing the strongest predictive value.

METHODS

Study Design and Participants

A cross-sectional study design was used to investigate the associations between anthropometric variables, upper-body muscular strength (isometric and isokinetic), anaerobic power, and 100-m freestyle swimming performance in young swimmers. A total of twenty-one young male swimmers (age: 11.62 ± 1.12 years; body mass: 52.40 ± 10.35 kg; height: 152.30 ± 9.85 cm) voluntarily participated in this study. All participants had a minimum of 3 years of structured swimming training experience and were actively training 3–5 sessions per week, with an average training volume of approximately 2–3 km per session. A formal a priori sample size calculation was not performed because the study used an available cohort of competitive young swimmers. However, studies examining physical determinants of swimming performance in youth athletes frequently involve relatively small sample sizes because access to trained competitive swimmers is often limited (Price et al., 2024).

At the time of data collection, all swimmers were free from musculoskeletal injuries and had no medical conditions that could affect their performance. Participants were instructed to avoid strenuous physical activity 24 hours prior to testing and to refrain from consuming caffeine or other stimulants at least 6 hours before the measurements. Prior to participation, both the swimmers and their parents or legal guardians were fully informed about the purpose, procedures, and potential risks of the study. Written informed consent was obtained from the parents or guardians, and verbal assent was obtained from the participants.

Ethical approval statement

The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board of the affiliated university (QU-IRB 417-A/06). All participants were familiarized with the procedures and were informed of their right to withdraw at any time without consequences.

Research Instruments

The present study employed a combination of laboratory- and field-based instruments to assess the physical characteristics associated with 100-m freestyle swimming performance. Upper-body muscular strength was evaluated using an isokinetic dynamometer (Biodex System, Biodex Medical Systems, NY, USA), which measured both isometric and isokinetic contractions of the elbow flexor and extensor muscles. Isometric strength was assessed through maximal voluntary contraction (MVC) at a fixed joint angle, while isokinetic strength was measured at angular velocities of 60°/s and 180°/s in concentric mode, as these velocities are considered representative of swimming movement patterns.

Anaerobic power was assessed using the 30-second Wingate Anaerobic Test (WAnT), performed on a cycle ergometer (Monark Ergomedic 894E, Sweden), with resistance adjusted relative to body mass. Peak power and mean power outputs were recorded as indicators of anaerobic capacity. Blood lactate concentration was measured using a portable lactate analyzer (Lactate Scout+, SensLab GmbH, Germany) to support the evaluation of anaerobic responses.

Swimming performance was assessed through a 100-m freestyle time trial conducted in a standard 50-m swimming pool. Performance time was recorded using a manual stopwatch, and swimming speed was subsequently calculated. All instruments used in this study have been widely applied in swimming research and demonstrated acceptable validity and reliability for assessing strength and anaerobic performance in young swimmers.

Procedures

The experimental procedures were carried out in Qatar University laboratory and a standard 50-m swimming pool. Prior to data collection, all participants attended a familiarization session to become accustomed to the testing protocols and equipment. Detailed instructions regarding strength and anaerobic performance assessments were provided to ensure consistency during testing.

Each participant completed three laboratory tests: (1) isometric maximal voluntary contraction (MVC) of the elbow flexors and extensors at a fixed joint angle, (2) isokinetic strength assessment of the elbow flexor and extensor muscles at angular velocities of 60°/s and 180°/s in concentric mode, and (3) a 30-second Wingate anaerobic test. Following the familiarization session, the main laboratory testing session was conducted under standardized conditions. A standardized warm-up was performed prior to laboratory testing, consisting of 5 minutes of cycling on a stationary ergometer at moderate intensity (70 rpm, 1 kilopond), followed by four submaximal contractions of the elbow flexor and extensor muscles at approximately 50–75% of MVC for 4 seconds each, with 10-second rest intervals. Verbal encouragement and visual feedback were provided to ensure maximal effort and proper execution of movements.

The field test was conducted 48 hours after the laboratory assessments to minimize fatigue effects. After a standardized 10-minute swimming warm-up, participants performed a 100-m freestyle time trial in a 50-m pool. The test was conducted as a maximal effort trial, and performance time was recorded using a manual stopwatch. Swimming speed was subsequently calculated for further analysis.

For the isometric assessment, participants performed two maximal voluntary contractions for each muscle group (elbow flexors and extensors), maintaining each contraction for 3 seconds with a 2-minute rest interval between trials. The highest peak torque value was used for analysis.

For the isokinetic assessment, participants performed five maximal concentric contractions at angular velocities of 60°/s and 180°/s. These velocities were selected as they reflect movement speeds commonly observed in swimming. The highest peak torque obtained at each velocity was retained for statistical analysis. All tests were performed using the dominant arm, and a rest period of 3 minutes was provided between test conditions.

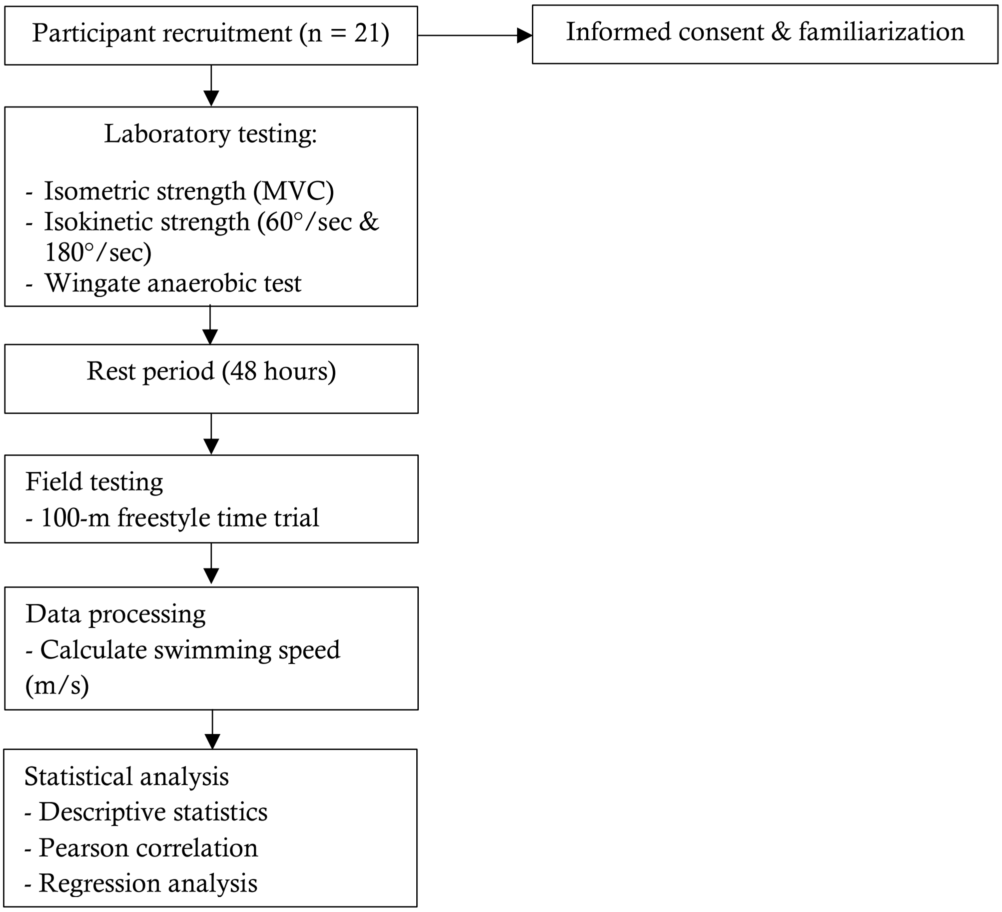

Figure 1. Flowchart of the Study Design and Testing Procedures

Data Analysis

Descriptive statistics are presented as mean ± standard deviation (SD) for all variables. Prior to inferential analysis, the normality of data distribution was assessed using the Kolmogorov–Smirnov test. Swimming performance was expressed as swimming speed (m/s), calculated from the 100-m freestyle time trial.

Pearson product–moment correlation analysis was performed to examine the relationships between anthropometric characteristics, upper-body muscular strength variables (isometric and isokinetic), anaerobic power measures, and 100-m freestyle swimming speed.

Variables demonstrating significant correlations with swimming speed were subsequently entered into separate simple linear regression models to determine their predictive value. Swimming speed (m/s) was treated as the dependent variable, whereas the significantly correlated physical variables were entered as independent variables.

Prior to regression analysis, the assumptions of linearity, homoscedasticity, and normality of residuals were evaluated through visual inspection of scatterplots of residuals versus predicted values and normal Q–Q plots of standardized residuals. No substantial violations of these assumptions were observed.

Regression coefficients (B), standard errors (SE), coefficients of determination (R^2), adjusted coefficients of determination (Adj. R^2), and associated p-values were reported. All statistical analyses were conducted using JASP (Version 0.95.1; JASP Team, Amsterdam, The Netherlands), and statistical significance was set at $p < 0.05$.

RESULTS

The general physical and performance characteristics of the participants are presented in Table 1. The swimmers demonstrated a mean swimming speed of 1.32 ± 0.06 m/s, indicating a relatively homogeneous performance level. Pearson correlation analysis revealed that height ($r = .41$, $p < .05$), body mass ($r = .36$, $p < .05$), and isometric peak torque of the elbow flexors ($r = .49$, $p < .05$) were significantly associated with 100-m freestyle swimming speed. Additionally, isokinetic peak torque at 60°/sec for both flexion and extension, as well as Wingate peak and mean power, showed significant moderate correlations with swimming performance. In contrast, age and isokinetic strength at higher velocity (180°/sec) were not significantly related to swimming speed.

Table 1. General Physical Characteristics and 100-m Swimming Speed of Participants

Variables	**Mean ± SD**	**100-m swimming speed (r)**
Age (years)	11.62 ± 1.12	0.28
Height (cm)	152.30 ± 9.85	0.41*
Body mass (kg)	52.40 ± 10.35	0.36*
100-m swimming speed (m/s)	1.32 ± 0.06	1
Isometric peak torque – Flexion 90° (Nm)	117.00 ± 5.67	0.49*
Isometric peak torque – Extension 90° (Nm)	110.50 ± 6.10	0.38*
Isokinetic peak torque – Flexion 60°/sec (Nm)	93.43 ± 4.57	0.41*
Isokinetic peak torque – Extension 60°/sec (Nm)	88.20 ± 5.02	0.34*
Isokinetic peak torque – Flexion 180°/sec (Nm)	85.10 ± 4.80	0.29
Isokinetic peak torque – Extension 180°/sec (Nm)	80.75 ± 4.95	0.26
Wingate peak power (W)	410.25 ± 65.30	0.37*
Wingate mean power (W)	315.40 ± 48.20	0.33*

Table 2. Results of Separate Simple Linear Regression Models Predicting 100-m Freestyle Swimming Speed

Predictor	B	SE	p	R^2	Adj. R^2
Isometric – Flexion 90°	0.005	0.002	.026	.235	.197
Isokinetic – Flexion 60°/sec	0.004	0.002	.038	.210	.172
Wingate Peak Power	0.001	0.000	.031	.198	.160

Note. Each predictor was analyzed using a separate simple linear regression model. B = unstandardized regression coefficient; SE = standard error; R^2 = coefficient of determination; Adj. R^2 = adjusted coefficient of determination.

Visual inspection of residual-versus-predicted plots indicated no apparent violations of linearity or homoscedasticity. In addition, normal Q–Q plots suggested that standardized residuals were approximately normally distributed. The results of the regression analysis with an intercept are shown in Table 2. Isometric elbow flexor strength at 90° was a significant predictor of swimming speed (B = 0.005, p = .026), explaining 23.5% of the variance in swimming speed. Similarly, isokinetic peak torque at 60°/sec (flexion) contributed significantly (B = 0.004, p = .038), accounting for 21.0% of the variance in performance. Furthermore, anaerobic capacity, represented by Wingate peak power, was also a significant predictor (B = 0.001, p = .031), explaining 19.8% of the variance. These findings indicate that both muscular strength and anaerobic power play a meaningful role in determining 100-m freestyle swimming performance.

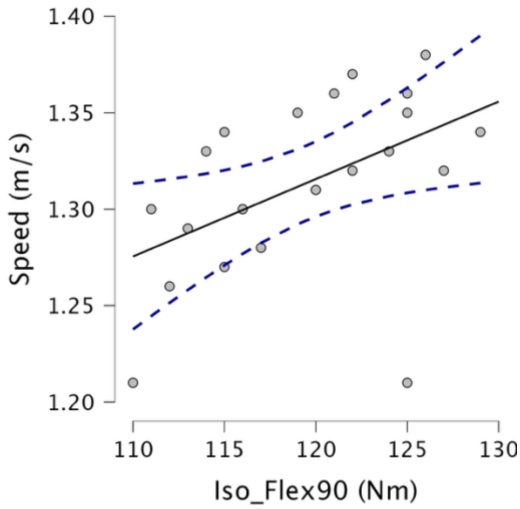

Figure 2. Relationship between isometric peak torque of the elbow flexors at 90° (Nm) and 100-m freestyle swimming speed (m/s). A moderate positive correlation was observed (r = .489, $p < .05$), indicating that greater upper-body strength was associated with higher swimming speed.

Figure 2 illustrates the relationship between the isometric peak torque of the elbow flexors and swimming speed. A moderate positive linear relationship was observed, indicating that swimmers with greater upper-body strength tended to achieve higher swimming speeds.

DISCUSSION

The present study aimed to examine the relationship between physical characteristics, upper-body muscular strength, and anaerobic capacity with 100-m freestyle swimming performance in young swimmers. The findings revealed that isometric elbow flexor strength, isokinetic strength at 60°/sec, and anaerobic power (Wingate peak power) were significant predictors of swimming speed. In particular, isometric elbow flexor strength showed the strongest association, indicating that upper-body strength plays a critical role in short-distance swimming performance. These results suggest that both muscular strength and anaerobic capacity contribute meaningfully to performance outcomes in youth swimmers.

The present findings support the physiological framework proposed in this study, whereby sprint swimming performance depends on the interaction between force-generating capacity and short-term anaerobic energy supply. Isometric strength may reflect the maximal force available for propulsion, whereas anaerobic power helps sustain high-intensity effort throughout the race. The significant contribution of both variables suggests that successful sprint performance in young swimmers requires the integration of neuromuscular and metabolic capacities.

Interestingly, isometric elbow flexor strength demonstrated a stronger association with swimming performance compared to isokinetic variables, despite swimming being a highly dynamic movement. This finding may be explained by the role of isometric strength as an indicator of maximal force-generating capacity, which serves as a fundamental foundation for dynamic muscular actions (Barbosa et al., 2015b). In strength and conditioning research, maximal force capacity is considered a key determinant of subsequent power production and movement efficiency (Suchomel et al., 2016). In the context of swimming, the ability to generate high levels of force against water resistance during the pull phase is essential for propulsion, and this capacity may be better reflected by isometric measures than by velocity-dependent strength assessments (Dai et al., 2025; Jones, 2019). Furthermore, isometric strength has been shown to correlate with dynamic performance outcomes in various athletic tasks, suggesting that it underpins the neuromuscular potential required for effective force application in sport-specific movements (Lum & Barbosa, 2019). Therefore, the present findings indicate that maximal strength capacity, rather than movement speed alone, may play a more critical role in determining sprint swimming performance in young athletes.

The present study also demonstrated that isokinetic strength measured at 60°/sec was significantly associated with swimming performance, whereas measurements at 180°/sec were not. This finding can be interpreted through the force–velocity relationship, whereby increases in movement velocity are accompanied by reductions in force production capacity. At lower angular velocities, such as 60°/sec, swimmers are able to generate higher levels of muscular force under more controlled conditions, which may better reflect the propulsive demands of the underwater pull phase in freestyle swimming. In contrast, at higher velocities (180°/sec), although movement speed increases, force output is reduced, potentially limiting its contribution to effective propulsion. Recent evidence in swimming performance research highlights that force production and muscular strength are key determinants of sprint swimming performance, particularly in youth athletes, where the ability to apply force effectively against the water is critical (Price et al., 2024). Furthermore, strength training literature suggests that moderate-velocity contractions are more closely related to sport-specific force application than high-velocity movements, especially in tasks requiring resistance against external media such as water (Wirth et al., 2022). Therefore, the present findings indicate that strength assessed at moderate velocities may be more functionally relevant to swimming performance than high-velocity contractions in young swimmers.

The observed relationship between elbow flexor strength and swimming performance can also be explained from a biomechanical perspective. During freestyle swimming, propulsion is primarily generated during the underwater pull and push phases of the stroke cycle (Psycharakis & Coleman, 2024; Stosic, 2020). In the pull phase, the elbow flexors play a dominant role in initiating force application against the water, while in the push phase, coordinated muscle action contributes to maximizing propulsive force. Therefore, swimmers with greater elbow flexor strength are likely able to generate higher propulsive forces, resulting in increased swimming velocity (Cochrane et al., 2015; Wiażewicz & Eider, 2021). Recent biomechanical analyses have emphasized that effective force application during the underwater phase is a key determinant of sprint swimming performance, particularly in front crawl swimming (Morais et al., 2021). Moreover, propulsion efficiency is closely related to the swimmer's ability to apply force in a direction that maximizes forward movement, which is strongly influenced by upper-body strength and coordination (Van Houwelingen et al., 2017). These findings support the present results, highlighting the importance of elbow flexor strength in enhancing propulsion and overall swimming performance.

The significant role of strength variables observed in this study should also be interpreted in light of the participants' developmental characteristics, who were aged 10 to 13 years. This age range is associated with substantial inter-individual variability in biological maturation, growth velocity, and neuromuscular development (Salami et al., 2024). During this period, increases in muscle mass, neural activation capacity, and limb dimensions may substantially influence both strength and swimming performance. Consequently, part of the observed relationships may reflect maturational differences rather than training adaptations alone. Previous research has demonstrated that biological maturation significantly influences strength, power, and athletic performance in youth athletes (Lloyd et al., 2012; Moran et al., 2018). Because maturity status was not directly assessed in the present study, the independent contribution of maturation cannot be determined. Future investigations should incorporate indicators such as peak height velocity (PHV) or maturity offset to better distinguish developmental effects from performance-related physical capacities.

Despite the significant relationships observed in this study, the relatively moderate coefficients of determination (R^2 ranging from approximately 0.20 to 0.26) indicate that a substantial proportion of variance in 100-m freestyle swimming performance remains unexplained. This highlights the multifactorial nature of swimming performance, which is influenced not only by physical capacities such as strength and anaerobic power but also by technical, biomechanical, and coordinative factors. Previous research has emphasized that stroke efficiency, coordination, and hydrodynamic positioning are critical determinants of swimming velocity, often accounting for a large portion of performance variability (Morais et al., 2019; Barbosa et al., 2015a). In particular, the ability to minimize drag and optimize stroke mechanics plays a crucial role in translating physical capacity into effective propulsion. Therefore, while strength and anaerobic power contribute meaningfully to performance, they represent only part of a broader and more complex system of interacting determinants that underpin sprint swimming performance.

An important observation is that the strongest predictor identified in the present study explained only 23.5% of the variance in swimming performance. Although statistically significant, this finding suggests that physical capacities alone are insufficient to explain sprint swimming success fully. Competitive swimming performance emerges from a complex interaction among physiological, biomechanical, technical, and anthropometric factors. Therefore, caution should be exercised when interpreting muscular strength as the primary determinant of performance, particularly in young swimmers whose technical skills and developmental characteristics vary considerably.

The findings of this study are consistent with previous research highlighting the importance of upper-body strength in swimming performance. For instance, a study by Garrido et al. (2010) demonstrated that dry-land strength is significantly associated with sprint swimming performance. Similarly, Morouço et al. (2011) reported that upper-body power and force production are key determinants of velocity in front crawl swimming. The present findings extend this evidence by showing that even in young swimmers, strength variables—particularly isometric strength—are significantly related to performance. However, the moderate magnitude of correlations observed in this study suggests that swimming performance is multifactorial, involving not only strength but also technique, coordination, and hydrodynamics.

From a practical perspective, the findings suggest that strength and conditioning programs for young sprint swimmers should prioritize upper-body force production, particularly in muscle groups involved in the pull phase of the freestyle stroke. Coaches may consider incorporating age-appropriate dry-land resistance exercises such as elastic-band pulling drills, rowing-based movements, pull-ups, medicine-ball throws, and suspended body-weight exercises two to three times per week in conjunction with regular swimming training. Furthermore, anaerobic conditioning through short-duration, high-intensity interval sets (e.g., repeated 25–50 m maximal efforts with incomplete recovery) may enhance the capacity to sustain race-specific power output during 100-m events. Such training strategies may improve both force application and sprint swimming performance.

Limitations of the study

Several limitations of this study should be acknowledged. First, the present study did not include detailed biomechanical or technical analyses of swimming performance, such as stroke mechanics, stroke efficiency, or propulsion patterns, which are known to play a crucial role in determining swimming velocity. As a result, the interaction between physical capacities and technical execution could not be fully explored. Second, no direct stroke analysis was conducted during the swimming trials, limiting the ability to examine how strength variables translate into specific movement patterns in the water. Third, the absence of neuromuscular assessments, such as electromyography (EMG), prevented a more comprehensive understanding of muscle activation patterns during swimming and their relationship with performance. In addition, swimming performance was measured using a manual stopwatch rather than an electronic timing system, which may have introduced measurement error despite standardized testing procedures. Furthermore, an a priori sample size calculation was not performed because the study used an available cohort of competitive young swimmers. Future research should integrate biomechanical, technical, and neuromuscular assessments alongside physical testing to provide a more comprehensive understanding of the determinants of swimming performance.

CONCLUSIONS

In conclusion, this study demonstrates that upper-body muscular strength, particularly isometric elbow flexor strength, is a significant determinant of 100-m freestyle swimming performance in young swimmers. Isokinetic strength at moderate velocity (60°/sec) and anaerobic capacity, as indicated by Wingate peak power, also contribute meaningfully to performance, although to a lesser extent. These findings highlight that maximal force-generating capacity plays a more prominent role than high-velocity strength in sprint swimming performance at early developmental stages. However, the moderate proportion of explained variance indicates that swimming performance is multifactorial, involving additional technical and biomechanical factors beyond physical capacities alone. Therefore, training programs for young swimmers should emphasize the development of upper-body strength alongside continued refinement of technique to optimize performance outcomes.

AI DISCLOSURE STATEMENT

During the preparation of this manuscript, the authors used NotebookLM (Google) as an artificial intelligence (AI)-assisted tool to support literature organization, document summarization, information synthesis, and language refinement. The AI-generated outputs were used solely as supportive materials and were carefully reviewed, validated, and revised by the authors. No AI tool was used to generate, interpret, or report the study findings independently. The authors assume full responsibility for the accuracy, originality, integrity, and final content of this manuscript.

DATA AVAILABILITY

The data supporting this study's findings are available on request from the corresponding author. The data are not publicly available because they contain information that could compromise the privacy of research participants

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CONFLICT OF INTEREST

The author hereby declares that this research is free from conflicts of interest with any party.

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