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REVIEW ARTICLE

Biomechanical and Technical Indicators of Talent Identification and Swimming Performance in Young Swimmers

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Abstract

The identification of talented young swimmers is a major focus in sports science, with increasing attention being directed toward biomechanical and technical indicators associated with future performance. This systematic review aimed to synthesize the available evidence regarding biomechanical and technical factors related to swimming performance and talent identification in young competitive swimmers. A systematic search was conducted in the PubMed, Web of Science, and Google Scholar databases following PRISMA guidelines. Eleven studies published between 2007 and 2023 met the inclusion criteria. The findings consistently demonstrated that higher-performing young swimmers exhibited superior biomechanical profiles characterized by higher stroke index, optimal combinations of stroke frequency and stroke length, greater swimming velocity, lower velocity fluctuations, and enhanced propulsive efficiency. Among these variables, stroke index emerged as the most consistent predictor of swimming performance and potential future success. Longitudinal studies further emphasized the importance of monitoring the development of these characteristics throughout growth and maturation. Overall, the evidence suggests that biomechanical and technical indicators should complement competition outcomes in talent identification programs and may provide valuable information for supporting long-term athlete development in youth swimming.

Keywords: youth swimmers · talent identification · biomechanics · stroke index · swimming performance · technical indicators

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Introduction

One of the major topics of interest in sports science is the identification of talented young athletes. This process is based on talent identification and development (TID) programs that aim to identify young athletes with potential for success in adult or elite sports (Blume and Wolfarth, 2019). Detecting talent at an early stage is considered a key factor in increasing a country's chances of achieving success in sports (Vaeyens et al., 2009). In competitive swimming, Olympic and World records are broken regularly, pushing athletes to their limits. Practitioners and researchers are eager to predict the next top-ranked swimmer who will contribute to their country's superiority at major international competitions.

Talent identification and development programs are typically based on three sequential steps: identifying athletes with the potential to attain elite performance and the factors associated with such achievements; understanding the development of performance and its determinants throughout the training process; and monitoring these variables over time to better understand their evolution and contribution to athletic success (Morais et al., 2017).

Swimming performance is determined by the complex interaction of multiple factors, including anthropometric, physiological, psychological, and technical characteristics (Barbosa et al., 2010; Figueiredo et al., 2016). Although several scientific disciplines have contributed to the understanding of performance in competitive swimming, biomechanics and energetics have been consistently recognized as the most influential domains for enhancing performance and achieving elite standards (Vilas-Boas, 2010).

Technical and biomechanical parameters have received considerable attention in swimming research because of their association with performance and their potential value in understanding the factors underlying successful swimming. Variables such as stroke length (SL), stroke index (SI), swimming velocity (v), velocity fluctuation (dv), propulsive efficiency (η_p), and hydrodynamic characteristics provide objective information about a swimmer's ability to generate propulsion and move efficiently through the water. Evidence from young swimmers suggests that biomechanical characteristics may help differentiate performance levels and provide additional information on individual development.

Accordingly, this systematic review aimed to synthesize the available evidence on biomechanical and technical indicators associated with swimming performance in young swimmers and to identify the characteristics most consistently associated with higher performance and long-term athlete development.

Method

This systematic review aimed to identify the biomechanical and technical skill predictors of swimming performance and athlete development. The methodology was defined according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021).

Search strategy

A comprehensive and systematic literature search was conducted in three electronic databases: PubMed, Web of Science (WoS), and Google Scholar. The literature search was updated on September 11, 2026 and no additional eligible studies were identified. In addition, a targeted search of Google Scholar was performed to identify potentially relevant studies that may not have been retrieved through the primary database search. The search aimed to identify studies addressing biomechanical and technical indicators of talent identification and swimming performance in young swimmers. Only studies published in English were considered eligible, with no restrictions on the publication year.

Boolean operators (AND and OR) were used to combine the keywords representing the main concepts of the review. The core concepts included swimming, swimmers, talent identification and development, biomechanics, technique, performance, and young swimmers. The search strategy was adapted to the specific functionalities of each database. The exact search strings used in each database are provided below to ensure transparency and facilitate reproducibility of the study.

For PubMed, the search strategy combined Medical Subject Headings (MeSH) terms with keywords searched in the title and abstract fields. The following search string was used: ("swimming" [MeSH Terms] OR "swimming" [Title/Abstract] OR "swimmers" [Title/Abstract]) AND ("talent identification" [Title/Abstract] OR "talent development" [Title/Abstract] OR "talent" [Title/Abstract]) AND ("biomechanics" [MeSH Terms] OR "biomechanical" [Title/Abstract] OR "technique" [Title/Abstract] OR "performance" [Title/Abstract]) AND ("young"[Title/Abstract] OR "youth" [Title/Abstract] OR "adolescent" [Title/Abstract] OR "junior" [Title/Abstract]).

A Boolean keyword-based search strategy was used. The following search string was applied: (swimming OR swimmers) AND ("talent identification" OR "talent development" OR talent) AND (biomechanic OR technique OR performance) AND (young OR youth OR adolescent OR junior) for the WoS.

A keyword-based search strategy was used. The following search string was applied: (swimming OR swimmers) "talent identification" (biomechanical OR technique OR performance) (young OR youth OR adolescent OR junior). In addition, a targeted Google Scholar search was conducted to identify potentially relevant studies that were not retrieved using the primary search strategy for Google Scholar.

Selection process

Following the electronic database searches, all identified records were imported into a single database using Rayyan reference management software, to facilitate the identification and removal of duplicate records. All stages of the study selection process were conducted by a single researcher (CB). Initially, CB screened the titles and abstracts of all unique records against predefined inclusion and exclusion criteria. Potentially eligible articles were subsequently retrieved in full text and independently assessed by CB for final eligibility.

In addition to the electronic database searches, CB manually screened the reference lists of all included studies to identify potentially relevant articles that may not have been retrieved through database searches. Furthermore, forward citation searches of selected key publications were conducted by CB to identify additional potentially relevant studies. As the entire screening and study selection process was performed by a single researcher, no independent duplicate screening or reviewer disagreement resolution procedure was undertaken. This approach was used to maximize the comprehensiveness of the literature search and identify potentially eligible studies.

Eligibility criteria

Studies were assessed for eligibility according to the PICOS (Participants, Intervention, Comparators, Outcomes, Study design) framework.

P (Participants): Competitive young swimmers of both sexes who were actively engaged in organized swimming training and competitions.

I (Intervention/Exposure): Biomechanical and technical characteristics associated with swimming performance, including stroke mechanics, SI, SL, SF, swimming efficiency, hydrodynamic variables, propulsion, starts, turns, and other performance-related biomechanical factors. As this was an observational review, the term “Intervention” refers to the biomechanical or technical characteristics investigated rather than a clinical Intervention.

C (Comparators): Where applicable, comparisons between swimmers of different performance levels, age categories, competitive levels, or maturation statuses, as well as longitudinal comparisons within the same cohort.

O (Outcomes): Swimming performance measures, including race time and competitive performance, together with biomechanical and technical variables associated with performance. Anthropometric, physiological, and maturation-related variables were considered when analyzed in relation to biomechanical or technical characteristics.

S (Studies): Cross-sectional, longitudinal, cohort, and controlled studies published in peer-reviewed journals were eligible. Systematic reviews, meta-analyses, conference abstracts, case reports, and studies not involving competitive young swimmers were excluded.

Inclusion and exclusion criteria

Studies were included if they investigated the biomechanical and/or technical characteristics associated with swimming performance in young competitive swimmers of either sex who were actively engaged in organized training and competitions. Eligible studies examined variables such as stroke mechanics, SI, SL, SF, swimming efficiency, propulsion, hydrodynamics, starts, turns, and other performance-related biomechanical characteristics. Only original peer-reviewed studies published in English, including cross-sectional, longitudinal, cohort, and controlled studies were considered.

Studies were excluded if they involved adults or recreational swimmers, participants from other sports, or did not assess biomechanical or technical characteristics related to swimming performance. Studies focused primarily on anthropometric, physiological, psychological, or nutritional variables were excluded unless these variables were directly examined in relation to biomechanical or technical performance outcomes. Systematic reviews, meta-analyses, conference abstracts, case reports, editorials, opinion papers, duplicate publications, and studies without sufficient full-text or methodological information for critical appraisal were also excluded. Studies investigating interventions unrelated to biomechanical or technical swimming characteristics were excluded from the review.

Data extraction

Data extraction was conducted independently using a predefined and standardized data extraction form developed in Microsoft Excel to ensure consistency and accuracy across all included studies. The extracted information was systematically organized into two separate tables to improve transparency and facilitate data synthesis. Table 1 presents the general characteristics of the included studies, including the authors, year of publication, study design, and participant demographics. Table 2 summarizes the intervention protocols, outcome measures, assessment instruments, and the main findings reported in each study.
Given the methodological heterogeneity across the included studies, a quantitative synthesis was not appropriate. Therefore, all outcomes were qualitatively synthesized using a descriptive approach. The findings were organized according to the type of intervention and outcome domains, allowing for the identification of consistent patterns, similarities, and differences among the included studies while providing a comprehensive overview of the available evidence.

Methodological quality of studies

The methodological quality of the included studies was assessed by a single reviewer using the Joanna Briggs Institute (JBI) Critical Appraisal Tools according to the study design. Cross-sectional studies were evaluated using the JBI Critical Appraisal Checklist for Analytical Cross-Sectional Studies, which consists of eight items assessing the methodological quality of participant selection, exposure and outcome measurement, management of confounding factors, and statistical analysis. Each item was rated as "Yes," "No," "Unclear," or "Not Applicable."
The overall methodological quality was determined based on the proportion of items rated as "Yes." Studies with ≥70% positive responses were classified as having a low risk of bias, those with 50–69% positive responses as having a moderate risk of bias, and those with <50% positive responses as having a high risk of bias.
Longitudinal (cohort) studies were assessed using the JBI Critical Appraisal Checklist for Cohort Studies, which comprises 11 methodological domains evaluating participant selection, exposure measurement, identification and management of confounding factors, outcome assessment, adequacy and completeness of follow-up, and statistical analysis. Each item was similarly rated as "Yes," "No," "Unclear," or "Not Applicable."
For cohort studies, the overall methodological quality was categorized using the same thresholds: low risk of bias (≥70% "yes" responses), moderate risk of bias (50–69%), and high risk of bias (<50%).

Results

Study selection

Study selection was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 (Page et al., 2021) guidelines (Figure 1).

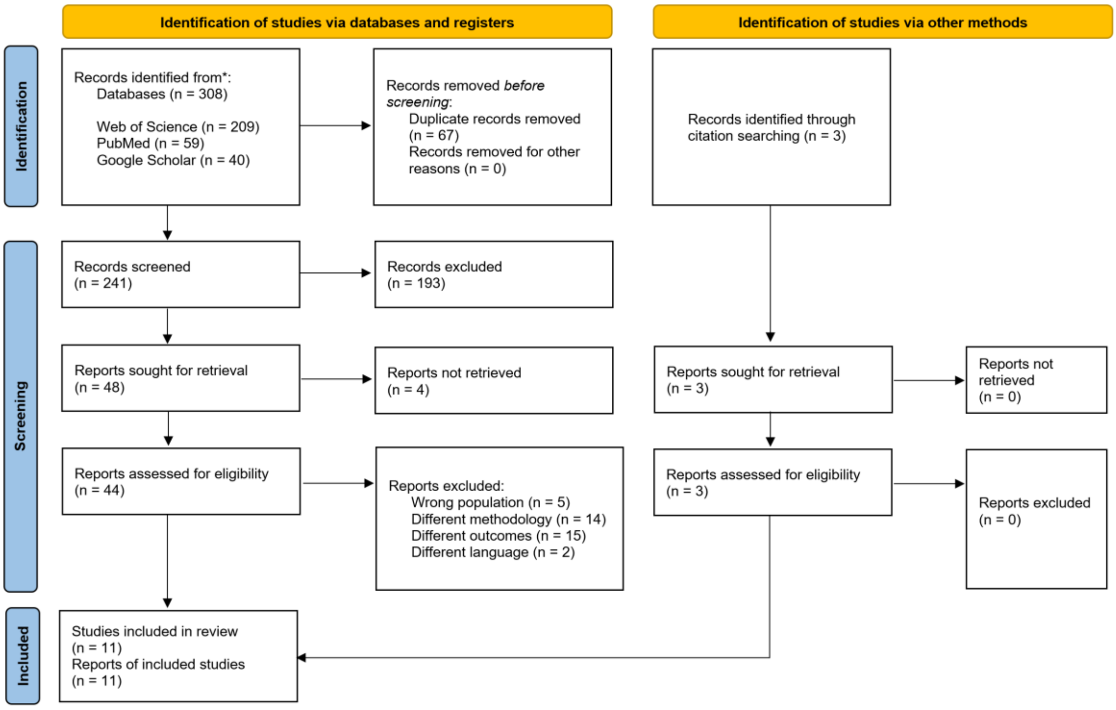

Figure 1. PRISMA diagram

During the initial search of electronic databases, Web of Science, PubMed, and Google Scholar, 308 studies (Web of Science = 209; PubMed = 59; Google Scholar = 40) were identified using a combination of keywords.

After removing duplicates (n = 67), 241 published papers were included in the further selection process. During the title and abstract review phase, 193 studies were excluded because they did not meet the predefined PICOS criteria. Consequently, 48 full-text articles were retrieved. The full texts of four studies could not be retrieved.

Following the full-text assessment, 36 articles were excluded for the following reasons: incorrect population (n = 5), inappropriate methodology (n = 14), different outcomes (n = 15), and publication in a language other than English (n = 2). In addition to systematic database searches, three additional relevant studies were identified through manual screening of the reference lists of all included articles and by conducting forward citation searches of selected key publications.

A total of 11 studies met the eligibility criteria and were included in the systematic review.

Characteristics of included studies

This review includes 11 studies published between 2007 and 2023, which primarily focused on identifying and analyzing the biomechanical and technical determinants of swimming performance in young athletes. The analyzed studies encompassed a wide range of methodological approaches, including cross-sectional studies that classified swimmers based on current performance (Barbosa et al., 2014; Barbosa et al., 2019; Figuierdo et al., 2016; Jürimäe et al. 2007; Lätt et al. 2010; Mezzaroba et al. 2014; Morais et al. 2022; Saavedra et al. 2010) and longitudinal research that tracked the development and stability of results over one or more competitive seasons (Morais et al., 2013; Morais et al., 2014; Post et al., 2023).

Most studies employed observational designs, predominantly cross-sectional approaches, whereas several investigations used longitudinal methodologies to monitor changes in performance and its determinants across one or more competitive seasons. Various swimming events and distances were examined, with front crawl performances over 25 m, 50 m, 100 m, 200 m, and 400 m being the most frequently assessed.

The investigated variables were categorized into anthropometric, biomechanical, and technical parameters related to swimming performance, such as SL, SI, *dv*, and η_p.

Table 1 presents the general characteristics of the included studies, including study design and participant characteristics.

Table 1. General characteristics of included studies

Authors, Year	**Study Design**	**Population Characteristics**
Jürimäe et al., 2007	Cross-sectional	29 boys (15 pre-pubertal: 11.9 ± 0.3 years old; 14 pubertal: 14.3 ± 1.4 years old).
Lätt et al., 2010	Cross-sectional	25 male swimmers, 15.2 ± 1.9 years old.
Saavedra et al., 2010	Cross-sectional	133 swimmers (66 males: 13.6 ± 0.6 years old, and 67 females: 11.5 ± 0.6 years old).
Morais et al., 2013	Longitudinal	33 young swimmers (15 male, 18 female), 11.81 ± 0.75 years old.
Morais et al., 2014	Longitudinal	30 young swimmers (14 boys: 12.33 ± 0.65 years old; 16 girls: 11.15 ± 0.55 years old).
Barbosa et al., 2014	Cross-sectional	Sixty-seven young swimmers (34 female and 33 male), 12.83 ± 1.26 years old.
Mezzaroba et al., 2014	Cross-sectional	46 male swimmers, 10-17 years old.
Figueiredo et al., 2016	Cross-sectional	103 swimmers (51 male and 52 female), 11.8 ± 0.8 years old.
Barbosa et al., 2019	Cross-sectional	75 boys, 11-13 years old.
Morais et al., 2022	Cross-sectional	38 swimmers (22 males: 15.92 ± 0.75 years old; 16 females: 14.99 ± 1.06 years old).
Post et al., 2023	Longitudinal	29 swimmers (12 males: 16–19 years old; 17 females:15–18 years old).

Table 2 provides a detailed overview of the intervention protocols, outcome measures, assessment instruments, and main findings of the included studies.

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Table 2. Characteristics of included studies

Authors, Year	Swimming test	Measurement Instruments	Outcomes
Barbosa et al., 2019	100 m freestyle best time ranking; anthropometric, biomechanical, and energetic assessments	Stadiometer (SECA 242; height), weighing scale (Tanita BC-545; body mass), digital camera (Nikon S9600; trunk transverse surface area), Swim Speedo-meter (v), Velocity Perturbation Method (active drag).	Significant variations in anthropometric, kinematic, and energetic characteristics exist among competitive tiers. Tier-1 (the highest-performing group of young swimmers, as classified in the original study) swimmers were taller and heavier, with longer limbs, higher SF, SL, *v*, SI, and η_p.
Barbosa et al., 2014	25 m maximal front-crawl swimming; 25 m swimming with/without a perturbation device.	Swim Speedo-meter (v), USB-6008 acquisition card (data acquisition), LabVIEW software (data acquisition and processing), AcqKnowledge software (signal processing).	Kinematics, hydrodynamics, and anthropometry help distinguish young swimmers from others. The key variables included normalized speed fluctuation (*dv/v*), *dv*, active drag coefficient (*CDa*), trunk transverse surface area (*S*), and v.
Figueiredo et al., 2016	25 m front crawl swimming at 50m pace.	Underwater video cameras (stroke kinematics: *v*, SL), calibration frame (spatial calibration), APAS software (kinematic analysis), anthropometric measurements (height, body mass, arm span, and hand and foot dimensions).	Anthropometric variables were the most significant determinants of the cluster solutions. SL and SI were also relevant. Differences in critical speed (CS), SF, and intra-cycle velocity variation were found.
Jürimäe et al., 2007	400 m maximal front crawl test.	Martin anthropometer (height, arm span), electronic scale (A&D Instruments; body mass), DXA densitometer (body composition, bone mineral density), electronically braked cycle ergometer (VO_2peak), and blood lactate analyzer (Dr. Lange enzymatic photometric method; blood lactate), SPSS software (statistical analysis).	SI, VO_2peak measured in water, and arm span were among the variables that were most strongly associated with swimming performance. The backward extrapolation method may provide an approach for estimating VO_2peak.
Lätt et al., 2010	100 m all-out front crawl swimming.	Respiratory snorkel and valve system (expired air); portable metabolic system (VO2); video analysis (*v*, SR, SL, SI); finger-prick blood samples (ΔLa); DXA (body composition).	Biomechanical factors explained the largest proportion of variability in 100 m front-crawl performance (90.3%), followed by anthropometric (45.8%) and physiological factors (45.2%). SI showed a strong association with performance among the biomechanical variables examined.
Mezzaroba et al., 2014	Maximal efforts at 100 m, 200 m, and 400 m front crawl.	Mechanical scale (body mass), stadiometer (height), anthropometric tape/segmometer (limb length), Lange skinfold caliper (body fat), manual stopwatch (swimming time), stroke cycle counting (SR, SL, SI), SPSS software (statistical analysis).	Distance significantly influenced all stroke parameters, while age was associated with SL and SI. SI showed a strong association with maximal performance across the 100 m, 200 m, and 400 m distances.

Authors, Year	Swimming test	Measurement Instruments	Outcomes
Morais et al., 2013	Three maximal 25 m front crawl trials with push-off start.	Official race times (100 m freestyle), digital scale and stadiometer (SECA), flexible anthropometric tape (RossCraft), digital photogrammetry (Xerox scanner and Sony digital camera), Universal Desktop Ruler software, Swim speedometer (Swimsportec), LabVIEW and AcqKnowledge software, velocity perturbation device, and chronofrequency counters.	Minimal improvement in performance and anthropometric factors, with moderate stability of results and key determinants (anthropometry, hydrodynamics, kinematics, and efficiency) over the season.
Morais et al., 2022	Three maximal 25 m freestyle trials with push-off start.	Body height, body mass, and hand dominancy (self-report), digital scale and stadiometer (SECA, 884 and 242, Hamburg, Germany), arm span (flexible tape), hand surface area (digital photogrammetry), pressure sensors (Aquanex System, Richmond, VA, USA) for mean propulsion and underwater stroke time, and *v*, SF, and SL calculated from time-distance measures.	Swimming speed prediction revealed a significant sex effect. Height, underwater stroke time, and mean dominant limb propulsion were predictors. Optimal SF - SL combinations for males and females were identified.
Morais et al., 2014	Three maximal 25 m freestyle trials with push-off start.	Swim speedometer (Swimsportec); USB-6008 data acquisition system (50 Hz), LabVIEW software, AcqKnowledge software (Butterworth filtering), Velocity Perturbation Method, manual stopwatch (Golfinho Sports MC 815).	High intra- and inter-subject variability in performance growth. Sex had a significant effect on the results. Different variables (Da, *dv*, SF) influenced the performance at different evaluation moments.
Post et al., 2023	Maximal-effort swimming tests, including starts, turns, and sprints, performed in the swimmer's best stroke; each test was repeated twice.	Stadiometer (body height), GymAware PowerTool (lower-body power), four underwater digital cameras (50 Hz) for swimming kinematics, R software for data analysis.	High-achieving swimmers showed greater rates of improvement in turning performance and maximal swimming speed among males and in SI among females, during the transition from junior to senior categories. Higher performance levels during the junior years were also associated with more successful progression to the senior level.
Saavedra et al., 2010	10 m maximal sprint test and 6 × 50 m speed endurance test.	ISAK anthropometric assessment (body dimensions), Eurofit test battery (general fitness), video analysis (flexibility and swimming technique), swimming performance tests (10 m sprint, 30 min endurance, 6 × 50 m speed endurance), hydrodynamic tests (glide and floatability), and LEN performance table (competitive performance).	Multivariate models explained 82.4% of performance variability in males and 84.5% in females. The main predictors were age, aerobic endurance (30 min test), speed endurance (6 × 50 m), SI, *v*, and anthropometric variables.

(SI - Stroke Index; SL - Stroke Length; SF - Stroke Frequency; η_p - Propulsive Efficiency; *v* - Velocity; *dv* - Speed Fluctuation; Da - Active Drag, CDa - Coefficient of Active Drag)

Methodological quality of studies

The critical appraisal analysis of the studies was conducted by a single researcher. The following sections present the results of the risk of bias assessment for the included studies, categorized into cross-sectional and longitudinal studies, using the JBI Critical Appraisal Checklists.

Table 3 presents the results of the JBI critical appraisal of the analytical cross-sectional studies based on eight criteria (Q1–Q8), along with the overall risk-of-bias assessment. Most studies fulfilled all appraisal criteria, including Barbosa et al. (2014), Mezzaroba et al. (2014), Morais et al. (2022), and Saavedra and Escalante (2010), and were classified as having a low risk of bias. Barbosa et al. (2019) were also classified as having a low risk of bias, although Q6 was assessed as unclear. Figueiredo et al. (2016) had methodological limitations in Q5 and Q6 and were therefore classified as having a moderate risk of bias. Jürimäe et al. (2007) did not fulfil Q1 and Q6, while Lätt et al. (2010) did not fulfil Q1 and Q8; both were consequently classified as having a moderate risk of bias. Overall, six of the eight studies were classified as having a low risk of bias and two as having a moderate risk of bias, with none classified as having a high risk of bias.

Table 3. JBI Critical Appraisal Checklist for Analytical Cross-Sectional Studies

Study	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Overall Risk
Barbosa et al., 2014	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Barbosa et al., 2019	Yes	Yes	Yes	Yes	Yes	Unclear	Yes	Yes	Low
Figueiredo et al., 2016	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Moderate
Jürimäe et al., 2007	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Moderate
Lätt et al., 2010	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Moderate
Mezzaroba et al., 2014	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Morais et al., 2022	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Saavedra and Escalante, 2010	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low

Table 4 presents the JBI critical appraisal of the cohort studies using 11 criteria (Q1–Q11) and the overall risk of bias assessment. All three studies were classified as having a low risk of bias. Morais et al. (2013) had one unclear criterion (Q5), whereas Morais et al. (2014) met all the criteria. Post et al. (2023) had one unclear criterion (Q6) and did not meet Q9 or Q10. Overall, the included cohort studies showed a low risk of bias, with some methodological uncertainties in the studies by Morais et al. (2013) and Post et al. (2023).

Table 4. JBI Critical Appraisal Checklist for Cohort Studies

Study	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Overall Risk
Morais et al., 2013	Yes	Yes	Yes	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Low
Morais et al., 2014	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Post et al., 2023	Yes	Yes	Yes	Yes	Yes	Unclear	Yes	Yes	No	No	Yes	Low

Anthropometric Indicators and Swimming Performance

Anthropometric characteristics, particularly body height, mass, and arm span, increase with age and biological maturation (Mezzaroba et al., 2014). Arm span was also identified as an important predictor of swimming performance in both the 400 m (Jürimäe et al., 2007) and 100 m front-crawl events (Lätt et al., 2010). Higher-performing swimmers generally showed greater body dimensions and longer limbs than their less successful peers (Barbosa et al., 2019).

Stroke Kinematics and Stroke Biomechanics

The results showed that v and SL continuously improved during a competitive season, whereas stroke SF exhibited lower variability (Morais et al., 2013). Elite swimmers (Tier-1) differentiate themselves from other cohorts by their ability to achieve a combination of longer SL and faster SF, resulting in a superior swimming speed (Barbosa et al., 2019). In contrast, Mezzaroba et al. (2014) observed that as distance increases (from 100 m to 400 m), there is a significant drop in SF across all age groups, while a growth trend in SL is observed around age 14, which is associated with technical skill development and physical maturation.

Swimming Efficiency Indicators and the Stroke Index (SI)

SI was consistently associated with swimming performance in the analyzed studies. Higher SI values were related to better performance in the 100 m, 200 m, and 400 m events (Jürimäe et al., 2007; Lätt et al., 2010; Mezzaroba et al., 2014). Less successful swimmers also show greater intra-cycle velocity fluctuations, indicating differences in swimming efficiency (Barbosa et al., 2014, 2019). Overall, these findings suggest that stroke efficiency and velocity stability may contribute to differences in swimming performance in young swimmers.

Hydrodynamic Profile and Drag

Hydrodynamic analysis indicates that parameters such as active drag and the Reynolds number are higher in top-tier swimmers, which is largely related to their higher *v* (Barbosa et al., 2019). However, CDa has also been identified as a relevant variable for distinguishing swimmers according to their hydrodynamic profiles, beyond *v* alone (Barbosa et al., 2014). Cluster analysis further suggests that hydrodynamic and anthropometric characteristics, together with *dv*, may contribute to the characterization and discrimination of young swimmers (Barbosa et al., 2014; Figueiredo et al., 2016).

Bioenergetic and Physiological Predictors

Physiological characteristics, including maximal oxygen uptake (VO_2peak) and lactate accumulation (ΔLa), are also associated with swimming performance. VO_2peak was related to performance in both the 400 m and 100 m events, while associations between stroke parameters and physiological characteristics suggest that technical efficiency and physiological capacity may jointly contribute to swimming performance (Jürimäe et al., 2007; Lätt et al., 2010).

Discussion

The findings of this systematic review highlight the multidimensional nature of swimming performance in young athletes, with biomechanical, anthropometric, and physiological factors contributing to performance differences. While physical growth may provide an important foundation, technical efficiency, particularly as reflected by SI, appears to be associated with swimming performance and may contribute to performance development during adolescence.

The significance of biomechanical efficiency in talent identification

Among the investigated variables, SI appears to be particularly relevant because it combines swimming velocity and SL, providing a more integrated indication of swimming efficiency than either variable considered separately. In contrast, SF and SL should be interpreted together, as increasing SF may reduce SL, while an excessively long SL may decrease swimming velocity. More successful swimmers may therefore be distinguished by their ability to maintain an effective balance between these variables.

Lower *dv/v* may also be relevant because it can indicate more continuous propulsion and fewer velocity losses during the stroke cycle. Anthropometric characteristics, such as body height and limb length, may support a longer SL and greater propulsive potential. However, these characteristics are strongly influenced by biological maturation and do not necessarily indicate superior long-term potential. Therefore, biomechanical indicators may be more informative when assessed longitudinally and alongside anthropometric, physiological, and maturational characteristics.

These findings suggest that biomechanical efficiency may be an important component of swimming performance and talent development in young swimmers. However, the relationship between SI and performance should not be interpreted as evidence that SI alone reflects neuromuscular coordination, technical efficiency, or long-term elite potential. Swimming performance is influenced by the interaction of biomechanical, anthropometric, physiological, maturational, and training-related factors, supporting a multidimensional approach to talent identification. Within this framework, SI may provide useful complementary information when interpreted alongside other characteristics and considered in the context of individual growth and development.

From an LTAD perspective, changes in SL and SI during adolescence may partly reflect ongoing growth and biological maturation. As body dimensions and physical capacities change, swimmers may need to adapt their stroke mechanics to maintain technical efficiency. Longitudinal evidence further suggests that the development of biomechanical characteristics should be considered a dynamic process rather than a fixed attribute, particularly during the transition from junior to senior performance levels.

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Practical implications for coaches

For swimming coaches and practitioners, these findings may provide useful, evidence-based information for monitoring technical development and supporting talent identification in young swimmers. Monitoring stroke efficiency indicators such as SI and the relationship between SL and SF may provide coaches with additional information when evaluating technical development and changes in swimming performance. Periodic biomechanical assessments, including SI, SL, SF, and *dv* measurements may complement conventional physical and performance assessments and help coaches monitor technical changes alongside growth and maturation. During talent identification, considering biomechanical, hydrodynamic, anthropometric, and energetic characteristics alongside performance outcomes may provide a more comprehensive profile of young swimmers. This approach may help reduce the reliance on performance or physical characteristics alone, particularly during periods of substantial growth and maturation.

Limitations of existing research

The interpretation of the available evidence is limited by the relatively small number of studies and generally modest sample sizes, as well as substantial variation in participant characteristics, including age, sex, competitive level, and biological maturation. This heterogeneity limits direct comparisons between studies and reduces the extent to which the findings can be generalized across different stages of youth development. The predominance of front-crawl research and the underrepresentation of female swimmers also limit the applicability of the current evidence to other competitive strokes and sex-specific developmental patterns in this regard. In addition, differences in the testing environments, measurement procedures, and operationalization of biomechanical variables may have contributed to the variability in the findings. Collectively, these limitations suggest that biomechanical predictors of swimming performance should be interpreted within the specific developmental and methodological context in which they were assessed rather than as universal determinants of performance across young swimmers.

Future directions

Future research should broaden the evidence base by including all four competitive strokes and more balanced samples of male and female athletes. Greater attention to biological maturation and longitudinal development would help clarify how biomechanical characteristics change across adolescence and whether the indicators measured during youth have meaningful associations with later performance. Standardized measurement procedures and consistent definitions of biomechanical variables would facilitate comparisons across studies.

The use of emerging technologies, including wearable sensors, inertial measurement units (IMUs), and automated video analysis, may provide additional opportunities to examine stroke mechanics and technical adaptations under ecologically relevant training conditions. Future studies should also investigate how biomechanical indicators can be integrated with anthropometric, physiological, maturational, and training-related characteristics to provide a more comprehensive understanding of performance. Establishing age- and maturation-sensitive reference values for key biomechanical variables may further support the interpretation of individual developmental trajectories and their potential relevance to LTAD.

Conclusion

The development of swimming performance in young athletes is a complex, multidimensional process influenced by biomechanical, anthropometric, physiological, maturational, and training-related factors. Among the biomechanical characteristics examined, SI was consistently associated with swimming performance, whereas SL, SF, *v*, *dv*, η_p, and Da provided complementary information on technical performance. However, no single variable appears to be sufficient to characterize swimming performance or long-term development.

Overall, the findings support the use of a multidimensional approach when monitoring young swimmers, with biomechanical characteristics considered alongside growth, maturation, physiological capacity, and training history of the swimmers. Further longitudinal research is needed to clarify how these characteristics change throughout development and to determine their relevance to long-term outcomes.

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