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Variability of energy cost in breaststroke technique: a systematic review

Miriam Alves^{a,b,c}, Tiago M. Barbosa^{d,e} and João Paulo Vilas-Boas^{a,b,c}

^aCentre of Research, Education, Innovation and Intervention in Sport (CIF12D), Porto, Portugal; ^bPorto Biomechanics Laboratory (LABIOMEPE-UP), Porto, Portugal; ^cFaculty of Sport, University of Porto, Porto, Portugal; ^dDepartment of Sport Sciences, Instituto Politécnico de Bragança, Bragança, Portugal; ^eResearch Centre for Active Living and Wellbeing (LiveWell), Instituto Politécnico de Bragança, Bragança, Portugal

ABSTRACT

This study aimed to synthesise the body of knowledge on kinematics, active drag and energetics determinants of energy cost variability in the breaststroke technique. Methodological procedures considering the standards for systematic reviews according to the “Preferred Reporting Items for Systematic Reviews and Meta-Analyses” were employed. Searches were conducted in four prominent databases. A total of 1,464 articles were identified, of which 201 met the eligibility criteria. After evaluation, 73 articles were included for synthesis in this review. The included studies had a mean score (\pm SD) of 9.14 ± 1.76 points regarding the quality assessment. The present review identified three distinct domains of variables: kinematics (including stroke kinematics and coordination parameters), active drag, and energetics. The findings underscored the pivotal role of stroke kinematics, including stroke rate, stroke length, stroke index, and intra-cyclic variations of velocity, in influencing energy cost during breaststroke swimming. Additionally, the analysis highlighted the significance of propulsive and non-propulsive phases, arm-to-leg timing, and buoyancy in breaststroke technique. Notably, breaststroke exhibited higher values of active drag, frontal area, and energy cost, while maintaining lower velocity compared to other swimming techniques. Overall, this synthesis of literature highlights the holistic nature of energy cost in breaststroke swimming.

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KEYWORDS

Swimming; kinematics; coordination; energy expenditure; active drag

Introduction

Swimming is an aquatic locomotion technique based on periodic limb actions to overcome drag force and propel the body forward in the water (Barbosa et al., 2013). Because of the nonconstant nature of the propulsive and resistive forces acting on a swimmer's body, its locomotion is characterised by accelerations and decelerations, even within a single stroke cycle. This fluctuation of the swimmer's velocity within a stroke cycle is paramount and deemed as a swimming efficiency proxy (Gourgoulis et al., 2018). Active drag is the water resistance acting upon the swimmer during the dynamic swimming motion. A swimmer's ability to swim faster is depended upon the ability to either

CONTACT Miriam Alves  up201505002@edu.fade.up.pt

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generate an increase in mean propulsive force such as to overcome the mean drag force presently acting on the swimmer's motion or to reduce the mean drag force on the body through better streamlining technique, or both (Mason et al., 2011).

Breaststroke is a swimming technique characterised by alternating propulsive actions of the upper and lower limbs, that must have contralateral simultaneous action, and the head must breakout the water surface at least once in each stroke cycle (Leblanc et al., 2007). While the upper limbs are propelling, the lower limbs remain extended, then the upper and lower limbs recoveries occur simultaneously, and, finally, the lower limbs perform their propulsive phase (Leblanc et al., 2010). Several breaststroke styles or variants have been described, such as, for instance, vertical, flat, undulated and undulated with overwater recovery of the arms (Vilas-Boas, 1996; Vilas-Boas and Santos, 1994). Research demonstrated that employing an undulated breaststroke technique with overwater arm recovery resulted in diminished efficiency and increased speed fluctuations compared to both flat and undulated breaststroke styles (Vilas-Boas, 1996). Colman et al. (1998) broke down the breaststroke into six variants based on the amplitude of undulation and showed that the most undulating style had less speed fluctuation. In the flat breaststroke, the paths of hands and legs are less vertical and more backward than in undulated styles, and the upward and downward movements of the body are less pronounced (Leblanc et al., 2005).

Performance is strongly underpinned by energetic variables and these are dependent on the biomechanical behaviour and motor strategies adopted by the swimmers (Barbosa et al., 2010b). The swimmer's technical ability (i.e., the subject propelling efficiency plus the ability to overcome drag), and the overall efficiency, strongly affect the energy cost (C) at a given velocity (Zamparo, 2006). Swimming velocity (v) is also related to the intra-cyclic variation of the horizontal velocity of the centre of mass (dv). Larger intra-cyclic variations of the impulse induce an additional mechanical work and, consequently, higher energy expenditure (Barbosa et al., 2010b). In the literature, the breaststroke technique is consistently identified as having the highest dv and active drag when compared to other competitive swimming techniques (Barbosa et al., 2013; S. V. Kolmogorov & Duplishcheva, 1992; S. V. Kolmogorov et al., 1997; S. Kolmogorov et al., 2021). This phenomenon can be attributed to the simultaneity of contralateral actions as well as to the underwater recovery of both the upper and lower limbs, which generates substantial hydrodynamic resistance counteracting the forward motion. For this reason, upper and lower limbs recoveries should not be performed in isolation: expert breaststroke coordination is characterised by synchronised recovery times to diminish this negative time (Chollet et al., 2004; Seifert & Chollet, 2005; Takagi et al., 2004). Furthermore, higher values of dv are correlated with less efficient swimming (Barbosa et al., 2005; Vilas-Boas, 1994). In fact, breaststroke has been described as the lowest economic swimming technique (Barbosa et al., 2006; Holmér, 1992; S. Kolmogorov et al., 2021).

Recently, a systematic review was carried out with the objective to synthesise the biomechanical factors influencing elite breaststroke swimming performance (Nicol et al., 2022). Nevertheless, a gap in literature persists regarding the consolidation of the state-of-the-art on the factors that influence the variations of the energy cost in the breaststroke swimming technique. This study aimed to synthesise the body of knowledge on kinematics, active drag and energetics determinants of energy cost variability in the breaststroke technique. We hypothesised that the variations in kinematic parameters play a significant role in influencing the energy cost variability observed in the breaststroke

swimming technique and that active drag contributes to the fluctuations in energy cost during breaststroke swimming.

Materials and methods

Methodological procedures considering the standards for systematic reviews according to the “Preferred Reporting Items for Systematic reviews and Meta-Analyses” (PRISMA) statement were employed (Page et al., 2021). The present review was registered on OSF registries on 15 June 2023 (osf.io/g2cp9).

Research sources and eligibility criteria

Scopus, PubMed, Web of Science and EBSCOhost databases were searched by two independent researchers until 31 December 2023 (Supplementary Table 3). Additional records were also identified through other sources (Figure 1). Research articles were included or excluded using the criteria defined by the PI(E)CO strategy (Population, Intervention/Exposure, Comparison and Outcome) (Methley et al., 2014) (Table 1). Only English original research articles were considered. After eliminating duplicates, results were screened according to the title and abstract in the ENDNOTE program (reference management software) to exclude any irrelevant articles. Then, the full-texts of potentially eligible studies were retrieved and independently evaluated for inclusion and synthesis

Research strategy and results extraction

Two independent researchers performed the selection process of relevant articles. First, all the studies obtained from the search of the databases were inspected,

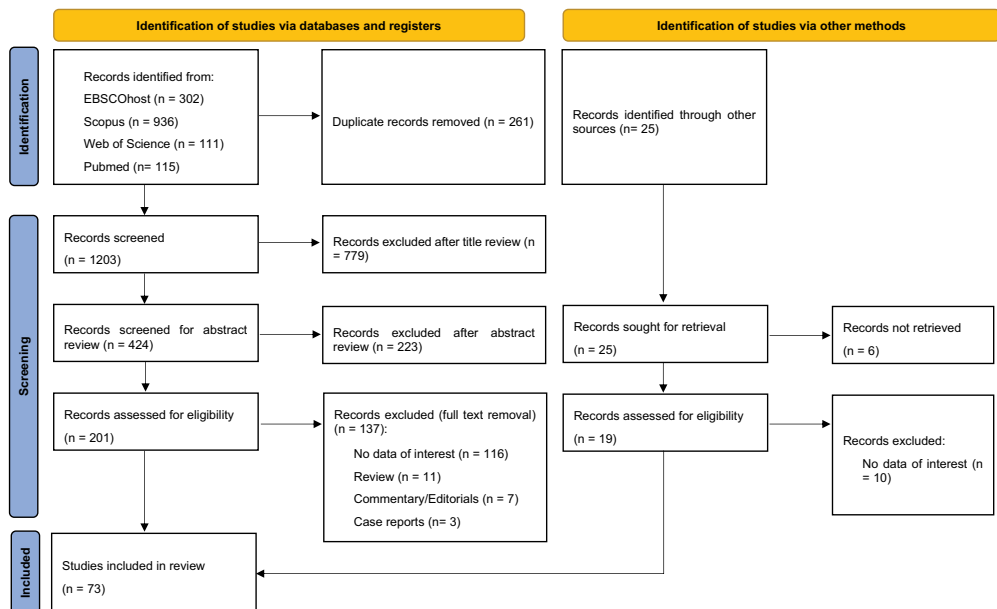


Figure 1. Summary of PRISMA flow for search strategy.

Table 1. Search strategy and inclusion/exclusion criteria based on PICO strategy.

Search terms		PI(E)CO	Inclusion criteria	Exclusion criteria
Swimmer*	Young*	Population	Healthy swimmers	Non-swimmers
Competition*	Adolescent*			Paralympic swimmers
Human*	Female*	Intervention and exposure (i.e., design)	Longitudinal studies	Master swimmers
Athlete*	Male*			Cross-sectional studies
Breaststroke		Comparison	Kinematics	Triathlon athletes
		Outcome	Active drag	Does not include breast stroke technique
			Energy cost	Does not include these variables
"Energy cost"	"Speed fluctuation"			
"Energy expenditure"	"Stroke length"			
"Metabolic power"	"Stroke distance"			
"Active drag"	"Stroke rate"			
Kinematic	"Stroke frequency"			
"Intra cyclic velocity"	"Stroke index"			
"Intracyclic velocity"				

Asterisks denote truncation to retrieve words with different endings.

duplicate articles were removed, and titles and abstracts were independently screened. The researchers applied the eligibility criteria defined above and disagreements were discussed until consensus was reached. Then, the same procedure was conducted after full-text screening of the remaining articles for the final inclusion or exclusion decision. Finally, the reference lists of the included articles were checked for relevant articles that might not have been identified in the initial databases search. The extraction process was conducted by one researcher and double-checked by another independent researcher. The items extracted were: 1) study reference; 2) main purpose; 3) demographics (i.e., number of participants per sex, age, and competitive level); 4) breaststroke test performed; 5) variables measured (i.e., outcomes); and 6) main findings. If there were papers with missing data or potential errors in the included data, the researchers discussed and either maintained the article (mentioning the missing data) or removed it from the included ones. When there were discrepancies between data extracted and the double-checking, the divergence was discussed between the two researchers until consensus was reached. The Kappa coefficient reached a value of 0.97, indicating a high level of agreement between the two independent researchers.

Assessing risk of bias

The quality of eligible studies was assessed using the risk of bias scale developed by Hindle et al. (2019b). This instrument was adapted for the assessment of sports research from other evaluation checklists (Hindle et al., 2019a; Natera et al., 2020). The scale features 16 standards: three standards for the study design, four standards for the sample characteristics, four standards for the methodology, and five standards for the results and discussion. One point is awarded for each standard met to a maximum total of 16 points. Risk of bias score is subsequently determined using the total number of points awarded. Articles scored ≥ 11 points are categorised as 'low bias risk', and articles scored 5–10 points are deemed as 'satisfactory bias risk'. Scores of < 5 are categorised as 'high bias risk'. Only articles with a low or satisfactory bias risk were included in the present review.

Results

In the first main search, 1464 articles were identified and 261 duplicates were removed. After the screening of titles and abstracts, 201 articles were accessed for eligibility. Seventy-three articles were included for synthesis, of which nine were identified by other methods (Figure 1). The characteristics of the included studies are shown in Table 2. Regarding the quality assessment (Supplementary Table 4), the included studies had a mean score (\pm SD) of 9.14 ± 1.76 points (range: 5 to 13 points). Fifteen papers were categorised as low bias risk and 58 as satisfactory bias risk. None of the studies got a score in the item related to the description of 'how the study size was arrived at'. All studies scored a point in the standards 'The results are well described' and 'The information provided in the paper is sufficient to allow a reader to make an unbiased assessment of the findings of the study'.

Thirty-three studies analysed both sexes (i.e., males and females) (45.2%), 25 papers recruited only males (34.2%), five just females (6.8%) and ten did not specify the participants' sex (13.7%). As far as the competitive level of the participants is concerned, it varied within all levels. Most articles recruited national (13.7%), elite (15.1%), regional to national (9.6%), international (11.0%) and national to international swimmers (5.5%). Other competitive levels were mentioned but only studied by one or two articles, including recreational to Olympic-level swimmers. The chronological age most often recruited was older than 18 years (45.2%) or aged between 15 and 18 years (21.9%). Ten studies evaluated multiple age-groups (13.7%), five studied participants between 12 and 15 years old (6.8%) and 11 articles did not mention the age of their subjects (15.1%). The age-group below 12 years-old was not reported in the included studies.

For the type of tests implemented, 38 articles selected maximum tests (52.1%) while the others used maximal and submaximal (19.2%), incremental (12.3%), competitive pace (6.8%), submaximal (6.8%), free-swim (2.7%) and incremental and all-out trials (2.7%). When considering the different domains of the variables in the studies that were included, 44 reported kinematic variables (60.3%), of which 26 assessed stroke kinematics variables such as stroke length (SL), stroke index (SI), stroke frequency (SF) and dv and 18 focused on coordination parameters. In addition, five articles focused on hydrodynamic drag (6.8%) and 12 on energetics (16.4%), such as oxygen uptake (VO_2) and blood lactate concentration ($[La^-]$). Finally, nine papers studied both energetics and kinematics (12.3%), one paper reported both drag and energetics (1.4%), and two papers studied both coordination and energetics (2.7%). The most studied variables among the articles were SR (55.9%) and SL (51.5%). Stroke phases (22.1%) were also common among papers, as well as dv (20.6%), $[La^-]$ (20.6%) and VO_2 (17.6%). Fewer studies evaluated C (10.3%), SI (8.8%), active drag (10.3%), time gaps (8.8%) and energy expenditure (7.4%).

Discussion and implications

This study aimed to synthesise existing literature on kinematics, active drag and energetics determinants of energy cost variability in the breaststroke technique. The main findings were that factors such as stroke rate, stroke length, stroke index, arm-to-leg timing and intra-cyclic variations of velocity were found to significantly impact C in the

Table 2. Summary of the main aim, participants' demographics, selected variables and main results of the included studies.

Authors	Main aim	Participants (age, level)	Br event/test (pace)	Variables	Main findings
Arellano et al. (2022)	To verify the variables that determined the differences between swimmers who reach the finals and those who did not.	56 international level males (23.78 ± 3.25 years); 60 international level females (24.66 ± 4.12 years)	50m (maximal)	SR and SL (15-25m, 35-45m and final)	Women were able to increase SR especially during the final and it was related to improved performance; men maintained similar SR values throughout the race, however, between rounds SR increased resulting in a reduction of the glide phase and thus SL. No changes for the 15m time in the different rounds. 15m time was shown to predict 25m time, but not 50m time. Fc was the most economical technique, followed by the Bk, the Bt and the Br for all selected v Increases of SR were associated to increases of C, even when controlling v. Increases in the SL promoted significant decreases of C, even when controlling v. Increase of v promoted an increase of C. 100m time was higher during snorkel swimming when compared with free swimming. No significant differences were found in any stroke parameter, although some smooth kinematical changes were verified for the stroke technique due to added drag. The dv was higher in the Br. In Br dv was characterized by a 2-peak profile.
Barbosa et al. (2006)	To measure and compare the total Etot of the four competitive swimming techniques.	18 of international level males and 8 females (5 Br)	7x 200m (incremental)	Etot	
Barbosa et al. (2008)	To analyse the relationships between C, v, SF and SL	3 males and 2 females elite level (17.40 ± 1.10 years)	n x 200m (incremental)	C, v, SR, SL	
Barbosa et al. (2010a)	To assess the kinematical changes when swimming maximal bouts in Br with the AquaTrainer® snorkel.	7 national level swimmers (19.10 ± 4.30 years)	2x 100m (maximal)	SR, SL, Si, dv	
Barbosa et al. (2013)	To assess the relationship between the dv and the v of the 4 competitive swimming techniques	23 males and 22 females regional to national level (12.78 ± 1.15 years)	4x 25m (maximal, one in each swimming technique)	dv	
Barbosa et al. (2016)	To compare the non-linear properties of the four competitive swim techniques.	34 national to international level males (17.06 ± 4.11 years) 34 national to international level females (14.97 ± 2.96 years)	4x 25m (maximal, one in each swimming technique)	dv, ApEn, Fd	The ApEn showed the lowest value in Fc, followed by the Br, Bt, and Bk. Fractal dimension had the highest value for the Br. The highest dv was for the Br technique.

(Continued)

Table 2. (Continued).

Authors	Main aim	Participants (age, level)	Br event/test (pace)	Variables	Main findings
Barbosa et al. (2017)	To examine the variation of linear and nonlinear proprieties of the behaviour in participants with different levels of swimming expertise among the four swim techniques	21 males and 4 females highly qualified expert level (15.73 ± 1.52 years) 11 males and 14 females expert level (15.74 ± 3.55 years) 18 males and 7 females nonexpert level (22.86 ± 3.40 years)	4x 25m (maximal, one in each swimming technique)	dv, ApEn, Fd	Br featured the highest dv and Fd. A lower ApEn was found for Br. The dv was higher in non-expert swimmers than their expert or highly qualified expert counterparts.
Bartolomeu et al. (2018)	To assess the effect of the limbs' actions on the nonlinear properties of the four competitive swimming techniques	24 males and 25 females regional to national level (14.20 ± 1.71 years)	12x 25m (maximal, 3 in each swimming technique in the conditions: full cycle, arms-only and leg kicking)	dv, SampEn, Fd	Br was the slowest technique and presented the lowest value of SampEn and highest values of Fd. Leg kicking was the slowest condition in all techniques with the exception of Br. The highest dv was in the Br. C increased monotonically with v. Br was the least economic technique.
Capelli et al. (1998)	To determine the C of swimming at different v in the four swimming techniques	20 elite level males (18.90 ± 0.94 years)	2.50 min in an annular pool (submaximal) 45.70 m, 91.40m and 182.90m (maximal)	C	v at AnT in Br was considerably lower than all other swimming techniques. Inflection points of SR and SL vs. v corresponded to v at AnT.
Carvalho et al. (2020)	To confirm the AnT as the boundary above which [La-], SR and SL exhibit significant changes	47 international level males (20.30 ± 3.10 years) 25 international level females (18.40 ± 2.50 years)	5x 200m (incremental)	[La-], SR, SL	100/200 SR difference was the greatest in Br. 200m SL was higher than that of 100m. No differences in SF were found between males and females, so SL was the main contributor to the higher v in male swimmers.
Chollet et al. (1996)	To compare stroking parameters such as SL and SR used by female and male top level swimmers during competition on 100 and 200m events in each technique	377 national to international level males 369 national to international level females	200, 100m (maximal)	SR, SL	

(Continued)



Table 2. (Continued).

Authors	Main aim	Participants (age, level)	Br event/test (pace)	Variables	Main findings
Chollet et al. (2004)	To propose a new method to evaluate arm-leg coordination in flat Br.	9 national to international level males (19.90 ± 2.30 years) 7 national to international level females (15.70 ± 1.20 years)	200, 100, 50m (maximal)	SR, SL, SP, TG, ESP	A faster pace corresponded to increased SR, decreased SL, increased propulsive phases, shorter glide phases and a shorter effective body glide. The top-level swimmers showed short time gaps which reflected the continuity in arm and leg actions.
Colman et al. (1998)	To establish differences in dv of the body's CM in Br swimmers with flat and undulating styles	25 international level males (19.90 ± 2.60 years) 20 international level females (17.90 ± 3.07 years)	25m (100m competitive pace)	dv	Undulating style presented less dv of the body's CM.
Conceição et al. (2013a)	To observe and characterize the Br technique concerning the correlation between kinematic and neuromuscular parameters in a 200m Br event	12 national level males (22.30 ± 2.90 years)	200m (maximal)	SL, SR, [La-]	SL decreased from the first 50m distance to the fourth 50m distance. SF decrease from the first 50m distance to the third 50m distance, slightly increasing in the last distance. The lactate concentrations increased from rest to the [La-] peak after the 200m. SL demonstrated strong correlation with SF, when SL increases, SF decreases.
Conceição et al. (2013b)	To examine the characteristics of waves generated when swimming with and without the use of Aquatrainer® snorkels	8 national level males (21.25 ± 6.73 years)	2x 25m (maximal)	SL, SR, SI, St	The use of the Aquatrainer® snorkel in the Br showed a lower SL, SI and v and a higher SF compared to the normal condition.
Craig and Pendergast (1979)	To study the basic relationships between SR, SL and v in competitive swimmers	110 competitive level 223 olympic level	nx 22m (incremental)	SL, SF, dv	Increases in v were associated with increases in SF but SL decreased much more than in the other techniques. dv values were the highest in Bt and Br. In the 100 m races, SR changed/increased the most in third lap, with similar trends for both the first and second lap.
Cuenca-Fernández et al. (2023)	To investigate performance variation in all race sections, i.e., start, clean swimming, and turns, of elite short-course races for all swimming strokes and to determine the effect of performance variation on race results.	64 males finalists (23.7 ± 2.8 years) 34 males semi-finalists (23.8 ± 3.4 years) 64 males non-qualified (23.0 ± 3.4 years)	100 and 200m (maximal)	SR and SL	

(Continued)

Table 2. (Continued).

Authors	Main aim	Participants (age, level)	Br event/test (pace)	Variables	Main findings
di Prampero et al. (2008)	To compare the critical v_c , calculated by taking into account the effect of a non-constant C , with the slope of the distance versus time relationship.	20 elite level males (18.90 \pm 0.90 years)	45.7, 91.4 and 182.9m (maximal)	VO_{2max} , C , E_{tot}	Br presented the highest value of C and lowest critical v_c value compared to the other swimming techniques.
Gonjo and Olstad (2023)	To investigate differences throughout 100m breaststroke between elite and sub-elite swimmers using time-series velocity data.	14 males breaststroke specialists (20.0 \pm 2.4 years)/7 males sub-specialists (17.7 \pm 0.9 years)	100m (maximal)	v	Elite swimmers had a larger mean clean-swimming v than sub-elite swimmers in all laps due to the shorter clean-swimming duration. On the other hand, no differences between the levels were observed in the pull-out segment variables.
Gatta et al. (2015)	To use the planimetric method to determine A_p throughout the stroke cycle in the four swimming techniques and during 'streamlined leg kicking'.	6 highly trained males (21.30 \pm 0.50 years) 4 highly trained females (20.80 \pm 0.50 years)	Swims in the 4 techniques and leg kicking	A_p , Da , nd	Da presented the highest values for the Br technique. Br and Bt showed the highest values of A_p .
Gourgoulis and Nikodellis (2022)	To compare the arm-stroke kinematics during maximal and sub-maximal Br swimming using both discrete and continuous data analysis.	9 males (21.57 \pm 4.20 years)	2x 25m (maximal and submaximal)	SP, SL, SR, hand, arm-stroke and CM length, width and depth, hand v in x,y and z axis and SP	Submaximal intensity presented lower v_c , greater SL and less SR than maximal trials. The absolute and relative duration of the glide phase was longer, while the relative duration of all the other phases was shorter. Additionally, hand v during the arm recovery was slower (in the 3 planes). The main discriminating factor between the two conditions concerns to the adjustment of the glide and the recovery phase and consequently the continuation of the propulsive movements.

(Continued)



Table 2. (Continued).

Authors	Main aim	Participants (age, level)	Br event/test (pace)	Variables	Main findings
Gourgoulis et al. (2018)	To compare the CM and hip dv in Br swimming using 3-dimensional kinematic analysis	9 moderate level males (21.57 ± 4.20 years)	25m (maximal)	CM and hip (in the resultant; x, y and z axis); dv (absolute, relative), SP v, v (min, max, mean), SRT, ALT, SPT; TI	The arm pull and the leg kick result in acceleration of the swimmer's v, whereas the glide and the arm and leg recovery result in deceleration of the swimmer's v. It was observed a steeper increase during the leg propulsive phase, in comparison with the arm propulsive phase, indicating that the acceleration of the swimmer's body produced by the legs was greater than that because of the arms' action. However, this greater acceleration did not produce a higher v than that obtained during the arm propulsive phase, probably because of the much smaller starting v or the limited ability of the swimmers to perform an effective leg kick. Despite this similar general pattern, discrepancies between the HIP and CM v curves were observed.
Hellard et al. (2008)	To assess SR variability in elite female swimmers	64 olympic level females (Br: 22.00 ± 3.00 years) 64 national level females (Br: 19.00 ± 3.00 years)	200m (maximal)	SR, SL, v (for full swim, for each 100m)	SL and SR were different for the four techniques. Fc presented the highest SL, followed by Bk, Br and Bt. SR variability was greatest for the Br.
Hermosilla et al. (2020)	To present and validate the SwimOne device for determining instantaneous propulsive force and power	4 regional to national males (22.67 ± 1.15 years)	8x 15 m (with a progression in the opposition force, in each technique)	Fa, MSP	Br presented the lowest Fa value compared to the other swimming techniques. Fc showed the higher values of MSP, followed by Br, Bt and Bk.
Hofelder et al. (2013)	to improve the interpretability of lactate diagnostics in swimming by identifying lactate-affecting variables and to present the Multilevel Analysis as a statistical method which is able to analyse the typical data structure in high performance sports in a formally correct way.	228 high performance males (19.10 ± 3.17 years) 170 high performance females (16.94 ± 2.78 years)	5 steps of 100m or 200m or 4 steps of 400m (incremental)	[La-], AT	Overall, the swimming technique seems not to play a key role in terms of affecting lactate parameters. The [La-] of the Br events were the lowest on average in direct comparison with the same distance for the other swimming techniques.

(Continued)

Table 2. (Continued).

Authors	Main aim	Participants (age, level)	Br event/test (pace)	Variables	Main findings
Holmér (1974a)	To study the VO_2 during swimming with arm strokes and leg kicks in the different swimming techniques.	19 elite level males (4 Br: 21.30 ± 5.50 years)	2 or 3 steps and 1 step (submaximal and maximal rate of work, in a swimming flume)	VO_2 , HR, PV, VC, Dp	In the Br VO_2 was approximately the same in all modes of swimming (whole stroke, arms only, leg kicking) in relation to v. During maximal leg kicking alone in the Br the speed was only 10% lower than for maximal swimming with the whole stroke.
Holmér (1974b)	To determine the np of arm stroke, leg kick and whole stroke in the Br and Fc, respectively.	3 top level (25, 17 and 16 years)	5, 4, 4, 4 min with and without extra loads (submaximal, in a swimming flume)	VO_2 , Da, Dp, np	Propulsive efficiency in the Fc was found to be greater than in the Br. Leg kicking in the Br displayed a consistently low level of efficiency, and arm stroke in displayed about the same efficiency as the whole stroke.
S. V. Kolmogorov and Duplishcheva (1992)	To present a new alternative approach to uncover the relation between Po, Da, the CDa and the maximal swimming v applied to the four competitive techniques.	73 national level	2x 50m (maximal)	Da, CDa, Dp, CDp, Po	Br presented one of the highest values of Da, for the same v, compared to the other techniques.
S. V. Kolmogorov et al. (1997)	To describe the hydrodynamic characteristics of the four techniques by gender and performance level.	487 males and 310 females all performance levels (10 to 28 years)	2x 50m (maximal)	Da, CDa, Dp, CDp, Po	According to the hydrodynamic indicators, Da, CDa, Po, in men and women, the swimming techniques were ranked as low to high resistance, Fc, followed by Bk, Bt and Br.
S. Kolmogorov et al. (2021)	To determine the main biophysical (energetic and biomechanical) reasons for the observed differences in maximal swimming v between the different competitive swimming techniques.	4 males and 4 females elite level (21 to 26 years)	8 x 1 min (incremental, in a swimming flume) 8 x 100m (incremental) 2x 30m (maximal)	Etot, Da, ep	Br presented the highest values of frontal component of Da and Etot.

(Continued)



Table 2. (Continued).

Authors	Main aim	Participants (age, level)	Br event/test (pace)	Variables	Main findings
Komar et al. (2014)	To compare interlimb coordination and indicators of swim efficiency and swim effectiveness between expert and recreational Br swimmers.	5 males and 3 females expert level (20.8 ± 2.1 years) 6 males and 4 females recreational level (20.4 ± 1.5 years)	3x2x25m (70%, 90% of maximal pace and maximal)	CRP, CM v (min, max, acceleration, deceleration at different SP), dv, distance covered by the CM (at different SP)	Experts exhibited a more effective arm-leg coordination pattern than recreational swimmers. Experts showed a better management of their arm-leg coordination during the glide phase, namely by maintaining a streamlined position with arms and legs during the glide. Experts and recreational swimmers spent the same time with arms and legs outstretched, therefore the same relative duration of the glide. No differences between the two groups were found in dv. Swimmers were able to moderate the increase in Wint at the highest SR.
Lauer et al. (2015)	To provide a predictive equation to estimate de Win of Br swimming and to check its accuracy against Win values measured from kinematic sequences captured at various stroke frequencies and to explore the frequency-internal work relationship in swimming and contrast aquatic vs terrestrial locomotion.	4 elite level males (25.00 ± 3.10 years) 4 elite level females (19.37 ± 6.10 years)	3x25m (at different self-chosen paces)	Wint, SR	
Leblanc et al. (2005)	To analyse the arm-leg coordination patterns of two groups of swimmers of different skill levels.	11 males and 9 females national to international level (19.90 ± 2.30 and 15.70 ± 1.20 years) 11 males and 9 females regional level (15.10 ± 0.90 and 14.80 ± 1.20 years)	3x25m (200, 100 and 50m pace)	SR, SL, SP, TG, ESP	Among each group, the increase of v is related to an increase of SR and a decrease of SL. The Br is the only technique where SL decreases when switching from v200 to v100. For the same SR, elite female and male swimmers had a greater mean v, accompanied with a greater SL, than non-elite swimmers. For the same swimming pace, elite swimmers of both genders have a shorter glide time and proportionally longer recovery and propulsive phases. Elite swimmers are able to swim at the same v as lower-level swimmers, by using a technique with more glide demonstrating a better propulsive efficiency and the ability to cover a longer distance during the non-propulsive phases of the movement.

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Table 2. (Continued).

Authors	Main aim	Participants (age, level)	Br event/test (pace)	Variables	Main findings
Leblanc et al. (2007)	To compare the distances covered during each phase of the stroke, dv and the intra-cyclic accelerations in two groups of male swimmers with different skill levels, at three swimming race paces.	9 national level males (19.90 ± 2.30 years) 9 regional level males (15.10 ± 0.90 years)	3x 25m (v200m, v100m, v50m paces)	dv, SR, SL, ADTR, SP	In the two group of swimmers, the switch from the 200m to the 100m and the 50m was associated with a decrease in SL and an increase in SR and swimming v. When race pace increased, the distance covered during the leg arm lag phase decreased, while the distance covered during the recovery phase and the propulsive phases of the arm and leg remained stable for both groups. For the leg-arm lag phase distance, the relative distance pattern tended to remain stable in elite swimmers. In nonelite swimmers, the decreased distance in the leg-arm lag phase was compensated by an increase in the relative distance covered in the arm and the leg propulsive phases. Elite male swimmers were able to simultaneously combine a high magnitude of hip dv and a better ADTR, resulting in greater SL. Recreational swimmers perform their arm recovery while doing their leg kick, showing a simultaneous extension of their two pairs of limbs and the arm propulsive phase started before the end of the leg in-sweep. Arm's recovery phase of recreational swimmers was longer than competitive swimmers. In recreational swimmers, the end of the extension of the lower and upper limbs was simultaneous. Recreational swimmers, having no glide time, can hardly modulate their coordination according to the swimming v.
Leblanc et al. (2009)	To make an accurate assessment of the temporal aspects of the arm-leg coordination of recreational swimmers and to analyse the evolution of the arm-leg coordination under different conditions.	12 competitive level males (16.20 ± 1.50 years) 12 regional level males (16.90 ± 1.60 years)	2x 25m (v400m and maximal pace)	SR, SL, SP, TG, ESP	

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Table 2. (Continued).

Authors	Main aim	Participants (age, level)	Br event/test (pace)	Variables	Main findings
Leblanc et al. (2010)	To measure swimmers' floatation parameters and to relate these data to their stroking characteristics.	23 club-level males (16.00 ± 2.20 years) 23 club-level females (15.30 ± 1.70 years)	2x 25m (v200m and v50m pace)	SR, SL, SI, SP (% and v), hydrostatic lift (N), sinking force (N), maximum glide length (m)	Female swimmers had greater hydrostatic lift and a smaller sinking force magnitude compared with male swimmers. In the female group, the hydrostatic lift and the maximal glide length were positively correlated with glide phase, the mean glide v and SI. In male swimmers, the sinking force was negatively correlated with glide phase and mean glide v. In both group of swimmers, the impact of floatation appeared of less importance at sprint pace.
Lomax et al. (2022)	To characterize the VO ₂ kinetic response during moderate-intensity in Fc and Br and to compare the ventilatory and metabolic responses to moderate-intensity and maximal v in Fc and Br flume swimming.	4 males and 4 females trained (20.00 ± 1.00 years)	2x progressive until Tlim (in a swimming flume) 3 or 4x 6min (at 80% of the v at VT in a swimming flume)	VO ₂ max	WT and maximal v were slower during Br. All other ventilatory and metabolic parameters, including VO ₂ max, are similar between Fc and Br during maximal swimming. During moderate-intensity, VO ₂ kinetics and both the ventilatory and metabolic responses were similar between the two techniques.
Marinho et al. (2011)	To determine and analyse AnCV in young swimmers comparing it with short distances performances in the 4 swimming techniques.	12 males and 8 females (12.10 ± 0.72 years)	10, 15, 20 and 25m (maximal)	AnCV	Relationships were found between the values of AnCV and the 50, 100 and 200m swimming event v in Br.
Mason et al. (1989)	To obtain information about the dv and acceleration profiles of elite Br swimmers and to identify if this information could be used to evaluate the technique efficiency of swimmers involved in the study so that any disclosed inefficiencies could be eliminated.	9 national to international level	2x 25m (maximal)	dv, CM (v, displacement and acceleration)	Three distinctive propulsive stages were observed in Br swimming. The first was biphasic and was associated with the hand pull and the insweep of arms and hands. In some swimmers this second aspect was almost nonexistent. The second propulsive stage was not associated with any particular propulsive action of the swimmers. The third propulsive stage was the largest and this was attributed to the leg kick.

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Table 2. (Continued).

Authors	Main aim	Participants (age, level)	Br event/test (pace)	Variables	Main findings
Morouço et al. (2011)	To characterize the force profiles of elite swimmers, through tethered swimming, in the four competitive techniques, identify the relationship between tether forces and swimming v, and to see if relative values of force production are better estimators of swimming performance than absolute values.	20 international level males (19.00 ± 2.88 years) 12 international level females (15.30 ± 1.68 years)	2x 30sec (maximal, tethered swimming)	Fmax, Fmean, Fatind	The simultaneous techniques (Br and Bt) presented both higher and lower values of force production, indicating maximum forces higher than the alternated techniques (Fc and Bk). Br swimmers recorded the highest tethered swimming force values. Br v50m presented the highest correlation value with Fmax.
Oliveira et al. (2016)	To analyse the VO ₂ slow component of trained Br swimmers during submaximal incremental exercise, using a multiexponential function.	12 high level males (16.90 ± 2.80 years)	4x 300m (incremental)	VO ₂ , [La ⁻]	Slow component appeared with exercise intensity above the 3.5 mm ⁻¹ lactate threshold.
Oliveira et al. (2023)	To understand whether there are significant differences in stroke kinematics between tiers in female swimmers competing in the four 50 m events of the 2021 European Championships and to understand the speed-time relationship in the four race events per tier.	75 female breaststroke swimmers	50m (maximal)	SL, SR and SI	SR had a significant tier effect in all race sections in the 50m race.
Olstad et al. (2017)	To investigate the relationship between muscle activation in eight different muscles and kinematic SP using 3D mo-cap with automatic motion tracking during three different effort levels in elite Br swimmers	4 elite level males (27.70 ± 7.10 years) 5 elite level females (20.30 ± 5.40 years)	3x 25m (200, 100 and 50m pace)	SR, SL, knee: angle, v, absolute, relative duration, distance during different SP	Increased v with increasing effort came from a significant decrease in distance during the knee extended phase combined with a decrease in the duration spent for the knee extended and knee flexion phases. In addition, the knee angle at the beginning of the knee extension decreased with increased effort providing a better mechanical advantage.
Olstad et al. (2020)	To identify segmental factors related to the finishing time in the modern 100m short course Br.	15 high level males (19.00 ± 2.50 years)	100m (maximal)	SL, SR, start, turn, swim, finish segments with underlying components	Nearly perfect or very large correlations with the 100m finish time observed in the 15m start time and the 10m turn-out time, even though the 15m start does not compile most of the finishing time.

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Table 2. (Continued).

Authors	Main aim	Participants (age, level)	Br event/test (pace)	Variables	Main findings
Oxford et al. (2017)	To compare arm–leg coordination between each lap of a 100m swim and relate this to changes in swim v , SL, SR and SI and to compare arm–leg coordination, swim v , SL, SR and SI between sexes;	18 competitive level males (18.90 ± 2.20 years) 8 competitive level females (19.10 ± 2.30 years)	100m (maximal)	SL, SR, SI, SP, TG	A decrease in SR from the 1st the 3rd lap of the swim with an increase seen on the final lap was observed. A decrease in SI was also reported through the swim. Though there was a significant decrease in swim v , there were no significant changes in the time spent in each of the SP and in SL over the duration of the swim. Males presented higher SL and v , but there were no differences between sexes in the time spent in any of the phases of the stroke.
Pai et al. (1984)	To determine SL and SF of elite swimmers in the four competitive techniques, to compare the results obtained for male and female swimmers, using the same technique in races over different distances, and at different stages of the same race and to determine the relationships between SL and SF.	16 males and 16 females international level (Br)	100 and 200m (maximal)	SL, SR	A unique pattern of SL and SF combinations for each of the four techniques was found. For Br, males presented higher values of SF in the 100m, but SL values were the same for both male and female swimmers.
Psycharakis et al. (2008)	To investigate and evaluate the relationships between stroke kinematics and [La-] for elite swimmers competing at the international level during incremental exercise in their specialist events and distances and, to examine the extent to which changes in these parameters are associated with swimming performance.	11 males (23.00 ± 2.50 years) 10 females (21.30 ± 3.50)	7x 200m (incremental)	SR, SL, [La-]	Swimmers increased v by increasing SR and decreased SL, while [La-] increased. Similar v were produced with different combinations of SR and SL, while the best combination for reaching a given v varied both between and within swimmers. Changes in SR and SL occurred rapidly in relation to [La-] during the early stages of the test, when [La-] levels were low.
Reis et al. (2010)	To correlate aerobic and anaerobic physiological measurements either with the subjects' performance in 100m and 200m simulated Br events respectively using the Aquatrainer valve or with the subjects' season best performance in competitions.	22 competitive level males (16.90 ± 2.60 years)	Incremental test 100 or 200m (maximal)	C, [La-], peak VO_2 , v_{peak} VO_2 , v_2 , v_4 , v_2 VO_2 , v_4 VO_2 , VO_2 mean, AOD	For the 200m performance was more accurately predicted by the combination of aerobic fraction on energy release, peak blood lactate post-exercise and v_2 VO_2 , whereas for the 100m it was best predicted by the combination of v_4 VO_2 and peak VO_2 .

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Table 2. (Continued).

Authors	Main aim	Participants (age, level)	Br event/test (pace)	Variables	Main findings
Sánchez and Arellano (2002)	To evaluate the correlation between final time and SI, to compare the SI among swimmers of different levels, to examine the differences across several race distances and swimming techniques and to compare the differences between sexes.	181 males and 313 females world level 217 males and 203 females national level	50, 100 and 200m (maximal)	SR, SI, SL	The Br SI had the smallest value. The SI values of the man's 50m breaststroke events were smaller than the values 200m.
Seifert and Chollet (2005)	To examine differences between the sexes in flat Br arm and leg coordination over three race paces (200, 100 and 50m) and to link arm and leg coordination and propulsion by the calculation of a new IBFP, which measures the total duration of propulsion.	9 elite level males (20.00 ± 2.50 years) 8 elite level females (15.70 ± 1.50 years)	3x 25m (incremental, 200, 100 and 50m pace)	SR, SL, SP, TG, IBFP	The increase in v from the 200m to the 100m event was related to the increase in SR and the decrease in SL. From the 200-m to the 50-m pace, men and women increased their body propulsion due to the increase in upper limb propulsion. They decreased the body glide, which was due to a decrease in arm and leg glide. IFBP was lower for the women than for the men at the fast paces. Men had a longer propulsive phase and shorter glide and recovery phases than the women.

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Table 2. (Continued).

Authors	Main aim	Participants (age, level)	Br event/test (pace)	Variables	Main findings
Seifert et al. (2010)	To analyse how swim v and skill level affect upper-lower limbs coupling during a complete Br cycle using the elbow-knee CRP.	12 recreational females (16.50 ± 1.90 years) 12 competitive females (15.70 ± 1.50 years)	2x 25m (80% of maximal and maximal pace)	SR, SL, CRP	Recreational swimmers displayed a superposition coordination, an overlap of arm recovery with leg propulsion or/and an overlap of arm propulsion with leg recovery. Competitive swimmers switched from anti-phase coupling (legs maximally flexed/arms maximally extended) to in-phase (legs maximally extended/arms maximally extended), and during arm propulsion, the swimmers switched from in-phase coupling (legs maximally extended/arms maximally extended) to anti-phase (legs maximally flexed/arms maximally extended). Between arm and leg propulsions, a second part of the cycle was devoted to glide time, which varied from 20% to 40% of the cycle depending on v. Conversely, recreational swimmers spent less time in in-phase mode than the competitive swimmers due to the absence of glide time. V influenced the amount of time spent in in-phase, which decreased from 43% to 33% of a complete stroke between slow v and maximal v.
Seifert et al. (2011)	To analyse the inter-individual variability of swimmers at different skill levels to test the proposed conceptual "hourglass" model of variability.	24 recreational (16.70 ± 1.70 years) 24 competitive (16.10 ± 1.50 years)	50m (maximal) 25m (80% of the maximal pace)	SR, SL, CRP	Recreational swimmers showed a superposition of the propulsion of one pair of limbs with the recovery of the other pair of limbs, whereas competitive swimmers displayed propulsion alternation and glide time. Higher inter-individual variability was observed in recreational swimmers.

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Table 2. (Continued).

Authors	Main aim	Participants (age, level)	Br event/test (pace)	Variables	Main findings
Seifert et al. (2014)	To examine how expert swimmers are able to adopt an economic inter-limb pattern of coordination and if they are able to vary this freely chosen coordination pattern to minimize energy.	8 national level Br (18.30 ± 2.10 years)	3x 200m (70% of 200m pace)	SP, TG, C, VO ₂ , [La-]	C was lower for the freely chosen coordination and no ideal coordination pattern was determined, as the freely chosen pattern emerged from interacting constraints. Swimmers exhibited the highest C when they swam with maximal glide in comparison with minimal glide. Br specialists showed higher coordination flexibility than Fc specialists when coordination was constrained.
Sharp and Costill (1989)	To assess the effect of shaving body hair on physiological responses to free and tethered Br swimming and to examine the effect on v decay during a prone underwater glide after a maximal push from the side of the pool.	13 collegiate level males (19 to 23 years)	365.8m (90% of maximal pace) 8min (tethered, retarding forces 6.27, 7.75 and 9.26kg) 6x maximal underwater leg push-off and glide	SL, VO ₂ , HR, [La-]	Removing body hair decreased physiological effort (reduced [La-] and VO ₂) and increased SL, required to maintain a given v during Br but had no effect on physiological responses during tethered swimming.
Stachowicz and Milde (2023)	To determine the changes in thrust force and effect size of training load in swimmers using four swimming strokes monitored 4 times a year.	5 elite males (22.0 ± 3.1 years)	Thrust force (60 s)	Thrust force changes vs. time	Breaststrokers were able to maintain maximum thrust force for the longest time and their force curves were characterized by the smallest drop before 60 seconds of measurement compared to other swimming strokes.
Staniak et al. (2016)	To develop a method for measurement and analysis of kinematics of the pelvic girdle movement in Br swimming to support training of technical skills.	5 elite males (20.60 ± 2.30 years)	3x or 2x or 1x 50m (submaximal)	acceleration components, angular v of rotation components	Mean duration of the effective propulsion of upper limbs was nearly twice shorter than duration of propulsive activity of upper limbs. The beginning of the range of propulsive motion of the upper limbs was indicated at the moment of obtaining the local minimum of v that occurred after the v maximum connected with lower limb propulsion. The end of the range was found after obtaining the v maximum connected with propulsive activity of the upper limbs.

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Table 2. (Continued).

Authors	Main aim	Participants (age, level)	Br event/test (pace)	Variables	Main findings
Stosic et al. (2022)	To examine the effect of the breakout movements on the stroking variables and coordinative patterns of competitive swimmers.	33 national level males (16.50 ± 1.29 years)	4x 25m (maximal, one in each swimming technique)	SF, SL (in different phases), relative duration of each upper, lower limb phase, CRP	In Br, swimmers increased the relative duration of the propulsive phases of the upper and lower limbs during breakout. The average v when transitioning from underwater to surface was still lower than the v obtained in free swimming.
Strzala et al. (2013)	To detect the parameters of the time structure of the cycle correlated with the maximal swimming v in order to focus to specific technical aspects in the Br training	23 regional or national level males (15.00 ± 1.17 years)	50m (maximal)	SR, SL, SP, GO, ALL	The reduction of the glide and even overlap of the propulsive movements of the upper and lower limbs influenced the swim v. A faster start of leg propulsion was also associated with the percentage of duration time of leg propulsion in each kick. A correlation was found between v and the execution time of the in-sweep phase of the upper limbs. The overall contribution of time in producing a propulsive force by the lower limbs in the movement cycle significantly influenced v. Trained swimmers could do effective propulsive movements resulting in the achieved higher v by adjusting movement coordination of the proper extremities with shorter or lack of inter-cyclic glide or overlapping propulsive arm-leg action.
Strzala et al. (2014)	To analyse the coordination, propulsion and non-propulsion phases in the 100m Br race in a group of young swimmers.	27 school or university level males (15.70 ± 1.98 years)	100m (maximal)	SR, SL, SP, TTG, GO	SL and upper limb in-sweep phase were strongly related to 100m v. A negative correlation between part of the arm recovery and v was found.

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Table 2. (Continued).

Authors	Main aim	Participants (age, level)	Br event/test (pace)	Variables	Main findings
Strzala et al. (2015)	To examine the influence of selected indicators of somatic properties and physiological capacity on the v in the 200m Br race, to analyse kinematic parameters of Br swimming as well as assessing their impact on the v in the 200m Br race and to test the level of contribution of clear surface Br and turning zones swimming in the 200m Br race.	27 school or university level males (15.70 ± 1.98 years)	200m (maximal) 90s (maximal, in an ergometer upper limbs cranking and cycling)	SR, SL, SP, GO, ALL, TTG, v of 200m, VO_2 peak, Wtot of upper limbs cranking, upper limbs cranking, cycling	v of 200m was related to VO_2 peak of cycling and Wtot of upper limbs cranking. Turn zones v was strongly correlated to 200m v . v of 200m was positively related to leg total propulsion phase and negatively related to leg total recovery phase and glide. No dependence between percentage of propulsive arm movement and v of 200m was found. As SL decreased, SR increased on the 3rd and 4th 50m sectors of the total 200m.
Strzala et al. (2016)	To examine how coordination and kinematic indices interplay with swimming performance measured by average v in 50m all-out test.	34 university level males (19.10 ± 1.91 years)	50m (maximal)	SR, SL, SP, GO, ALL, TTG, acceleration, angular v components	SR and ample arm propulsion phase duration impulse were highly associated with v . TTG was related to v and SR, indicating the ability to perform effective limb and body movements together with shortening inter-cycle gap-glide or overlap.

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Table 2. (Continued).

Authors	Main aim	Participants (age, level)	Br event/test (pace)	Variables	Main findings
Takagi et al. (2004)	To compare differences in SP, arm-leg coordination and dv in Br due to event and performance level for both male and female swimmers at the FINA 2001 World Championship.	46 world level males 35 world level females	50, 100 and 200m (maximal)	SR, SL, SP, SRT, ALT, SPT, dv	SR and SL were inversely related to each other and better swimmers adopted a greater SL than less proficient swimmers. SR values were not significantly different by gender and performance levels. The time from the start of leg propulsion to the beginning of arm propulsion became higher as the distance increased, and it was higher for qualified swimmers than for the eliminated swimmers. For the phase of simultaneous propulsion of arms and legs, there were differences between gender and performance level. As the event distance increased, the value changed from positive to negative, a change indicative of decreasing overlap of propulsion. For the non-propulsive phase of the stroke values tended to increase as the distance increased, with no difference between performance levels.
Thompson (1998)	To test if improved swimming time may be coincident with increased [La-] production during Br competition.	6 national (21.00 ± 3.20 years)	100 and 200m (maximal)	[La-]	The 200m final yielded a greater absolute [La-] than the 100m final

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Table 2. (Continued).

Authors	Main aim	Participants (age, level)	Br event/test (pace)	Variables	Main findings
Thompson et al. (2000)	To evaluate the interrelationships between 'swimming' and 'non-swimming' variables and performance, to compare changes in kinematic variables as the swimmers progressed through the race and to make comparisons between 100m and 200m races.	318 national to elite males 316 national to elite females	100 and 200m (maximal)	SR, SL, finishing, start, turning and end time	Mid-pool v decreased over each consecutive 50m of a race, with the first length being swum faster than the final length irrespective of race distance or sex. SR and SL were not related to finishing time but were negatively related to each other. Mid-pool v, turning time and SL were generally found to deteriorate as the races progressed. Male 200m swimmers were anomalous in that they demonstrated a much greater variation in mid-pool v and turning time and poor correlations with finishing time in the latter stages of the race. 100m swimmers exhibited greater mid-pool v and SR coupled with shorter start times, turning times and SL than 200m swimmers.
Thompson et al. (2003)	To investigate the effect of even, positive and negative pacing strategies on selected metabolic, kinematic and temporal variables during Br trials.	9 regional to national males (21.00 ± 3.00 years)	200m (maximal) 3x 175m (even, positive or negative pacing)	SR, HR, [La-], VO ₂ , RPE	The positively paced racing strategy was selected by all the swimmers. High [La-] were observed in all trials. A reduced [La-], RPE and unchanged final time observed in the evenly paced trial suggest a less physical strain compared with the positively paced trial and so even pacing could be an alternative pacing strategy for competitive Br swimmers.
Thompson et al. (2004)	To investigate the effects of subtle changes in pace on selected metabolic and kinematic variables, during high-speed Br swimming.	9 regional to national males (23.00 ± 5.00 years)	200m (maximal) 3x 200m (98%, 100% and 102% of maximal pace)	SR, HR, [La-], VO ₂ , VCO ₂ , RER, RPE	Swimming at a pace greater than the mean v for a maximal 200m trial caused increases in stroke kinematics and a significant increase in anaerobic metabolism but no differences were found in final time compared to the even-paced trial.

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Table 2. (Continued).

Authors	Main aim	Participants (age, level)	Br event/test (pace)	Variables	Main findings
van Houwelingen et al. (2017)	To explore whether the leg-arm coordination within the Br cycle can be influenced with acoustic pacing, and whether the so induced changes are accompanied by changes in dv.	14 regional males and 12 regional females (20.00 ± 3.30 years)	50m (maximal) 10x 50m (70% of maximal pace)	dv, RPE, phase relation	The executed mean phase relation was affected by acoustic pacing and mean executed phase relation increased with increasing imposed phase relation. The average v did not differ for imposed phase relations of 180°, 225° and 270°, with the former being the most efficient coordination among the studied patterns, yielding significantly lower dv.
Vilas-Boas and Santos (1994)	To compare swimming economy between the three Br techniques: the flat style, the undulated style, and the undulated style with overwater recovery of the arms.	3 males and 6 females national level (15.80 ± 2.17 years)	3x 200m (two submaximal and one maximal)	VO ₂ , [La-], Etot, RC, C	Etot demonstrated a linear function with v. A lower economy was found for the undulated techniques, especially the overwater recovery of the arms.
Vilas-Boas (1996)	To compare dv and swimming economy among three different Br techniques: flat style, undulated style and undulated style with overwater recovery of the arms and to study the relationships between these parameters.	13 national level (15.80 ± 2.17 years)	3x 200m (two submaximal and one maximal) 3x 20m (200m pace)	VO ₂ , [La-], Etot, RC, C, dv, St	Undulated style with overwater recovery of the arms presented the highest values of dv and was the least economic compared to the other styles. dv and Etot were correlated when interindividual results were considered.
Vilas-Boas et al. (1994)	To evaluate the relationship between Br maximum propulsive impulse per SP, estimated from light trace photographic method, and maximum propulsive tethered force and to evaluate gender differences in maximum Br tethered propulsive force and maximum propulsive resultant impulse during the stroke cycle.	5 top level males (17.60 ± 1.67 years) 7 top level females (14.60 ± 1.72 years)	5 to 10 sec plus 6sec (submaximal and then maximum tethered swimming)	Max propulsive resultant impulses per SP, max propulsive tethered forces, dv, SP	Br technique is characterized by a succession of resistive and propulsive phases, and that is during the acceleration phase associated to the leg kick that is observed the higher positive, or propulsive, horizontal resultant impulse. The second higher positive impulse may be associated to the arm stroke. Male swimmers obtained higher values of maximum tethered force and maximum propulsive horizontal resultant impulse per phase.

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Table 2. (Continued).

Authors	Main aim	Participants (age, level)	Br event/test (pace)	Variables	Main findings
Wettengl et al. (2023)	To establish differences in load-velocity profiling, active drag and drag coefficient between three age groups of female swimmers.	33 females (11, 13 and 16 years)	3x 25m (semithethered)	Da, CDa	In breaststroke, maximal load, load normalized to the BM, and Da had large correlations with maximal v in the oldest swimmers, but those correlations were not observed in the 2 younger age groups. Conversely, medium to large negative correlations between CDa and maximal v were detected in the 11- and 13-year-old athletes, but this was not observed in the oldest swimmers.
Xin-feng et al. (2007)	To develop a new device to measure the Da during maximal v based on the assumption of equal useful power output in two cases: with and without a small additional drag.	3 males and 3 females national level	2x 25m (maximal)	Da	v of all participants in the FC was larger than that in the Br, which means that the power expended in the FC is greater than that in the Br, so propulsive efficiency in the FC is greater than that in the Br for a given swimmer. Br coefficient were all greater than the FC coefficients for all swimmers, irrespective of sex.
Zompanakis et al. (2020)	To examine whether breathing frequency in Br, effects swimmers' performance, [La-], and the different swimming efficiency parameters in the 25 and 50m distances.	8 males and 8 females (15.60 ± 3.20 years)	25 and 50m (maximal)	[La-], SR, SL, SI	1 on 1 breathing frequency resulted in a higher [La-] in the 25m.

[La-] - blood lactate concentration; ADTR - acceleration-deceleration time ratio; ALL - arm-leg lag; ALT - percent arm lag time; AnCV - anaerobic critical velocity; AnT - anaerobic threshold; AOD - accumulated oxygen deficit; Ap - frontal area; ApEn - Approximate entropy; AT - anaerobic threshold; Bk - backstroke; Br - breaststroke; Bt - butterfly; C - energy cost; CD - drag coefficient; CDa - active drag coefficient; CDp - passive drag coefficient; CM - centre of mass; CRP - continuous relative phase; D - drag force; Da - active drag; Dp - passive drag; dv - intra cycle velocity variation; ep - propelling efficiency; ESP - effective stroke phases; Etot - total energy expenditure; eWPS - effective work per stroke; Fa - average propulsive force; Fatind - fatigue index; Fc - front crawl; Fd - Fractal dimension; Fmax - maximum force; Fmean - mean force; GO - glide or overlap; HR - heart rate; IBFP - index of flat breaststroke propulsion; MSP - maximum swim power; nd - drag efficiency; np - propulsive efficiency; Po - power output; PV - pulmonary ventilation; RC - respiratory coefficient; RER - respiratory exchange ratio; RPE - rating of perceived exertion; S - Frontal surface area; SampEn - sample entropy; SI - stroke index; SL - stroke length; SP - absolute and relative duration of stroke phases; SPT - simultaneous propulsion time; SR - stroke rate; SRT - Simultaneous recovery time; St - Strouhal number; TI - trunk inclination; TG - time gaps; TTG - total time gap; v - swimming velocity; v2 - swimming velocity corresponding to the 2mmol.L-1 threshold; v2 VO2 - VO2 elicited at v2; v4 - swimming velocity corresponding to the 4mmol.L-1 threshold; v4VO2 - VO2 elicited at v4; VO2 - oxygen uptake; VC - ventilation coefficient; VCO2 - carbon dioxide expired; VO2max - maximal O2 uptake; VO2mean - mean VO2; vpeak VO2 - velocity associated to the peak VO2; Win - mechanical internal work; Wtot - total work.

breaststroke technique. We accepted our hypothesis regarding the influence of kinematic parameter variations on energy cost variability in breaststroke swimming, as well as the role of active drag as key-driver to fluctuations in energy cost in breaststroke swimming.

The quality of eligible studies was assessed using the risk of bias scale developed by Hindle et al. (2019b). One notable finding is that none of the studies reported on how the sample size was determined. This information is important for understanding the sample power computation and the external validity of the findings reported. While some papers demonstrated low bias risk (15 articles), others showed room for improvement, such as addressing the key limitations of the research. Nearly half of the studies acknowledged the importance of considering both sexes in their research (45.2%). However, 34.2% recruited exclusively males, and 6.8% only females, raising concerns about findings' generalisability and applicability across the population. This gender bias limits the ability to draw conclusions about the specific sexes. In addition, it is worth noting that ten studies did not specify the participants' sex. This lack of reporting is a limitation as it precludes a thorough analysis of gender differences and further contributes to the overall gender inequality in the body of knowledge found in the literature.

The predominance of elite and high-level swimmers in the studies reflects a clear emphasis on performance-oriented research. While this focus offers valuable insights into peak performance and training optimisation for competitive athletes, it may inadvertently neglect other tiers of the swimming population, such as recreational swimmers or those in developmental stages. Moreover, the lack of studies targeting younger age groups, particularly those under 12 years old, underscores a critical research gap that warrants attention. The prevalence of maximum tests (52.1%) as the preferred protocol indicates a predominant focus on evaluating swimmers' peak performance. Additionally, researchers employed a combination of both maximal and submaximal tests, along with incremental tests. This comprehensive approach enables a thorough assessment of performance across a spectrum of intensities, providing valuable insights into swimmers' capabilities under various exertion levels.

The present review identified three distinct domains of variables: stroke kinematics (including stroke kinematics and coordination parameters), hydrodynamic drag, and energetics. In the forthcoming sections, we will explore each of these variable domains drawing upon existing literature to provide a comprehensive analysis.

Stroke kinematics

In the scope of this review, a significant majority of the included studies (60.3%) focused on reporting kinematic variables. Among them, 26 studies specifically assessed stroke kinematics, such as stroke rate (SR), stroke length (SL), stroke index (SI), and intra-cyclic variations of velocity (dv). Breaststroke swimming consists of propulsive and non-propulsive phases, which affect the swimmer's velocity (v).

Arm-to-leg timing

During the arm pull (insweep) and leg kick, the swimmer experiences acceleration and an increase in v , whereas the recovery of the arms and legs and the gliding phase result in deceleration and a decrease in v (D'Acquisto & Costill, 1998; Gourgoulis et al., 2018; Leblanc et al., 2007; Mason et al., 1989; Vilas-Boas, 1994). There are two peaks associated

with the leg and arm propulsive phases and two minimal velocities that correspond to the arm and leg recovery phase and the transition time between the leg and arm propulsive phases, respectively (Gourgoulis et al., 2018). Although the leg propulsive phase produces a steeper increase in v compared to the arm propulsive phase, the latter is equally important, and elite swimmers are able to achieve a better arm-to-leg timing, resulting in a faster v (Leblanc et al., 2005). While the leg propulsive phase produces greater acceleration than the arm propulsive phase, it may not necessarily result in a higher v , as it depends on the swimmer's starting v or their limited ability to perform an effective leg kick (Gourgoulis et al., 2018).

Although the gliding phase (when it occurs) in breaststroke swimming does not generate propulsion, it plays a paramount role in optimising the swimmer's performance, as adopting a more streamline position in this critical phase enables the swimmers to reduce drag preventing a substantial decrease in v (D'Acquisto & Costill, 1998). Notwithstanding, this transition phase of breaststroke is important for distance covered, and expert swimmers are skilled at adopting a streamlined position during this phase, which can have a significant impact on their swimming economy and overall performance (Leblanc et al., 2005; Takagi et al., 2004). To achieve optimal efficiency during these non-propulsive phases, elite swimmers focus on minimising drag by using a better-streamlined position and arm-to-leg timing, which can be the key performance discriminator among top performers (Komar et al., 2014; Leblanc et al., 2005).

General stroke parameters

At low intensities, when the v slows down, SL increased and SR decreased in breaststroke swimming (Conceição et al., 2013a; Craig & Pendergast, 1979; Leblanc et al., 2007; Gourgoulis and Nikodelis, 2022; Takagi et al., 2004; Thompson et al., 2000, 2004). This is mainly caused by the longer duration of the gliding phase (Chollet et al., 1996). Moreover, breaststroke was the only swimming technique where SL decreased when switching from 200 m to 100 m paces (Chollet et al., 2004; Craig et al., 1985; Manley & Atha, 1992). Within the 200 m race laps a greater SR variability for the breaststroke than for the other three strokes was found (Hellard et al., 2008). SR was highly associated with the 50 m performance (Strzała et al. 2016) but poorly related with finishing time in the 200 m (Thompson et al., 2000). An increase in SR between heats, semi-finals and finals in the 50 m breaststroke, was found for men and women. However, only in women, this was related to improved performance (Arellano et al., 2022). Among swimmers who advanced through the rounds, the rise in SR may be a crucial factor, as seen in women. However, in cases where the increase in SR leads to a significant reduction in stroke length (SL), performance deterioration may occur, as evidenced in men (Arellano et al., 2022).

Differences were found between the first and second 50 m lap of a 100 m breaststroke race (long course metre). In the second 50 m, SR was 3.53% faster, and SL and v decreased by 9.73% and 6.04%, respectively (Thompson et al., 2000). Another study found that there was a similar drop in v (7%) but the SR declined noticeably from the first lap to the second and third laps, but rebounded with an increase seen on the final lap, without any difference compared to the initial lap (short course metre) (Oxford et al., 2017). Interestingly, SL remained relatively consistent throughout the swim, with no significant changes observed (Oxford et al., 2017). SI is defined as the product of average

v and SL and a proxy of swim efficiency. High SI values are strongly associated with a low energy cost (C) (Costill et al., 1985). The decrease in v in the 100 m race was related to the change in the ratio of SL and SR, with a decrease (13%) in SI which indicates that the participants were becoming less efficient as they progressed through the swim (Oxford et al., 2017). Front crawl has the highest SI, followed by backstroke, butterfly and breaststroke (Sánchez & Arellano, 2002).

Between the 50 m and the 200 m, where mean v decreases, SR is severely reduced while SL increased, more for elite compared to non-elite swimmers (Chollet et al., 1996; Leblanc et al., 2005, 2007; Pai et al., 1984, Takagi et al., 2004, Thompson et al., 2000). In fact, for the same SR, elite female and male swimmers had a greater mean v and SL than non-elite swimmers. So, an elite swimmer can achieve the same or a greater v as a non-elite swimmer, using a different technique with longer SL and lower SR (Leblanc et al., 2005, 2007). Interestingly, there was no significant correlation between SL and SR and clean swimming time (Olstad et al., 2020). This suggests that fast swimmers do not necessarily rely on a long SL, but rather employ their own individual strategies to achieve high clean v (Pai et al., 1984). In addition, SR was not different by gender and performance levels in the 50, 100 and 200 m races (Hellard et al., 2008; Takagi et al., 2004).

In the 100 m, males presented higher values of SR and v compared to women, but SL values were the same for both male and female swimmers (Oxford et al., 2017, Pai et al., 1984; Seifert & Chollet, 2005). In the 200 m, males presented higher SL and v and lower SR compared to women, suggesting that SL was the most important factor influencing performance (Psycharakis et al., 2008). Differences in the ratio of SR and SL may be related to variation in the stroke phases (Chollet et al., 1996; Chollet et al., 1999; Seifert & Chollet, 2005; Soares et al., 1999) or the anthropometric differences, the swimmer's technique and the resultant active drag and v (Kolmogorov & Duplishcheva, 1992). Compared to women, men exhibited greater propulsion in both their upper and lower limbs during swimming (Seifert & Chollet, 2005). Male swimmers have also been reported to generate greater mechanical power outputs than females (Kolmogorov et al., 1997).

Buoyancy

Women showed a larger reduction in glide duration from the 200 m to the 50 m pace. Despite these differences, men had a smaller arm glide compared to women (Seifert & Chollet, 2005). No difference between sexes in the time spent in any of the phases of the stroke in the 100 m race was found (Oxford et al., 2017) which is not consistent with other study that reported that males spend significantly longer in the propulsive phase of the stroke (Seifert & Chollet, 2005). Female swimmers exhibit greater buoyancy and tend to maintain a more horizontal position when in a static position compared to male counterparts (Leblanc et al., 2010). Correlations between floatation and improved glide were established, highlighting the potential advantages of buoyancy in swimming performance for female athletes. This could be related to a lower drag during this phase of the stroke in female swimmers (Leblanc et al., 2010).

The better buoyancy of females may have decreased their frontal area, thus reducing resistance in the water and promoting a longer and more efficient glide. Additionally, a relationship was found between the SI and hydrostatic lift in female swimmers at a slow pace, highlighting the impact of flotation on stroke efficiency (Leblanc et al., 2010). These findings suggest that buoyancy enhances hydrostatic lift, thereby contributing to stroke

effectiveness. The impact of buoyancy on swimming performance may be limited at high velocities, particularly during sprinting, as noted by some researchers (Leblanc et al., 2010). This may be due to a 'ceiling effect', whereby the advantages of buoyancy are only held up to a certain range of v , beyond which the benefits diminish. Two possible interpretations can be made: increased v may result in greater lift, which could help to counteract the sinking force experienced by male swimmers, thereby minimising the benefits of buoyancy. Alternatively, as v increases, there may be changes in arm-leg coordination that lead to a decrease in the glide phase of the stroke. This decrease may reduce the effect of buoyancy on overall swimming performance, as less time is spent in the static phase where buoyancy can have a significant impact (Leblanc et al., 2010).

Intra-cyclic variations of velocity

A swimming technique is more economical when the dv is more even for a given average v , because the swimmers do not have to overcome the forces of inertia as well as the hydrodynamic resistance (Kolmogorov et al., 1997). In breaststroke, Vilas-Boas (1996) reported a correlation between the dv and C , signalling that swimmers who exhibit fewer fluctuations are more likely to swim economically. Breaststroke has been defined as the swimming technique with the highest dv and characterised by a two-peak profile (T. Barbosa et al., 2010b, 2013, 2016, 2017; Xin-Feng et al., 2007). One peak related to arm's actions and the other one to the leg's action (T. Barbosa et al., 2010b). At times, a third peak was described in the transition between arms and legs' actions.

It is expected that elite swimmers present a lower dv compared to non-elite swimmers. However, higher values of dv for elite swimmers were reported (Komar et al., 2014; Leblanc et al., 2007). The higher values can be attributed to the fact that elite swimmers achieve higher peak v during the arm propulsive phase, while maintaining nearly the same minimum dv during the recovery phase and that elite swimmers employed a glide coordination style even at sub-maximal v (Leblanc et al., 2009). This introduces a bias when studying the relationship between dv and performance if the v of elite and non-elite swimmers is not at the same % of maximum velocity. Additionally, their drop in v is less pronounced during the leg-arm transition time (glide phase) (Leblanc et al., 2007; Takagi et al., 2004). Therefore, it is important not to decelerate rapidly during the recovery phase, and to keep a relatively higher hip v during the arms' glide phase (Takagi et al., 2004).

Colman et al. (1998) compared the dv of flat and undulation breaststroke styles, and concluded that there was considerably less difference between the maximum and minimum v peaks in the most undulating style than in the lowest flat style. Some swimmers used an overwater arm recovery, described as inefficient as it involves a higher dv related to the trunk drag and a higher energy expenditure (Vilas-Boas and Santos, 1994). In addition, an undulated movement of the body was related to the v of the 50 m race (Strzala et al., 2015). A swing-like forward immersion during streamlined recovery of arms after their pull and breath, as well as to the lower body movements: straightened legs are then being pulled up to the buttocks, which enhances swinging action called 'wave action' (Conceição et al., 2013b; Colman et al., 1998; Mason et al., 1989).

Power output

In the front crawl, the product of force and v was greater than that in the breaststroke (Xin-feng et al., 2007). This indicates that more power is expended in the front crawl

compared to the breaststroke. Since the total useful power output is fixed, it can be concluded that the propulsive efficiency in the front crawl is higher than that in the breaststroke for a given swimmer (Xin-feng et al., 2007). Breaststroke presented the lowest average propulsive force value compared to the other swimming techniques (Hermosilla et al., 2020) as a result of the simultaneous actions of both arms and legs and, consequently, leading to a higher dv (Barbosa et al., 2006). Front crawl showed the higher values of maximum swim power, following by breaststroke, butterfly and backstroke (Hermosilla et al., 2020). In a tethered swimming protocol, breaststroke and butterfly showed both higher and lower force production values compared to front-crawl and backstroke (Morouço et al., 2011). Notably, breaststroke swimmers recorded the highest tethered swimming force values, and the v of a 50 m breaststroke was found to have the highest correlation with maximum force production (Morouço et al., 2011). In addition, maximum propulsive tethered force and maximum propulsive horizontal resultant impulse per breaststroke phase, were higher in male than in female swimmers (Vilas-Boas, 1994).

Complexity and predictability

Approximate entropy (ApEn) and sample entropy (SampEn) provide insight of the randomness of the inter-cyclic variations over a time-series. The lower its values, the higher the predictability of a time-series (Pincus, 1991). Fractal dimension (Fd) describes the properties of a system that demonstrates fractality or other properties that do not change over time and/or space. The higher the Fd, the more complex the time series is (Bravi et al., 2011). Breaststroke showed the highest value of Fd, the second lowest values of ApEn and the lowest value of SampEn comparing to the other swimming techniques. So, comparing to the four competitive techniques, breaststroke has a more complex but more predictable swimming pattern (Barbosa et al., 2016, 2017; Bartolomeu et al., 2018).

Coordination parameters

A total of 18 articles included in this review reported coordination parameters, emphasising their significance within the research. Additionally, two papers investigated both coordination and energetics, providing a comprehensive examination of these interrelated aspects. In breaststroke, a change in v is related to an increase in limbs' v , a change in the arm-leg coordination and the change of the relative duration of the separate stroke phases (Leblanc et al., 2007; Oxford et al., 2017; Takagi et al., 2004). With increasing v , a greater arm and leg propulsion and decreased arm and leg glide phases has been described (Chollet et al., 1996, 1999, 2004; Seifert & Chollet, 2005).

Relative percentages of arm and leg recoveries presented higher values in the 50 m compared to the 200 m pace (Chollet et al., 2004; Leblanc et al., 2005). Conversely, the absolute duration of the arm recovery was reported to become higher as the event distance increased (Soares et al., 1999). A longer arm recovery in the fastest pace may be explained by the need to catch the water before the arms are pulled out (Chollet et al., 2004). During the breaststroke, the leg recovery phase is considered the most significant braking phase. As swimming v increases, so does the active drag, particularly during this phase, which results in a need for longer leg recovery time (Chollet et al., 2004; Leblanc et al., 2005). Despite this, the distance covered during the leg and arm recoveries and

during the absolute arm-stroke was not influenced by race pace in either elite or non-elite swimmers (Leblanc et al., 2007; Olstad et al., 2017).

In the 100 m race, between laps the participants showed no change in the amount of time spent in the propulsive phases of the stroke or the recovery phases of the stroke (Oxford et al., 2017). In addition, the elbow push and leg insweep remained stable throughout the 50, 100, and 200 m paces (Chollet et al., 2004). This can explain why the SL did not change during the 100 m swim. In addition, even with increasing effort, the absolute duration and distance during the knee extension phase remained similar (Olstad et al., 2017). This suggests that the swimmers maintained a strong kick even at lower effort levels, or it could be attributed to the change in knee angle, which provided a better mechanical advantage. Specifically, the swimmers pulled their feet higher up towards the buttocks, resulting in a longer distance to travel and increased force on the water. Moreover, this change in knee angle also aided to a better upper body streamline at the beginning of this phase (Olstad et al., 2017).

Between elite and non-elite swimmers, differences in swimming v did not correspond with differences in arm propulsion duration, which might suggest that elite swimmers had a better propelling efficiency (Leblanc et al., 2005, 2009). For instance, the duration of the insweep phase was longer in the non-elite male and female groups. These swimmers make a common technical mistake by dropping their elbows back and by pushing down with their arms which causes drag and is time consuming (Leblanc et al., 2005). In addition, the outswEEP phase was shorter in non-elite swimmers as they did not move out their hands to the side enough. By doing so, they tended to push down against the water with a dropped elbow position (Leblanc et al., 2005).

Elite swimmers tend to have longer duration of the leg recovery than non-elite counterparts, but a shorter duration of the arm recovery (Leblanc et al., 2005, 2009). The longer arm recovery of non-elite swimmers may be linked to a longer breathing time of the non-elite swimmers. In fact, a negative correlation between the arm recovery and v was found, showing that a slow transport of the upper limbs after the end of propulsion production or prolonging their transfer in this phase is unfavourable for achieving higher swim v (Strzala et al. 2014). In addition, elite swimmers presented a lower leg glide phase duration compared to non-elite swimmers. Conversely, the arm glide phase did not differ between the two groups (Leblanc et al., 2005) and results showed that the experts and recreational swimmers spent the same time with arms and legs out-stretched, therefore the same relative duration of the glide (Komar et al., 2014). However, for expert swimmers, the glide phase corresponds to an effective in-phase coupling of limbs movement (i.e., simultaneous extension of legs and arms), and varying with the v (Komar et al., 2014).

In the researches by Leblanc et al. (2005, 2007), the effective propulsion times of the elite groups were longer and their effective glide times shorter than non-elite swimmers. Indeed, the ability to swim fast on the surface was positively associated with the percentage time of propulsion generation and the non-propulsive phase (leg recovery of the legs, including gliding) was negatively correlated to v (Strzala et al., 2015). The adaptation to v mostly comes from a regulation of the glide time (Komar et al., 2014). This strategy enables experts to maintain effectiveness of propulsions and glide, but also leads to higher dv . Nevertheless, both experts and recreational swimmers exhibited greater dv during the low v condition, mainly due to higher deceleration related to greater time spent gliding, which is in agreement with a previous study (Leblanc et al.,

2007). A study on deterministic models in competitive swimming (T. M. Barbosa et al., 2010a), showed that high-level swimmers are characterised by lower inter limb coordination total time gap (TTG—the sum of the different time gaps between propulsive movement of the upper and lower limbs) (Chollet et al., 2004; Leblanc et al., 2005, 2009). In fact, TTG showed a significant interplay both with v of the 50 m race and SR (Strzala et al., 2015). Elite breaststrokers are able to lower the percentage of non-propulsive phases in cycle movement (which means longer periods of effective propulsion) (Leblanc et al., 2009).

Recreational swimmers tend to perform arm recovery and leg kick simultaneously, characterised by the extension of both pairs of limbs at the same time (Leblanc et al., 2009). This produces a movement that resembles an ‘accordion-like’ motion, as the propulsion of one pair of limbs is thwarted by the underwater recovery of the other pair of limbs (Seifert et al., 2011). Competitive swimmers organise their cycle by doing the propulsion of one pair of limbs while the other pair of limb’s glide in a hydrodynamic position (i.e., extended) and synchronise both recoveries of the arms and legs (Komar et al., 2014; Seifert et al., 2011). Given that both arm and leg recoveries are underwater and thus cause high drag, they should be synchronised (Chollet et al., 2004). The simultaneous recovery time tends to increase with increasing distance (Takagi et al., 2004).

There are three general styles of breaststroke timing, i.e., overlap, continuous and glide. With increasing v , an exaggerated overlap time led the swimmers to start their arm propulsion while their leg kick was still accelerating their body, leading to a higher active drag (Leblanc et al., 2009; Oxford et al., 2017). Elite swimmers, on the other hand, start the arm propulsion earlier after the leg extension and the squeezed leg position. This reduces the propulsion gap and motor gap between the leg insweep and the arm catch, resulting in reduced v fluctuations (Leblanc et al., 2005; Seifert & Chollet, 2005). By utilising overlap timing and better body position, the period of deceleration can be reduced and higher minimum linear body v before the propulsive phase generated from the arm pull established, and sprinting ability enhanced (D’Acquisto & Costill, 1998). The flat breaststroke is characterised by this coordination style. Research has shown that the flat style, with its smaller v fluctuations, is more economical than the undulated breaststroke with over-water arm recovery (Vilas-Boas, 1996). So, by beginning arm propulsion earlier, these swimmers anticipated and limited body deceleration (Craig et al., 1988; Maglischo, 1993) and were also capable of producing a higher SR (Chollet et al., 2004; Leblanc et al., 2005; Takagi et al., 2004).

Competitive swimmers exploit a gliding coordination style at slower v , while elite swimmers employed a glide coordination style even at sub-maximal v (Leblanc et al., 2009). By incorporating a gliding phase into their swimming technique, competitive swimmers are able to take advantage of the propulsive force generated by their leg kick, since their arms are already in a well-aligned and recovered position. This contrasts with recreational swimmers, who typically lack a gliding phase and may experience reduced efficiency in their strokes and leg propulsive action (Leblanc et al., 2009; Seifert et al., 2011).

Hydrodynamic drag

There is limited amount of data available on the active drag (D_a) in breaststroke swimming technique. Only five articles reported hydrodynamic drag and one paper

reported both drag and energetics. The breaststroke technique exhibits higher values of D_a and frontal area compared to other swimming techniques (Gatta et al., 2015; Kolmogorov & Duplishcheva, 1992; Kolmogorov et al., 1997, 2021; Xin-feng et al., 2007). In addition, breaststroke exhibits approximately twice the amount of D_a compared to the passive drag, a feature that is not as prominent in other swimming techniques (Gatta et al., 2015).

Numerous experiments have been conducted to determine D_a in swimming. For instance, early measurements involved indirect calculations of D_a based upon changes in oxygen consumption with additional drag loaded onto the swimmer (Di Prampero et al., 1974). Another approach involved using the Measuring Active Drag (MAD) system, which directly measures D_a (Hollander et al., 1986). The MAD system is widely regarded as the gold standard for assessing D_a , however, it is limited to evaluating the front crawl technique. The velocity perturbation method (VPM) was introduced as a method that allows for the measurement of D_a in all four swimming techniques (Kolmogorov & Duplishcheva, 1992). The VPM relies on the assumption that a swimmer can generate the same maximum power output during two bouts—one towing an additional buoy with a known resistance (Kolmogorov & Duplishcheva, 1992). Xin-feng et al. (2007) developed a new device based on the same assumption as Kolmogorov and Duplishcheva (1992) and was able to measure D_a in breaststroke. Finally, Gatta et al. (2015), estimated D_a based on the average frontal area values measured during a complete stroke cycle in each swimming technique.

Energetics

Approximately 33% of the studies included in this review focused on reporting bioenergetical parameters, such as lactate concentration ($[La^-]$), oxygen uptake (VO_2), C and energy expenditure. Breaststroke has consistently been described as the swimming technique with the highest C compared to other swimming techniques (Barbosa et al., 2006; Capelli et al., 1998; Holmér, 1974a; Kolmogorov et al., 2021). The C and E_{tot} in breaststroke exhibit a linear increase across a range of v (Capelli et al., 1998; Vilas-Boas and Santos, 1994). While theoretical models suggest that energy output should vary with the cube of v , observed results may be attributed to variations in efficiency, drag, and synchronisation across a range of v (Vilas-Boas and Santos, 1994). The substantial energy expenditure required to accelerate the body during the push phase likely accounts for this discrepancy. Such compensation is necessary to counterbalance the v loss experienced in the non-propulsive phase of the stroke (Capelli et al., 1998).

SF and SL have been found to influence C in breaststroke. Increasing SF results in higher energy expenditure, even when controlling for v . Conversely, increasing SL leads to a significant decrease in C , independent of v (Barbosa et al., 2008). Increasing the duration of the gliding phase after the kick action, leads to an increase in the SL. Consequently, there will be a decrease in C (Barbosa et al., 2008). The freely chosen inter-limb coordination pattern in breaststroke minimises C , suggesting that swimmers can optimise their coordination to reduce energy expenditure (Seifert et al., 2014). Additionally, breaststrokers exhibit higher coordination flexibility compared to front crawlers under constrained coordination conditions, without significant extra C when a ‘minimal glide’ is imposed (Seifert et al., 2014).

While breaststroke exhibits higher C , it demonstrates lower v compared to front crawl for the same metabolic power (Kolmogorov et al., 2021). Breaststroke also presents lower values of lactate concentration ($[La^-]$), v at the anaerobic threshold and anaerobic critical v compared to other swimming techniques (Carvalho et al., 2020; Di Prampero et al., 2008; Holfelder et al., 2013; Marinho et al., 2011). However, other ventilatory and metabolic parameters, including $VO_2\max$, are similar between breaststroke and front crawl during maximal swimming, suggesting comparable physiological demands (Lomax et al., 2022). V at ventilatory threshold was slower during breaststroke comparing to front crawl (Lomax et al., 2022). It is worth noting that while increasing SR and decreasing SL can result in higher v , it also leads to increased $[La^-]$ (Psycharakis et al., 2008). Increasing the SR in breaststroke swimming can lead to an increase in the C . This increase is caused by the loss of energy due to increasing resistance during rapidly performed non-propulsive movements of the leg recovery phase (Chollet et al., 2004; Manley & Atha, 1992; Vorontsov & Rumyantsev, 2000) or/and reducing the amount of glide time between each cycle can eliminate the brief period of rest.

It has been reported that C correlates negatively with performance, but results for breaststroke do not support such data, since C was not included in any of the regression models that were found (Reis et al., 2010). Another commonly reported association in the literature is a positive correlation between peak $[La^-]$ and performance (Bonifazi et al., 1993). However, support for such a relationship was not found in a study (Reis et al., 2010).

The 200 m breaststroke event presents a significant anaerobic contribution (Conceição et al., 2013a; Capelli et al., 1998; Thompson, 1998). In fact, the 200 m final resulted in a greater absolute $[La^-]$ compared to the 100 m final, suggesting a higher anaerobic demand in the longer race (Thompson, 1998). Interestingly, when the 200 m trial was performed with an even pace, a reduced $[La^-]$ was observed, indicating a lower physical strain compared to a positively paced trial (Thompson et al., 2003, 2004). The v in the 200 m race and the v during turns have been found to correlate with the leg peak oxygen consumption measured during a cycling test (Strzala et al., 2015).

It has been shown that peak VO_2 is a reliable predictor of performance in swimming (Chatard et al., 1990; Costill et al., 1985). Surprisingly, in the case of the 100 m breaststroke event, a negative correlation was observed between peak VO_2 and the athletes' best performance of the season (Reis et al., 2010). This suggests that successful breaststroke swimmers may possess a larger anaerobic capacity, allowing them to meet the demands of the stroke and the event. Troup (1992) also found a relationship between certain anaerobic variables and breaststroke performance, further supporting this notion. Furthermore, in the 100 m breaststroke, a negative correlation was observed between the VO_2 elicited at a v corresponding to the 4 mmol. l^{-1} lactate threshold and peak VO_2 in relation to performance. This indicates that higher levels of aerobic ability may hinder optimal performance in this event (Reis et al., 2010). Given the event's short duration and high intensity, it is likely that the influence of anaerobic ability outweighs the importance of extremely high levels of aerobic capacity.

Limitations and research gaps

In the present review, none of the included studies reported on participants under 12 years of age. This suggests a gap in research concerning younger swimmers and signals

a need for future studies catering this age group. Understanding the determinants of energy cost in breaststroke swimming for younger swimmers is important, considering their unique physiological and developmental characteristics.

Additionally, the variation in methodologies, measurement techniques, and terminology used across different studies can make it challenging to compare and generalise findings. Establishing standardised methodologies and terminology would enhance the reliability and comparability of research in this field. For instance, the information highlights various coordination parameters such as arm-leg coordination, relative duration of stroke phases, and coordination styles. However, there may be a lack of standardised definitions and measurement techniques for these parameters. Establishing consistent definitions and measurement protocols would enhance the comparability of research findings and facilitate a deeper understanding of coordination patterns.

Future studies should also address the scarcity of available data on the active drag associated with the breaststroke swimming technique. This lack of data limits our understanding of the specific characteristics and factors influencing active drag in breaststroke. In addition, there is a need for multidisciplinary studies that do not focus on only one scientific domain, as only approximately 18% (12 articles) of the papers described associations between domains.

Conclusions

Findings revealed that stroke kinematics, including SR, SL, SI, and dv , play a crucial role in influencing C in breaststroke swimming. Moreover, the analysis highlighted the importance of propulsive and non-propulsive phases, arm-to-leg timing and buoyancy of breaststroke.

With increasing v in breaststroke, a greater arm and leg propulsion and decreased arm and leg glide phases has been described. Relative percentages of arm and leg recoveries also presented higher values at higher v . Non-elite swimmers present a higher duration of the insweep phase and a shorter outswEEP phase of the upper limbs. The effective propulsion times of the elite groups were longer and their effective glide times shorter than non-elite swimmers. Recreational swimmers tend to perform arm recovery and leg kick simultaneously, competitive swimmers exploit a gliding coordination style at slower v , while elite swimmers employed a glide coordination style even at sub-maximal v .

The breaststroke technique exhibits higher values of active drag, frontal area, energy cost and lower velocity compared to other swimming techniques. Overall, this synthesis of literature highlights the holistic nature of C in breaststroke swimming and it provides a comprehensive understanding of the determinants influencing energy cost.

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ORCID

Tiago M. Barbosa  <http://orcid.org/0000-0001-7071-2116>

João Paulo Vilas-Boas  <http://orcid.org/0000-0002-4109-2939>

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