Longitudinal Interventions in Elite Swimming: A Systematic Review Based on Energetics, Biomechanics, and Performance

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Abstract

Costa, MJ, Bragada, JA, Marinho, DA, Silva, AJ, and Barbosa, TM. Longitudinal interventions in elite swimming: A systematic review based on energetics, biomechanics, and performance. *J Strength Cond Res* 26(7): 2006–2016, 2012–Longitudinal information requires the notion of repeated measurements throughout time. Such data is important because it allows the determination of the effectiveness of an intervention program. Research in competitive swimming has given special emphasis to energetics and biomechanics as determinant domains to improve performance. The purpose of this systematic review was to summarize longitudinal evidences on the energetic, biomechanical, and performance status of elite swimmers. A computerized search was made in 6 databases, conference proceedings, and department files. The 28 studies that satisfied the inclusion criteria were selected for analysis. Studies' qualitative evaluation was made by 2 independent reviewers using the Quality Index. These studies were then gathered into 3 main categories according to their reported data: energetics ($n = 18$), biomechanics ($n = 9$), and performance ($n = 8$). The conclusions were as follows: (a) elite swimmers are able to demonstrate from slight to substantial changes in their performance and energetic and biomechanical profiles within and between seasons; (b) the magnitude of change is dependent on the characteristics of the training programs, the duration of the intervention, and subject's gender; and (c) future research should emphasize the use of more complex procedures to improve the quality of the interventions.

Key words elite swimmers, seasonal variation, kinematics, training

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Introduction

Research in competitive swimming has given special emphasis to energetic and biomechanical assessments. The performance is strongly linked to energetic variables, as those are dependent on biomechanical profile and motor strategies adopted by the swimmers (5). At the moment, most of the recent reviews conducted about this topic (5,42,43) report evidences exclusively based on cross-sectional studies. The defining feature of a cross-sectional study is that it can compare different population groups (i.e., cohort groups) and different variables at a single time moment. Such interventions are less comprehensive and informative about the cause-and-effect relationships in a long-term perspective. On the other hand, the longitudinal assessment implies the notions of repeated measures, that is, the observations are collected at a certain number of occasions. Extending its measurements beyond a single time moment, a sequence of events can easily be established (45). Thus, it seems that longitudinal interventions can bring more benefits than cross-sectional studies.

There are a few longitudinal studies on competitive swimming when compared to other sports (e.g., running). Most of those articles were published in peer-reviewed and indexed journals showing the strong effect of their findings. Indeed, the consolidation of those evidences retrieving some major guidelines is an important tool for coaches' daily intervention. However, to the best of our knowledge, it does not seem to exit any review about longitudinal interventions on competitive swimming.

Longitudinal data play a major contribution in helping coaches defining realistic goals and training procedures between competitions or between seasons (30). This kind of information on energetic and biomechanical terms is a useful tool to determine the effectiveness of the previous load, helping enhanced performance (40). Moreover, the longitudinal performance judgment by itself can be a useful adjunct for the prediction phenomena. Chronological points can be used to predict performance levels (6) or even to determine the probability of winning a medal in a specific event (30,44).

The purpose of this systematic review was to summarize evidence about the changes and relationships between energetics, biomechanics, and performance throughout longitudinal interventions in elite swimmers. This type of work was thought to breach more clearly the gap between theory and practice by assisting the coaches in their training prescription and to highlight areas for further research.

Methods

All the methodological procedures were conducted considering the standards for systematic reviews suggested by the Institute of Medicine of the National Academy (Washington, DC, USA). Systematic searchers in the thematic conducted the process to fulfill the suggestions and guidelines given by McGowan and Sampson (24), such as (a) the need of transparency (readers should be able to verify that the review is not open to bias) and (b) reproducibility (readers and other researchers should be able to replicate the methods and arrive at the same results).

Search Strategy

A search of the literature (Figure) was conducted from January 1, 1970, until December 31, 2010, using electronic literature databases (PubMed, ISI Web of Knowledge, Index Medicus, MEDLINE, Scopus, and SPORTDiscus) and use of departmental files, including conference proceedings. Several keywords (longitudinal, kinematics, biomechanical, energetics, physiological, performance, swimming, elite swimmers, training season, monitoring, variation, relationships, tracking, and changes) were used in the search strategy, with multiple combinations and with no language restrictions. Two independent searches produced 2 different lists of publications that were then consolidated into a single list. Results were initially screened by title to exclude any obviously irrelevant articles. Potential hits that meet the inclusion criteria were after hand searched. When necessary, attempts were made to contact the authors to obtain the missing article.

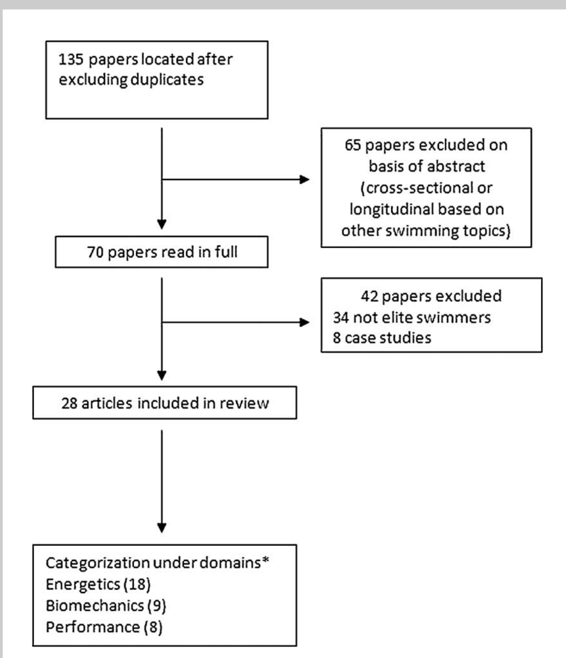

Figure. Search strategy: *7 studies categorized into both energetic and biomechanic domains.

Inclusion and Exclusion Procedures

Included studies focused on longitudinal interventions on energetics, biomechanics, and performance of elite swimmers. "Elite swimmer" is defined as an athlete at adult age that is near or has already reached his/her top career, demonstrating regular presence on the most important National or International level Competitions. Excluded were (a) studies not having at least 2 equal field interventions with the same subjects, (b) studies based on other swimming topics, (c) studies using other chronological ages (e.g., children, age group, or masters) instead of adult elite swimmers, and (d) studies that focused on a single individual or on a few number of swimmers (e.g., $n < 5$).

In respect to the research question, relevant studies were categorized into 3 main groups: (a) energetics, where interventions generally aimed to observe the evolution of energetic confounders throughout time or to detect possible changes according to training prescription and its influence on performance; (b) biomechanics, where interventions aimed to understand the contribution of biomechanical changes to performance enhancement; and (c) performance, where authors aimed to analyze the performance behavior to predict future results. The information extracted from the included studies was based on (a) design and setting, (b) sample characteristics, (c) aim of the intervention, and (d) major findings.

Quality Assessment

All relevant studies underwent a formal evaluation by 2 independent reviewers. Because there is no validated quality assessment tool suitable for this kind of field interventions (i.e., sports performance), the Quality Index was used (12). This index presents a large range of scoring profiles: reporting, internal validity, external validity, and power. In each profile, all items received rating scores, where the maximal score possible to obtain from the index was 32 points. When necessary or appropriate, disagreements between reviewers were solved by discussion and consensus. The degree of agreement in scoring procedure was obtained based on the Kappa index (K), and thresholds were interpreted according to Landis and Koch's suggestion (23), where there is (a) no agreement if $K \leq 0$, (b) poor agreement if $0 < K \leq 0.19$, (c) fair agreement if $0.20 < K \leq 0.39$, (d) moderate agreement if $0.40 < K \leq 0.59$, (e) substantial agreement if $0.60 < K \leq 0.79$, and (f) almost perfect agreement if $0.80 < K \leq 1.00$.

Table 1. Summary of the studies concerning longitudinal interventions on energetics.*

Authors (reference)	Quality score	Design and setting	Sample characteristics	Intervention	Findings
Houston et al. (17)	10	2 testing occasions in 6.5 weeks	10 university swimmers	Effects of 2 types of training on $\dot{V}O_2max$ and HR	$\dot{V}O_2max$ remained unaltered. HR was significantly lower.
Sharp et al. (36)	9	3 testing occasions during 6 months	12 university swimmers	Detect changes in [La$^-$] and HR	[La$^-$] at submaximal velocity improved. HR remained unaltered.
Ryan et al. (34)	10	6 testing occasions during 6 months	14 university swimmers	Effects of training volume on [La$^-$]	[La$^-$] at submaximal velocity improved.
Costil et al. (10)	11	7 testing occasions during 25 weeks	24 collegiate swimmers	Effects of an increased training volume on [La$^-$]	[La$^-$] at submaximal velocity improved.
Wakayoshi et al. (46)	11	2 testing occasions spaced by 6 months	8 college swimmers	Effects of aerobic training on [La$^-$]	[La$^-$] at submaximal improved.
Pelayo et al. (28)	10	6 testing occasions during 23 weeks	6 international and national swimmers	Effects of training on the [La$^-$] related with recovery	Maximal [La$^-$] related with recovery increased with overtraining.
Bonifazi et al. (6)	11	2 testing occasions spaced by 18 weeks	8 international swimmers	Relationships between postexercise [La$^-$] and performance	Increases in maximal [La$^-$] were positively correlated with performance.
Termin and Pendergast (40)	11	12 testing occasions during 4 seasons	22 U.S. Division 1 swimmers	Effects of high-velocity training on maximal [La$^-$], $\dot{V}O_2max$, and C	Maximal [La$^-$], $\dot{V}O_2max$, and C improved.
Pyne et al. (29)	12	4 testing occasions during 8 months	12 world-ranked swimmers	Association between [La$^-$] and performance	[La$^-$] at submaximal velocity improved but was not associated with performance.
Thompson and Cooper (41)	12	2 testing occasions during 12 months	11 nationally ranked swimmers	Association between [La$^-$] at submaximal speeds and performance	[La$^-$] at submaximal velocities were significantly related with performance.
Anderson et al. (1)	12	396 tests during 6 seasons	40 international and national swimmers	Characterize seasonal changes in [La$^-$] at submaximal speeds and HR	[La$^-$] at submaximal velocity and maximal [La$^-$] improved. HR presented trivial changes.
Roels et al. (33)	12	4 testing occasions during 10 weeks	8 international swimmers	Effects of altitude training on $\dot{V}O_2max$ and C	$\dot{V}O_2max$ and C remained unaltered.

Atlaoui et al. (3)	10	3 testing occasions during 7 weeks	13 international and national swimmers	Relationships between HR and performance	HR remained unaltered and was not related with performance.
Rodríguez et al. (32)	19	4 testing occasions during 11 weeks	13 collegiate swimmers	Effects of altitude training on $\dot{V}O_2$max and C	$\dot{V}O_2$max and C remained unaltered.
Anderson et al. (2)	11	10 tests by swimmer during 5 seasons	40 international and national swimmers	Seasonal changes in [La$^-$] at submaximal speeds	[La$^-$] at submaximal velocity improved.
Faude et al. (14)	12	4 testing occasions during 5 weeks	10 national swimmers	Effects of 2 types of training on [La$^-$] and HR	[La$^-$] at submaximal velocity and maximal [La$^-$] improved. HR remained unaltered.
Santhiago et al. (35)	11	4 testing occasions during 14 weeks	23 Olympic and international swimmers	Submaximal [La$^-$] responses in different training phases	[La$^-$] at submaximal velocity remained unaltered.
Robertson et al. (31)	13	4 testing occasions during 21 weeks	18 international and national swimmers	Effects of altitude training on [La$^-$] at submaximal velocities	[La$^-$] at submaximal velocities presented modest changes.

*HR = heart rate.

Results

Our search identified 135 potential relevant articles of which 107 did not meet the inclusion criteria. As shown in the Figure 1, the reasons for exclusion were being cross-sectional (32 studies), longitudinal focused on other topics (33 studies), participants from other chronological ages (34 studies), and case studies (8 studies). A total of 28 studies were considered for further analysis. From these, the earliest one was published in 1981 (17) and the most recent in September 2010 (9). Studies were assigned for each category according to their reported data (Table 1): (a) energetics (18 studies), (b) biomechanics (9 studies), and (c) performance (8 studies). Because 7 studies demonstrated evidences in different domains, they were included in both energetic and biomechanical categories.

The Quality Index scores ranged from 9 to 19 points individually, representing a mean of 11.68 points. Studies scored similar in their reporting style. All studies performed poorly in their external validity, internal validity, and power. Only one study used random sampling to include subjects that would be representative for the entire population. In 9 studies, subjects could not be aware of which interventions they received. At least 3 studies indicated the power magnitude to detect an important practical effect. The reliability between both reviewers showed an almost perfect agreement (0.87) in the scoring procedure.

Group 1: Studies of Longitudinal Interventions on Energetics

Eighteen studies in Table 1 have monitored changes in elite swimmers' energetic profile. The overall quality scores ranged between 9 and 19 points. Interventions generally aimed to assess blood lactate concentrations ([La$^-$]) at submaximal swimming speeds (1,2,10,29,31,34,35,36,41,46), maximal [La$^-$] (1,6, 14,28,40), maximal oxygen consumption ($\dot{V}O_2$max) (17,32,33,40), heart rate (HR) (1,3,14,17,36), and energy cost (C) (32,33,40). The reported duration of field interventions ranged from 5 weeks (14) to 6 seasons (1).

Group 2: Studies of Longitudinal Interventions on Biomechanics

Table 2 included 9 relevant studies that tracked changes in elite swimmers' biomechanical profile. The quality scores ranged from a minimum of 10 points to a maximum of 12 points. Interventions generally aimed to assess stroke frequency (SF) (1,14,18,20,40,41,46) and stroke length (SL) (1,10,18,20, 40,46). The duration of the interventions ranged from 14 days (20) to 6 seasons (1).

Group 3: Studies of Longitudinal Interventions on Performance

Table 3 summarizes the 8 studies that analyzed the performance variation within or between seasons. Quality scores ranged between 9 and 13 points individually. Studies used race times (8,9,19,27,30,38) or ranking positioning (37,44) for

TABLE 2. Summary of the studies concerning longitudinal interventions on biomechanics.*

Authors (reference)	Quality score	Design and setting	Sample characteristics	Intervention	Findings
Costil et al. (10)	11	7 testing occasions during 25 weeks	24 collegiate swimmers	Effects of an increased training volume on SL	SL significantly improved.
Johns et al. (20)	10	3 testing occasions during 14 days	12 intercollegiate swimmers	Effects of taper on SL and SF	SL and SF remained unaltered.
Wakayoshi et al. (46)	11	2 testing occasions spaced by 6 months	8 college swimmers	Effects of aerobic training on SL and SF	SL increased significantly. SF remained unaltered.
Termin and Pendergast (40)	11	12 testing occasions during 4 seasons	22 U.S. Division I swimmers	Effects of high-intensity training on SL and maximal SF	SL and maximal SF increased.
Thompson and Cooper (41)	12	2 testing occasions during 12 months	11 nationally ranked swimmers	Association between SF and performance	Increases in SF were significantly related with decreases in performance.
Huot-Marchand et al. (18)	11	2 testing occasions spaced by 2 years	17 international and national swimmers	Association between SL, SF, and performance	SF increased and was significantly related with performance improvements. SL remained unaltered.
Anderson et al. (1)	12	396 tests during 6 seasons	40 international and national swimmers	Seasonal changes in SL and SF	SL decreased and SF increased in males. SL increased and SF decreased in females.
Anderson et al. (2)	11	10 tests by swimmer during 5 seasons	40 international and national swimmers	Variation of SF at submaximal velocity	Submaximal SF improved.
Faude et al. (14)	12	4 testing occasions during 5 weeks	10 national swimmers	Effects of a taper on SF	SF remained unaltered.

*SF = stroke frequency; SL = stroke length.

Table 3. Summary of the studies concerning longitudinal interventions on performance.*

Authors (reference)	Quality score	Design and setting	Sample characteristics	Intervention	Findings
Stewart and Hopkins (38)	13	Performances collected between 20 days	221 national-level swimmers	Performance consistency within and between competitions	Performance variation was 1.4% in the same event, 1.7% between distances for a given stroke, and 2.7% between strokes for a given distance.
Mujika et al. (27)	13	Performances collected in 2 major competitions	99 Olympic swimmers	Performance progression in the final stage leading to the 2000 Olympic Games	Performance improved 2.57 and 1.78% for males and females, respectively.
Pyne et al. (30)	12	Performances collected during 12 months	676 performances of 51 Olympic swimmers	Performance progression leading to the 2000 Olympic Games	Performance improved 1% within a competition and 1% within a year. An additional 0.4% enhancement increased the chance to win a medal.
Trewin et al. (44)	13	Performances collected during 9 months	407 Olympic swimmers	Relate the annual ranking positioning with the 2000 Olympic Games performance	Most of Olympic medalists had a top 10 world ranking. An additional 0.6% enhancement in performance will increase the chance to win a medal.
Sokolovas (37)	9	Ranking positioning during 9 seasons	U.S. top 100 performances	Presence in U.S. top 100 ranking positioning from 10 to 18 years	Low stability was presented.
Issurin et al. (19)	13	Performances collected in 2 major competitions	301 Olympic swimmers	Performance progression in the final stage leading to the 2004 Olympic Games	Performance improved ~0.6% between trials and Olympics.
Costa et al. (9)	13	Performances collected during 5 seasons	2,385 performances of 477 world-ranked swimmers	Performance progression during the 2004–08 Olympic cycle	Performance improved between seasons ~0.6–1%, reaching high stability ($r > 0.60$) in the third season of the Olympic cycle.
Costa et al. (8)	13	Performances collected during 7 seasons	905 performances of 35 nationally ranked swimmers	Stability of breaststroke performance from 12 to 18 years	Low stability ($r < 0.30$) was presented. The prediction of adult competitive level increased at the age of 16.

that purpose. The time of the intervention lasted between 20 days (38) and 9 seasons (37).

Discussion

The main focus of this investigation was to summarize evidence about longitudinal interventions on elite swimmers. In this research, it was verified that elite swimmers presented from slight to substantial changes in performance, energetics, and biomechanical profiles through intervention period. The magnitude of change is dependent on the characteristics of the training programs, duration of the intervention, and the subject's gender.

There is a trend for the majority of the articles included in this study to present low quality scores, when compared to similar approaches in other scientific domains (e.g., health sciences and social sciences). Overall, swimming teams have only a small number of caliber swimmers to be assessed. To overcome this issue, most researchers in this field adopt convenience samples. The main disadvantage for this kind of sample is the inability to extrapolate the result for all populations. In addition, the existing tools used for quality assessment were built based on more accurate scientific areas. On a regular basis, they are focused on complex procedures such as randomization, blindness, and the use of control group or practical effects. The absence of such procedures affects the quality score given to swimming interventions. In this sense, low/moderate quality score for these kinds of studies. In the near future, swimming researchers should consider those aspects aiming to improve the quality of further interventions.

Energetics

One important practical consideration for coaches is the importance of monitoring energetic adaptations within and between seasons. The studies included in this review regarding the aerobic capacity present similar trends. Aerobic capacity determined by the [La$^-$] at submaximal swimming speeds improves over the season. Two studies (1,29) indicated a small but meaningful annual improvement in the 4 mmol of lactate speed by ~2.2% for females and ~1.5% for males. Four studies (10,34,36,46) reported that an increase in training volume is sufficient to induce such adaptations. From those, 2 studies (34,36) observed that the highest degree of change is achieved in the earliest months of the season. At that season's stage, the muscle is more sensitive and able to improve the ability to produce energy aerobically (29). In this sense, coaches should develop aerobic capacity of their swimmers at the beginning of the season, before more specific and high-intensity training. From this moment forward, aerobic capacity remains almost stable until the end of the season. Conversely, additional volume increases will not promote significant changes in the aerobic capacity. At least one study (34) reported that increases in training yardage above 54.000 yd$\cdot$wk^{-1} during the remainder of the training season did not alter the aerobic capacity in elite female swimmers. At this point of the season, elite swimmers have reached their personal aerobic peak. To improve or maintain the performance at higher levels, coaches should focus on different training intensities aiming to develop other energy sources.

The maximal [La$^-$] can be used as an anaerobic capacity estimation (4). Included studies about this topic observed that maximal [La$^-$] increases throughout the season as well (1,6,14,40). One of those studies (14) reported significant improvement from mid phases until the end of the season. An improved anaerobic capacity allows the swimmer reaching higher velocities at an increased oxygen debt and reduced muscle fatigue. Studies included in this review observed substantial improvements (from ~12 to ~27%) in the maximal [La$^-$] of male swimmers within one full season (1,6,40). In contrast, only trivial changes (~2%) were evident for their female counterparts (1). Indeed, one of those studies (1) determined a large degree (~28%) of within-athlete variation in respect to maximal [La$^-$] improvements. Differences in the magnitude of change can be accounted to the type of the training done and to gender-specific adaptations within the season.

At least 3 studies (1,29,34) reported that improvements within the season in aerobic and anaerobic capacities are cyclical in nature. It is expected that some capacities will be lost (i.e., detraining phenomena) in off-season. One of those studies (1) determined a loss of ~0.9% for males and ~1.2% for females in their aerobic fitness during the transition from one season to the following one. Previous observations have already reported that elite swimmers should keep their conditioning, or at least minimize the detraining effects, during the transition period. This concern showed to be beneficial to training adaptation in the beginning of the following season (26). For this reason, coaches should advise their swimmers to remain active in off-season. It is important to perform other physical activities rather than swimming to maintain their fitness at higher levels. Added to that, swimmers should also undertake some swimming sessions, mainly to maintain the water sensitivity and their basic technique efficiency.

There seems to exist a few studies and little consensus regarding the $\dot{V}O_2$max status throughout the season. From the 2 studies found, only one study (40) presented an increase in the $\dot{V}O_2$max within the season. Conversely, the other one (17) observed that $\dot{V}O_2$max remained slightly unaltered with training. Two hypothetical explanations for the discrepancy between results are (a) the training intensity selected in those studies and (b) the duration of the intervention program. The 6.5 weeks of moderate- and high-intensity training were not sufficient to promote substantial adaptations in the $\dot{V}O_2$max (17). Any attempt to induce substantial adaptations may require a new specific type of training or a longer period to be expressed. One full season of high-intensity training with lower volumes was able to increase the $\dot{V}O_2$max in 20% (40). Although the capacity to transport and use oxygen increases as a result of high-intensity training, this increase tends to decrease through consecutive seasons. Termin and Pendergast (40) observed increases in $\dot{V}O_2$max of 20, 9, 8, and 5% after each of 4 consecutive seasons, respectively. Because at some point of their careers, elite swimmers reach their predetermined genetic limit, from a statistical point of view, it becomes very difficult to observe significant differences between seasons.

Regarding HR variability, 5 studies (1,3,14,17,36) were included in the present review. Four studies (1,14,17,36) were focused on maximal HR values, whereas 1 study (3) reported adaptations in HR at rest. Evidence suggests that elite swimmers present trivial changes in HR variability over the season. There are also gender-specific differences in

HR adaptations between seasons. Whereas the maximal HR for the males was relatively stable between seasons, females had a 1.1% decrease each year (1). It is known that meaningful changes in stroke volume do not appear in trained athletes (22). Indeed, the HR variability within the season is not correlated with performance (3). However, one study (14) reported a significant decrease in maximal HR for these kinds of subjects. In such article, swimmers were submitted to a 6.5 weeks of high-intensity training program. It could be hypothesized that the training load may lead to central adaptations, promoting an HR decrease. Added to that, these data can also suggest an overtraining issue.

In an attempt to explore further adaptations beyond conventional training, some coaches dedicate some part of their periodization programs to train in altitude. Three studies (31,32,33) assessing energetic adaptations induced by altitude training were found. The interventions consisted of short duration periods living in high (>2,500 m) and training at low (~600–1,200 m) or moderate (~1,350–2,500 m) altitudes. Whereas the $\dot{V}O_2$max and C remained unaltered after interventions (32,33), the $[La^-]$ related to submaximal swimming speeds presented modest changes (31). The absence of substantial gains was already reported in other closed and cyclic sports (e.g., running, cycling). There still remains a doubt of the usefulness of such programs inducing positive effects in elite athlete's performance.

Therefore, in respect to further longitudinal energetic programs, it can be useful to highlight evidences regarding the within-season and between-season variation of other energetical variables. In addition, new highlights are required to understand the effects of reduced and prolonged detraining period and also to more deeply explore the effects of altitude training in these kinds of subjects.

Biomechanics

The biomechanical adaptations within and between seasons are important for coaches to determine the effectiveness of their technical sets to enhance stroke kinematics. The SL and SF have been described as useful variables to monitor swimming technique (11). Whereas the SL is the distance that the body travels during a full stroke cycle, the SF represents the number of full strokes performed within a given period.

Coaches should know the existence of gender-specific adaptations in these biomechanical variables within and between seasons. Two included studies (1,40) showed that males tend to increase SF and decrease SL in 1–2% each season. In contrast, female swimmers typically have a nonmeaningful decrease in SF and an increase of 0.9% in SL (1). Individual adaptations to similar training programs may explain the discrepancies between genders. Males tend to become stronger by increasing lean mass throughout the season (1). Their higher availability for dryland training than females may contribute to higher benefits for performance. The positive transfer between dryland strength gains and swimming propulsive force only are evident with specific training (39). Programs combining swimming training with dryland strength (80–90% of the maximal load) (15) or with in-water assisted and resisted training (16) have demonstrated to be effective for sprint velocity and were more efficient than swimming alone. This represents an improved ability to generate power on water to reach higher SF and SL (15). An increase in maximal SF of 1–2% represents an increase of 0.6–0.8% in maximal swimming speed each season (1). Indeed, increases in male's maximal SF and SL from one season to the next had strong association with increases in 200 m freestyle performance (18) but not with the 100 and 200 m breaststroke events (41). On the other hand, females tend to increase efficiency over the season. Female swimmers are unable to increase significantly the lean mass as their male counterparts (1). In this sense, the within-season improvements in velocity are reached by increasing stroking kinematics, namely, the SL.

Within-season adaptations on stroking variables are also dependent on individual kinematical characteristics. At least one study included in the present review (1) reported between-individual variations of 2–5% in maximal stroke characteristics over the season. Earlier speculations about this large variability on biomechanical adaptations (21) are now confirmed. It seems that each swimmer uses the most freely chosen combination (e.g., an increased SL and lower SF or vice versa) to reach higher performances throughout the season.

Seasonal adaptations in SF and SL are also dependent on the type of training program. The high volume programs have been found to increase SL (10,46) but not SF (14,46). High-volume training programs have been reported to inhibit the development of muscular power and strength (13). Because the increase in maximal SF within the season is dependent on those aspects, there is little margin of improvement using these kinds of programs. In contrast, swimming at lower speeds allows focusing on stroke phase aspects and therefore increasing the distance swum per stroke. However, at some point of the season, a maximal SF vs. SL combination is reached. To induce further adaptations, they may require new training intensity or a taper period to obtain the benefits of the long distance load.

Studies based on high-intensity programs with lower volumes have reported that maximal SF either remained unchanged (14) or improved (40) with training. The difference in SF output between studies may also be accounted to the duration of the training programs. Five weeks of intensity training were not sufficient to induce substantial adaptations in SF during 100 and 400 m front crawl maximal efforts (14). On the other hand, the manipulation of SF-velocity curve over 4 consecutive seasons increased maximal SF in 8% and improved the 100- and 200-yd freestyle velocity (40). The ability to shift to the right the SF-velocity curve by ~10% per season will substantially improve performance (40). High-intensity training also promotes increases in maximal SL. At least one study (40) showed a 16% increase in maximal SL after 4 seasons of high-intensity training. Thus, high-intensity training with lower volumes appears to be more effective in improving stroke characteristics than high-volume training. Earlier observations have already reported that performance depends mainly on training intensity and less from volume or frequency (26).

When preparing for a major competition, elite swimmers on regular basis employ significant reductions in weekly training volume and promote high intensities nearly the race pace, often know as the "taper period." There are still a few studies regarding biomechanical adaptations during such "period." Two studies (1,10) have found increases in SL and slight declines in SF during taper phases within the season. One study (20) reported that taper did not result in significant alterations either in SF or SL. The intervention duration has an important role on swimmers' response to taper (25). Taper phases of the included studies lasted about 10–14 days (20) and 3–4 weeks (1,10). The time constant of decay of the training load can also affect the swimmers' response (25). Weekly volume was reduced in 60–76% throughout taper, which can explain the absence of improvement in biomechanical characteristics of those subjects (20). A 2-week taper during which training volume is exponentially reduced by 41–60% seems to be the most efficient strategy to induce adaptations (7). Although the taper can be conducted in many ways, there still remain some doubts if this last approach is the most effective way of doing it and deeper research is needed.

Therefore, further longitudinal investigations in biomechanics should use more complex procedures (e.g., videometric) to expand the analysis to other biomechanical domains. Although being more time consuming, it is necessary to increase the reliability and to improve the quality of the interventions. It is also important to report evidence about other biomechanical variables directly associated with performance (e.g., stroke index, propelling efficiency, index of coordination, drag force, propulsive forces, and buoyancy force) and to provide quick practical information for swimmers and coaches to adjust training methods.

Performance

Longitudinal performance assessment can be developed by tracking race times and analyzing ranking positioning for a given period. This information is important to help coaches selecting appropriate training methods and to predict chronological points for better results.

Two studies used race times (8) and ranking positioning (37) to analyze the performance progression from childhood to adulthood. It reported a significant improvement in performance (8) and high variability in ranking positioning (37) from 12 to 18 years old. At adult age, most of the U.S. top 100 swimmers were never ranked in that top at younger ages (37). Added to that, the magnitude of change in 100-m breaststroke performance was not similar between all seasons, reaching high stability at the age of 16 years (8). There seems to be uncertain regarding the determination of the adult competitive level based on the result at earlier ages. So, coaches should design the periodization program based on swimmer's growth and maturation process. In addition, coaches should also help early maturing swimmers to keep their sports success in perspective and that maturation process involves until 16–17 years in some young athletes.

Another study (9) showed evidences regarding the performance progression during an Olympic cycle. World-ranked swimmers were able to demonstrate a 3–4% of performance improvement in freestyle events between Athens 2004 and Beijing 2008 Olympic games. However, the range of performance improvement was not so obvious through consecutive seasons. Swimmers started to demonstrate high stability in freestyle race times around the third season of the Olympic cycle (9). To ensure an Olympics presence, they should be near of their best performances in this specific point. Performance improvements were also reported within the last season of an Olympic cycle. The magnitude of improvement in race times of world-ranked swimmers was around 0.6–1% in both Sydney 2000 (30) and Beijing 2008 (9) Olympic games season's. Despite being small, those performance enhancements are important in reaching a better ranking positioning throughout the season and to increase the chance to win a medal at the main competition. Most of the swimmers (87%) who won a medal in the Sydney 2000 Olympic games were in the top 10 World ranking in that year (44). In this sense, coaches are advised to track the magnitude of performance change and the ranking positioning within the season to ensure an Olympic participation and the possibility to win an Olympic medal.

The magnitude of change in performance within the season seems to be dependent on the type of stroke and the distance swum. Two studies have analyzed the performance variation between 2 national level competitions. It was reported a performance variation of 0.8% for international swimmers between national trials and the Olympics (30). On the other hand, it was observed a 1.4% of performance variation in the same event for national swimmers, participating in 2 national championships spaced by 20 days (38). One possible explanation for the differences in the magnitude of change can be the sample characteristics. The less consistency for national swimmers (38) is related to the lower experience in racing than international ones (30). National swimmers also demonstrated less consistent between distances for a given stroke (1.7%) and least consistent between strokes for a given distance (2.7%) (38). Thus, coaches should be aware that swimmers are stroke specialists rather than distance specialists. Because different distances represent different physiological challengers, training should emphasize specific sets concerning a particular stroke and adjacent distances (e.g., 50 and 100 m or 100 and 200 m) from that stroke.

The last stage of preparation before the main event is the most important phase in peaking for the optimal performance. Two studies (19,27) have analyzed the performance change in the final weeks of preparation, leading to the Olympics competition. There were improvements of 2% (27) and 0.6% (19) in race times of swimmers preparing to the Sydney and Athens Olympic Games, respectively. The difference in the magnitude of change can be explained by the characteristics of the sample. Although both studies considered race times from the top-level swimming nations with regular presence at the Olympics (e.g., Australia, South Africa, Germany), one of those studies (27) included performances from lower level nations (e.g., Angola, Guam, and Singapore). Swimmers in the bottom of the ranking list are able to have a larger improvement than the top ones.

Therefore, further longitudinal interventions regarding exclusively the performance analysis should focus on the prediction approach to other competitive swimming strokes or distances. In addition, some attempts should be made trying to discriminate genders' differences in a large range of age as possible.

Practical Applications

The scientific evidences reported in this article may be encouraging for swimmers and coaches. The stability and change in some variables can be a useful tool for training control and performance diagnosis. Based on these scientific evidences, coaches can use submaximal and maximal $[La^-]$ data for daily training prescription at the various exercise intensities. Conversely, the reduced changes observed in $\dot{V}O_2max$ and HR within the season suggest that those variables are less informative at least for elite swimmers. Most of technical drills for elite swimmers should focus on increasing SL. Although there are only evidences for male swimmers, in both genders, performance enhancement might also be obtained increasing the SF. On top of that, coaches should identify the swimmer's optimal relationship between SF and SL.

There is a need to rethink the type of training in an attempt to promote further adaptations in elite swimmers. The training intensity seems to be the best way to develop both energetic and biomechanical profiles. Because the majority of the competitive swimming events last less than 3 minutes at high intensity, training programs based mainly on low intensity and high volumes might not be the most suitable. Coaches should design training sets with intensities nearly or similar to those used by the swimmer on main events.

Finally, coaches can also use the magnitude of performance progression and ranking positioning data. Those are useful tools for the performance prediction in important competitions or throughout swimmers' career.

Future research in swimming should emphasize the use of more complex research designs (e.g., control groups and practical effects) to improve the quality of the studies. Those are procedures used on regular basis in more advanced scientific areas, such as for instance health sciences. Added to that, we tried to explain the need to have further interventions on other swimming events besides those reported above (200 and 400 m freestyle).

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