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Analysis of lap times in international swimming competitions

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Abstract

Swimming performances were analysed for the top 16 finishers (semi-finalists, finalists) in nine international competitions over a 7-year period (1530 males, 1527 female). Total race time and intermediate lap times were log-transformed and analysed for effects of sex (male, female), stroke (freestyle, form strokes, individual medley), event (100, 200, and 400 m), and place (1–16). Between-athlete correlations characterized the relationship of each lap to final time, and within-athlete estimates quantified the effect of lap time on improvements in final time. Finalists exhibited very large correlations ($r = 0.7$–0.9) with final time in the second 50-m lap of 100-m events and the middle two 50-m and 100-m laps of 200-m and 400-m events respectively. For an individual swimmer, an achievable change in lap time was associated with an approximate 0.4–0.8% improvement in final time for finalists and an approximate 0.5–1.1% improvement in final time for semi-finalists, depending on sex, stroke, and event. The pattern of lap times was similar for the top 16 swimmers and between the best and worst swims for finalists. These findings indicate that substantial improvements can be made via the final lap in sprints and the middle two laps of 200- to 400-m events, but the overall pattern of lap times should not be changed.

Keywords: *Mixed modelling, correlation, pattern of pacing, performance*

Introduction

Successful performance in competition relies on a complex interaction of many factors, and in top-ranked athletes small differences can determine a competition outcome (Hopkins & Hewson, 2001). Pacing strategies are considered a key element in performance (Foster et al., 1993; Tucker, Lambert, & Noakes, 2006), especially in closely matched athletes when appropriate pacing can be the difference between winning or losing (Foster, Schrager, Snyder, & Thompson, 1994; Fukuba & Whipp, 1999). To determine the most effective pacing for an event, it is important to characterize the self-selected pattern of pacing adopted by elite athletes in competition (Foster et al., 2004). Observations at the 1980 and 1988 Olympic Games indicated a marked reduction in pace in the latter stages of sprint cycling and speed skating events, and a comparatively even pace for the longer duration 4000-m cycling and 3000-m speed skating events (Foster et al., 1993). These findings have been confirmed experimentally in 2000-m cycle time-trialling (Foster et al., 1993), 1500-m cycling (Foster et al., 2003), 2-min kayak ergometry (Bishop, Bonetti, & Dawson, 2002), and via computer simulations in speed skating (van Ingen Schenau, de Koning, & de Groot, 1990) and track cycling events (de Koning, Bobbert, & Foster, 1999; van Ingen Schenau, de Koning, & de Groot, 1992). Accordingly, an "all-out" or fast start is considered to be the most successful strategy in events of shorter duration (~ 60 s), while in middle-distance events (2–4 min) a fast start followed by a transition to comparatively even pacing results in the best performance.

Recent competition analysis has demonstrated that world records in 800-m running events (< 110 s) are typified by a fast first lap and a notably slower second lap (Tucker et al., 2006). In 2000-m rowing events (6–8 min), the strategy employed by most athletes in international competition is a fast start in the first 500 m, a progressive slowing through the second and third 500 m, and a comparatively faster final 500 m (Garland, 2005). Race analysis in international swimming competition has predominantly

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characterized kinematic and temporal aspects (Arellano, Brown, Cappaert, & Nelson, 1994; Chengalur & Brown, 1992; Kennedy, Brown, Chengalur, & Nelson, 1990; Thompson, Haljand, & MacLaren, 2000; Wakayoshi, Nomura, Takahashi, Mutoh, & Miyashito, 1992). In these investigations, stroke kinetics were highly individualized (Chengalur & Brown, 1992; Kennedy et al., 1990; Wakayoshi et al., 1992) and therefore a poor predictor of performance (Thompson et al., 2000); in contrast, mid-pool swimming speed was highly related to finish time (Arellano et al., 1994; Thompson et al., 2000; Wakayoshi et al., 1992). The non-swimming components (start and turning times) also have a direct bearing on performance (Arellano et al., 1994; Thompson et al., 2000).

To the authors' knowledge, only one previous study addressed differences in pacing strategy and performance in swimming competition, and presented a selection of individual world record and gold medal winning performances as examples of the most successful strategies (Maglischo, 2003). Overall, winners of 100-m events paced positively with a fast first lap, 200-m and 400-m events were mainly evenly paced, some 400-m swimmers demonstrated a faster finish, while distance events (800 to 1500 m) were generally paced evenly (Maglischo, 2003). However, the pattern of pacing of an individual swim might not be reflective of the optimal strategy or even a deliberate strategy from the outset of the race.

Preliminary analysis (unpublished observations) conducted by the Australian Institute of Sport on pacing in Olympic swimming events identified two main trends: sprint events were decided in the last 25 m of the 50-m event and last 50 m of the 100-m event; and middle-distance events were set up with the second lap speed (second 50 m of the 200-m events and the second 100 m of the 400-m events). However, no published study has used statistical modelling to characterize the pattern of pacing adopted by a large cohort of elite swimmers over several international competitions.

Although coaches routinely advise swimmers to adopt a particular pacing plan for an event, there are limited quantitative data on how variations in lap times affect swimming performance in international competition. The main aim of this study was to determine differences in the relationship of specific laps to final time and the overall pattern of pacing between finalists and non-finalists in events differing in stroke (freestyle, backstroke, breaststroke, and butterfly) and distance (100 to 400 m) in international swimming competitions. A secondary aim was to calculate the magnitude of change needed in performance for a swimmer to improve his or her placing in competition.

Methods

Swimming performances (1530 males, 1527 females) from nine international competitions (two Olympic Games, three World Championships, two Commonwealth Games, two European Championships) over a 7-year period were analysed retrospectively. The events were 100- and 200-m freestyle, backstroke, breaststroke, and butterfly, 200- and 400-m individual medley and 400-m freestyle. All results were obtained from Internet sources. All data were in the public domain.

Statistics

We used magnitude-based inferences and precision of estimation expressed as 90% confidence intervals (Batterham & Hopkins, 2006) to characterize changes and differences in lap times in international swimming competitions. Total race time, intermediate 50-m or 100-m split times, and placing for the top 16 finishers (the eight finalists and eight semi-finalists) were log-transformed and analysed in the Statistical Analysis System (Version 9.1, SAS Institute, Cary, NC) for sex (male, female), stroke (freestyle, form strokes, individual medley), event (100, 200, and 400 m), and finishing place (1–16). Log-transformation of the outcome measures reduces non-uniformity and is necessary when effects are analysed as a percent or factor. Effects and errors are converted to uniform additive effects, which can be modelled linearly and then back-transformed (Hopkins, Marshall, Batterham, & Hanin, 2009). The distribution of the log-transformed times showed little deviation from normality, other than a minor skewness attributable to a small tail of slower swimmers. Plots of residual versus predicted values were examined for each analysis to check for extreme outliers and non-uniformity of the residuals. Five race times were >4.0 residual standard deviations (s) from the predicted value and deleted ($<0.2\%$ of race times). From a possible 16 race times in 11 individual events over nine competitions for male and female swimmers ($n = 3168$), a small number of race results were unavailable because there were less than 16 entrants in some events (0.9%), swimmers had been disqualified (0.3%), or semi-final results were not accessible for 400-m events in two competitions (2.0%). Race times for each event are presented as mean and between-athlete standard deviation to represent the average and typical spread over nine competitions for the finalists (Table I).

To quantify the relationship (or association) of each lap time to final time, we employed three complementary analyses: correlational analysis, within-athlete mixed linear modelling (effect of 2 standard deviation change on final time), and

Table I. Mean lap times (s) and final time (min : s) for 100- to 400-m events for male and female finalists (top eight swimmers) in nine international competitions.

		Freestyle	Backstroke	Breaststroke	Butterfly	Individual medley
Men's 100 m	Lap 1	23.58 ± 0.38	26.71 ± 0.36	28.72 ± 0.38	24.62 ± 0.31	
	Lap 2	25.64 ± 0.39	28.34 ± 0.40	32.55 ± 0.54	28.07 ± 0.51	
	Final time	**49.22 ± 0.54**	**55.05 ± 0.60**	**1:01.27 ± 0.63**	**52.69 ± 0.69**	
Women's 100 m	Lap 1	26.54 ± 0.27	30.02 ± 0.37	32.26 ± 0.51	27.68 ± 0.50	
	Lap 2	28.49 ± 0.44	31.67 ± 0.48	36.31 ± 0.54	31.39 ± 0.56	
	Final time	**55.03 ± 0.55**	**1:01.69 ± 0.68**	**1:08.58 ± 0.88**	**59.07 ± 0.85**	
Men's 200 m	Lap 1	25.33 ± 0.55	28.06 ± 0.46	30.22 ± 0.42	26.42 ± 0.41	26.33 ± 0.42
	Lap 2	27.24 ± 0.43	29.99 ± 0.45	33.70 ± 0.47	29.76 ± 0.42	30.92 ± 0.76
	Lap 1	27.74 ± 0.49	30.61 ± 0.56	34.20 ± 0.50	30.37 ± 0.55	34.88 ± 0.77
	Lap 2	27.61 ± 0.64	30.72 ± 0.66	34.67 ± 0.74	30.97 ± 0.81	28.79 ± 0.68
	Final time	**1:47.91 ± 1.62**	**1:59.37 ± 1.68**	**2:12.79 ± 1.42**	**1:57.53 ± 1.61**	**2:00.93 ± 1.36**
Women's 200 m	Lap 1	28.17 ± 0.39	31.35 ± 0.35	33.73 ± 0.59	29.25 ± 0.52	29.29 ± 0.60
	Lap 2	30.16 ± 0.29	33.14 ± 0.55	37.43 ± 0.56	32.85 ± 0.59	34.38 ± 0.83
	Lap 1	30.63 ± 0.34	33.75 ± 0.59	37.96 ± 0.68	33.56 ± 0.71	39.15 ± 1.08
	Lap 2	30.63 ± 0.34	33.74 ± 0.81	38.34 ± 0.89	34.22 ± 0.88	31.76 ± 0.80
	Final time	**1:59.41 ± 1.11**	**2:11.98 ± 1.67**	**2:27.47 ± 2.26**	**2:09.89 ± 2.26**	**2:14.58 ± 1.74**
Men's 400 m	Lap 1	55.31 ± 0.85				58.85 ± 0.96
	Lap 2	57.99 ± 0.75				1:06.54 ± 2.00
	Lap 1	58.05 ± 0.93				1:12.97 ± 1.74
	Lap 2	57.14 ± 1.21				59.54 ± 1.25
	Final time	**3:48.49 ± 3.18**				**4:17.90 ± 3.96**
Women's 400 m	Lap 1	1:00.69 ± 0.68				1:04.55 ± 1.46
	Lap 2	1:03.63 ± 0.61				1:12.58 ± 1.94
	Lap 1	1:03.73 ± 0.84				1:22.25 ± 2.33
	Lap 2	1:02.51 ± 1.24				1:04.84 ± 1.79
	Final time	**4:10.53 ± 2.87**				**4:44.22 ± 4.92**

examination of the pattern of lap times (between-athletes and within-athlete). First, we derived correlation coefficients (r) between individual 50-m or 100-m lap times and finish time. Correlations were interpreted based on Cohen's scale of magnitudes (Cohen, 1988) comprising 0.1 (small), 0.3 (moderate), and 0.5 (large), augmented (Hopkins et al., 2009) to include 0.7 (very large) and >0.9 (nearly perfect). Mean correlations between consecutive laps were compared using the paired t-statistic. The practical implication of the correlations was assessed by estimating the number of between-athlete standard deviations of change needed in a predictor variable (lap time) to increase a swimmer's ranking based on a correlated outcome measure (performance). From statistical first principles, the relationship between the change in a predictor (Δx) and outcome measure (Δy) is $\Delta y/s_y = r\Delta x/s_x$, where s_y and s_x are the standard deviation of y and x respectively, and r is the correlation coefficient. Assuming the predictor and performance scores were normally distributed for the finalists, we used this relationship to calculate changes in x (as a factor of s_x) needed to change the ranking of an athlete (based on quantiles of the outcome measure) when there are eight competitors in the final.

Second, a mixed linear model (Proc Mixed) provided estimates of the effect of change in lap time on final time, with a random effect for athlete to account for repeated measures. A change in lap time of 2 s was deemed appropriate to gauge the effect of a continuous predictor, by ensuring congruence between Cohen's threshold magnitudes for correlations and standardized differences (Hopkins et al., 2009). Two standard deviations of a normally distributed predictor also corresponds approximately to the mean separation of lower and upper tertiles (2.2 s). The threshold for the smallest worthwhile enhancement in swimming performance in international competition has previously been established as 0.4% (Pyne, Trewin, & Hopkins, 2004; Trewin, Hopkins, & Pyne, 2004). The percent effect of each lap time on final time was converted to an approximate change in swim time (seconds) to assist practical interpretation.

Finally, to examine the pattern of lap times for the finalists and semi-finalists, the mean lap times for all the swimmers (placed 1–16) were plotted for each event (between-athletes). For those swimmers competing in the same event in at least three competitions, a similar approach was used to inspect the pattern of lap times for their swims grouped as fastest, slowest, and intermediate. The mean lap times were plotted to compare the pattern of lap times of the groups in each event (within-athlete).

Results

Correlation of lap time to final time

The mean correlation for all four strokes combined shows that the highest correlations with final time were in the final 50-m lap of 100-m events and the third 50-m lap of 200-m events for finalists and semi-finalists (Table II). Each 100-m lap of 400-m freestyle had a very large correlation with final time for finalists, but the second ($r = 0.85$) and third laps ($r = 0.91$) were the highest, while the semi-finalists exhibited the highest correlation in the third lap ($r = 0.79$).

Freestyle and form strokes exhibited subtle differences in correlation of lap times to final time. The last lap had the strongest relationship with final time in all 100-m events, except men's 100-m freestyle, where both laps had the same correlation. In 200-m events, the strongest correlations were exhibited in the middle two laps of backstroke and breaststroke, the third lap in freestyle, and the third and fourth laps in butterfly and individual medley. In 200-m individual medley, the final lap (freestyle) was correlated most strongly with final time both for males and females ($r = 0.66$). However, in 400-m individual medley, where each stroke is swum for two consecutive laps, the strongest correlation with final time was the third 100-m lap for males (breaststroke; $r = 0.73$) and the fourth 100-m lap for females (freestyle; $r = 0.83$).

The relative change in lap time needed to improve an individual swimmer's placing in a race was calculated from the lap correlation. The lap with the strongest correlation to final time requires less improvement to change placing in a race. For example, a correlation of $r = 0.72$ in lap 4 in men's 200-m freestyle requires an improvement equal to approximately 0.5 of the typical between-athlete standard deviation (~0.3 s) to improve placing in a race from non-medallist (fourth) to medallist (third) position, and about 0.9 *s* (~0.6 s) to move from silver (second) to gold (first). A stronger correlation of $r = 0.89$ in lap 2 would require less improvement in that lap to move up one place to third (~0.4 *s*, ~0.2 s) or to move from second to first place (~0.7 *s*, ~0.3 s).

Effect of lap time on final time

The improvement in final time that was associated with an achievable change in lap time was quantified by modelling the effect of lap time on final time (Table III). The effect of each lap time on final time was of similar magnitude across all the strokes for male and female finalists in 100-m (~0.6–0.8%), 200-m (~0.4–0.8%), and 400-m (~0.5–0.8%) events. These effects equate to an overall improvement in final time of approximately 0.3–0.5 s in 100-m events, 0.4–1.1 s in 200-m events, and 1.3–2.0 s in 400-m freestyle. The semi-finalists demonstrated a similar pattern in 100-m (~0.7–0.9%), 200-m (~0.6–1.1%), and 400-m (~0.8–1.1%) events, equating to a possible improvement of approximately 0.4–0.6 s in the 100-m events, 0.6–1.1 s in the 200-m events, and 2.1–2.6 s in the 400-m freestyle.

Pattern of lap times

All swimmers tended to follow a similar pattern of lap times (shape of the curve) in an event. Mean times for each lap for the top 16 swimmers in men's 100-m, 200-m, and 400-m freestyle are shown in

Table II. Between-swimmer correlation of each lap time to final time for finalists and semi-finalists in 100- and 200-m events.

		Freestyle		Backstroke		Breaststroke		Butterfly		
		Men	Women	Men	Women	Men	Women	Men	Women	Mean
Finalists										
100 m	Lap 1	0.67	0.32	0.70	0.69	0.51	0.75	0.70	0.80	**0.64**
	Lap 2	0.67	0.89	0.76	0.85	0.80	0.83	0.88	0.83	**0.81**
200 m	Lap 1	0.66	0.53	0.60	0.28	0.49	0.66	0.53	0.65	**0.55**
	Lap 2	0.89	0.45	0.77	0.81	0.65	0.78	0.49	0.78	**0.70**
	Lap 3	0.81	0.70	0.84	0.87	0.63	0.91	0.85	0.90	**0.81**
	Lap 4	0.72	0.56	0.63	0.70	0.67	0.68	0.83	0.83	**0.70**
Semi-finalists										
100 m	Lap 1	0.27	0.55	0.43	0.58	0.40	0.74	0.44	0.53	**0.49**
	Lap 2	0.60	0.72	0.65	0.84	0.54	0.72	0.58	0.58	**0.65**
200 m	Lap 1	0.17	0.08	0.48	0.47	0.62	0.48	0.23	0.50	**0.38**
	Lap 2	0.33	0.47	0.67	0.68	0.76	0.62	0.51	0.49	**0.57**
	Lap 3	0.77	0.73	0.72	0.86	0.83	0.91	0.79	0.71	**0.79**
	Lap 4	0.64	0.73	0.40	0.65	0.35	0.64	0.54	0.66	**0.58**

Note: The mean correlation, in the final column, is the average lap correlation for male and female swimmers from all four strokes combined. Data are mean correlations for the swimmers placed 1–8 and 9–16 in nine competitions.

Table III. Percent effect of (2 *s*) improvement in lap time on final time (mean; ± 90% CL) for finalists and semi-finalists in 100- and 200-m events.

		Freestyle		Backstroke		Breaststroke		Butterfly		
		%	(s)	%	(s)	%	(s)	%	(s)	Mean
Finalists										
100 m	Lap 1	0.6; ± 0.1	0.3	0.8; ± 0.1	0.5	0.7; ± 0.1	0.4	0.7; ± 0.1	0.4	**0.7**
	Lap 2	0.6; ± 0.1	0.3	0.7; ± 0.1	0.4	0.7; ± 0.1	0.5	0.7; ± 0.1	0.4	**0.7**
200 m	Lap 1	0.4; ± 0.1	0.4	0.6; ± 0.2	0.7	0.5; ± 0.1	0.8	0.6; ± 0.1	0.8	**0.5**
	Lap 2	0.7; ± 0.1	0.8	0.7; ± 0.1	0.9	0.8; ± 0.1	1.1	0.7; ± 0.1	0.9	**0.7**
	Lap 3	0.7; ± 0.1	0.8	0.7; ± 0.1	0.9	0.7; ± 0.1	1.0	0.7; ± 0.1	0.9	**0.7**
	Lap 4	0.4; ± 0.1	0.4	0.4; ± 0.1	0.5	0.5 ± 0.1	0.6	0.5; ± 0.1	0.6	**0.4**
Semi-finalists										
100 m	Lap 1	0.7; ± 0.1	0.4	0.9; ± 0.1	0.5	0.8; ± 0.1	0.6	0.8; ± 0.1	0.5	**0.8**
	Lap 2	0.7; ± 0.1	0.4	0.8; ± 0.1	0.5	0.7; ± 0.1	0.5	0.8; ± 0.1	0.5	**0.7**
200 m	Lap 1	0.7; ± 0.1	0.8	1.0; ± 0.1	1.3	1.1; ± 0.1	1.6	0.9; ± 0.1	1.1	**0.9**
	Lap 2	0.8; ± 0.1	1.0	0.9; ± 0.1	1.2	0.9; ± 0.1	1.4	0.9; ± 0.1	1.1	**0.9**
	Lap 3	0.7; ± 0.1	0.8	0.9; ± 0.1	1.1	0.9; ± 0.1	1.3	0.9; ± 0.1	1.1	**0.8**
	Lap 4	0.5; ± 0.1	0.6	0.7; ± 0.1	0.9	0.8; ± 0.1	1.1	0.7; ± 0.1	0.9	**0.7**

Note: Mean effect is the average effect for male and female swimmers from all four strokes combined. The approximate improvement in final time (s) associated with a 2 *s* change in lap time is shown for each stroke. Data are mean effect for male and female swimmers placed 1–8 and 9–16 in nine competitions.

Figure 1. All 16 placed swimmers showed a similar pattern of lap times, but winners of the 100-m freestyle had a faster final lap than the other swimmers, and winners in the 200 m and 400 m generally maintained a lead through each of the intermediate laps. The pattern of lap times in 100-m events shows a faster first lap (~ 1–3 s) because of the influence of the start. In 200-m and 400-m events, a fast first lap from the dive start is followed by mainly even pacing through the middle laps, and an evenly paced or slightly faster final lap. For swimmers who competed in more than three competitions, a similar pattern of lap times was observed for their fastest, intermediate, and slowest finish times. An example, for men's 100-m, 200-m, and 400-m freestyle finalists is shown in Figure 2.

Discussion

The pattern of pacing adopted in international swimming competition was evaluated by quantifying the relationship of each lap to final time and characterizing the pattern of lap times. Overall, the lap with the strongest relationship to final time was the final lap for sprint events and the middle two laps for 200-m and 400-m events. Our modelling shows that improvements in these lap times were associated with performance enhancements that would substantially increase the likelihood of a medal in top-ranked swimmers (Pyne et al., 2004; Trewin et al., 2004). A similar pattern of lap times was adopted in each event regardless of the sex, finish position or the best and worst swims for an individual. Successful swimmers were faster through each of the laps and in final time, suggesting fitness and technique (rather than pacing strategy) need to be developed in less successful swimmers. In this investigation, we did not directly address whether the pattern of pacing was reflective of a deliberate strategy, although these combinations of lap time were the most successful in these international competitions. Collectively these outcomes confirm that improvements in specific lap times are associated with substantial gains in performance, but the overall pattern of lap times should not be changed.

Differences between sprint and middle-distance events

Taken together, the correlation of specific laps and their effect on final time indicate where the greatest improvements can be made to performance. Individuals with a faster final lap in sprint events can substantially improve their final time, with less-skilled swimmers reported to have a larger differential between first and second lap speed (Chollet, Pelayo, Delaplace, Tourny, & Sidney, 1997). The fast–slow pattern in sprint events is in agreement with that previously reported during 100-m swimming (Maglischo, 2003) and running (Tucker et al., 2006), where a reduction in speed in the second lap is tolerated to be competitive early on. This characteristic reduction in speed suggests a limited ability of the physiological processes that underpin performance to increase in pace in the latter half of short-duration events (Tucker et al., 2006). In other sprint events where resistive forces are smaller, such as cycling (de Koning et al., 1999;

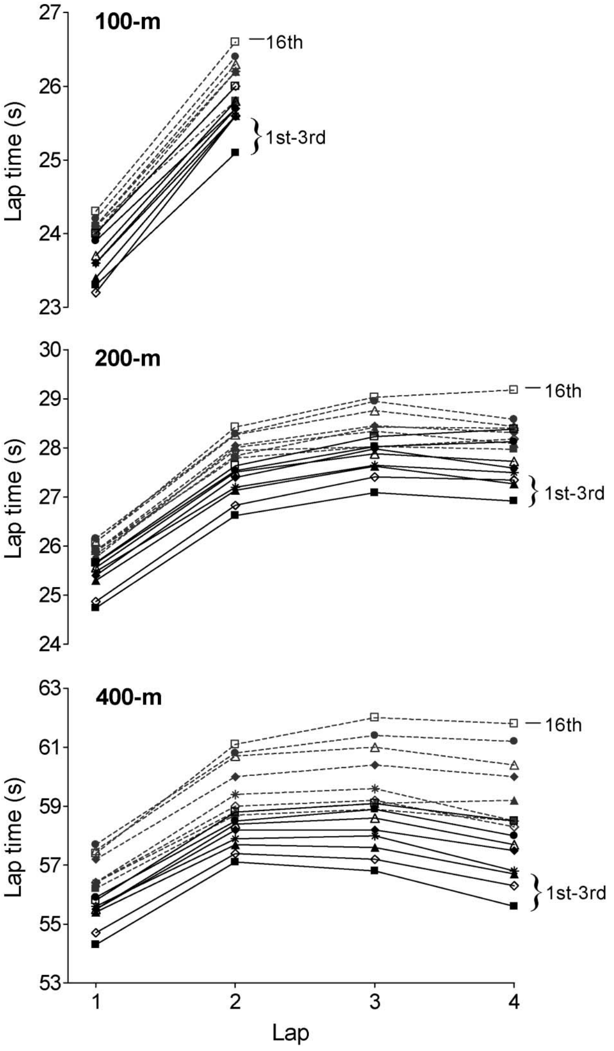

Figure 1. Mean lap time (s) for the men's 100-, 200-, and 400-m freestyle. All 16 placed swimmers show a similar pattern of lap times in each event. Each data point is a mean of nine competitions, except 9–16th for the 400-m, which is the mean of seven competitions.

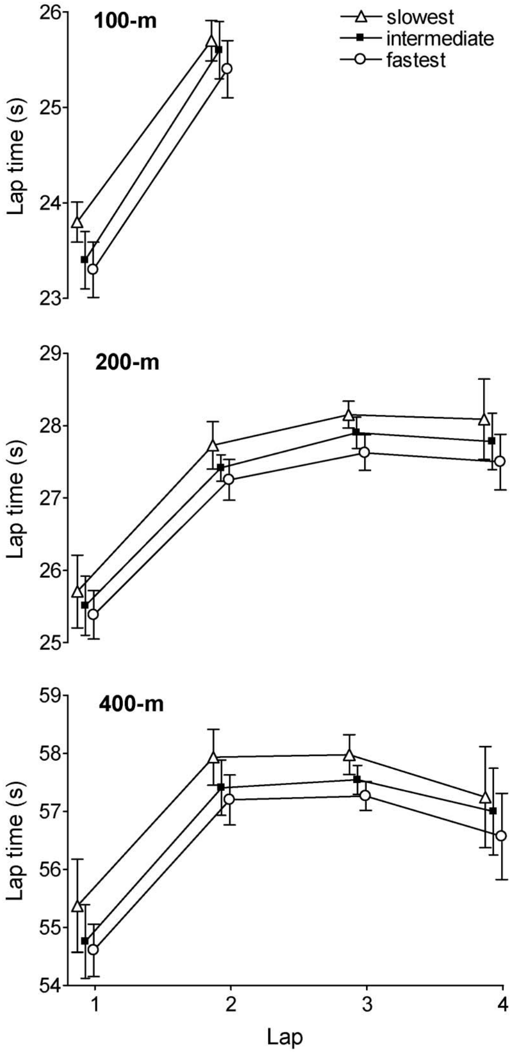

Figure 2. Mean lap time (s) for men's 100-, 200-, and 400-m freestyle finalists who competed in more than three competitions. Performances are evenly distributed into fastest, intermediate, and slowest groups for an individual swimmer and demonstrate a similar pattern of lap times for the best and worst swims. Data points are mean ± *s* and have been offset for clarity.

Foster et al., 2003) and speed skating (van Ingen Schenau, de Koning, & de Groot, 1994), an all-out strategy is considered optimal, as high speeds can be maintained even when power output is reduced. However, because of higher drag forces in swimming, a reduction in power output results in a large deceleration (Foster et al., 2003). It follows that the most successful sprint swimmers in this analysis were able to maintain swimming speed in the final lap (Chollet et al., 1997; Thompson et al., 2000; Wakayoshi et al., 1992).

On the whole, 200-m events are evenly paced and the middle laps have the strongest relationship with final time. Similarly in 400-m freestyle, the middle two laps appear to set up the race for the top swimmers. This mainly even pacing has previously been reported in 200-m swimming with the most successful swimmers starting the race at the highest speed that can be maintained for four laps, while in 400-m events a gradual build up through the middle 200–300 m before a faster finish lap has been observed (Maglischo, 2003). In other middle-distance events lasting 2–4 min, predominantly even pacing has been reported as the most successful approach for cycling and speed skating (de Koning et al., 1999; Foster et al., 1993; van Ingen Schenau et al., 1994). The observed differences between the correlation of lap times to final time in sprint (100-m) and middle-distance (200- and 400-m) events is consistent with the notion that one of the key factors determining pacing is the duration of the event.

Differences between finalists and semi-finalists, sex, and stroke

Semi-finalists exhibited smaller correlations of lap time to final time, although performance enhancements associated with a change in lap time were of the same magnitude as the finalists. The similarity in pattern of lap times for the 1st to 16th placed swimmer in international competition is comparable to that found in sprint running where the last placed runners adopted the same pacing strategy as the winners (Tucker et al., 2006). Similarly, competitive rowing crews adopt a fast start strategy regardless of finish position in 2-km races (Garland, 2005). In this study, we did not have temporal data for the laps, so our interpretation is based on differences between lap times. Successful swimmers in this study were characterized by faster lap times, which is in agreement with previous findings that swimming speed is highest in better performing swimmers who are able to maintain their speed during a race (Chollet et al., 1997; Thompson et al., 2000; Wakayoshi et al., 1992), and have faster start, turn, and finish times (Arellano et al., 1994). In the present analysis, it is not possible to ascertain if faster lap times are a consequence of faster mid-pool swimming speed that explains most of the variation in finishing time (Thompson et al., 2000), or the non-swimming components such as starts and turns (Arellano et al., 1994; Thompson et al., 2000).

The pattern of pacing was largely similar across each of the events for male and female swimmers. The exception is 100-m freestyle, where the correlation of lap times was identical in the first and second lap for males. Notably, the winners of the men's freestyle had a slower first lap than the second placed swimmers, but were differentiated by a smaller drop off (differential between first and second lap time) in the final lap. In contrast, women's 100-m freestyle winners were faster in both laps. We interpret these findings as the need for freestyle swimmers to have a fast start to stay in contention and maintain second-lap speed for success in sprint events. Start time has previously been reported to be no different for swimmers of varying standard (Wakayoshi et al., 1992), but another study of male breaststroke swimmers found that start times were related to finish time (Thompson et al., 2000).

There were some variations in the magnitudes of correlations between the different strokes at each distance. In the 200-m butterfly, the third and fourth laps had a stronger relationship with final time than the middle laps. This difference is likely related to butterfly being a less economical and streamlined stroke. To maintain stroke length in butterfly, the power output of the arms must be increased, resulting in local muscle fatigue (Chollet, Pelayo, Tourny, & Sidney, 1996). In 200-m butterfly, more of a balance is required between increasing arm power and maintaining elevation of the hips to reduce drag and improve streamlining (Chollet et al., 1996). Similarly, in 200-m breaststroke, a positive pacing strategy is observed (Thompson et al., 2000) with a reduction in lap speed in the latter half of the race associated with fatigue from a greater reliance on leg propulsion in this event (Maglischo, 2003).

Elite swimmers need a progressive improvement in performance time (~1%) from heats to final in a competition, plus an additional enhancement of more than about 0.4% to increase the likelihood of a medal (Pyne et al., 2004; Trewin et al., 2004). Taking into account the precision of the estimates (90% confidence limits, ±0.1%), improvements in specific lap times are associated with clear substantial improvements in final time for 100- to 400-m swimming events. The laps that are most strongly correlated with final time need a smaller change in lap time to alter placing in a race. Elite coaches and swimmers seeking improvements in lap time need to identify if changes in fitness or technique (start, turn or stroke technique) can be addressed.

Analysis of pacing and performance

We employed a novel analysis combining correlations and mixed linear modelling to quantify relationships between lap time and performance enhancement in international swimmers. Interpreting the correlations in relation to the improvement in final time is a practical means of instructing the coach where improvements in lap speed should be focused. This modelling approach combines between- and within-swimmer effects. The between-swimmer effect quantifies the magnitude of improvement required by an individual swimmer to increase his or her chances of a medal. The within-swimmer effect indicates the magnitude of improvement in final time an individual swimmer can anticipate. Taken together, these effects give an estimate of the change needed in a particular lap to improve placing in a race, and the magnitude of performance gains modelled for an individual swimmer. This approach could be useful for applied research and provides a quantitative framework to evaluate performance in other sports.

Given the long-standing debate on the suitability of correlational analysis to characterize the degree of association in dependent and independent measures (Aldrich, 1995; Hopkins et al., 2009), we employed three separate criteria to evaluate the relationship between lap time and final time. One limitation of the correlations in this analysis is that each lap time contributes to final race time.

As such, these variables are not independent and the resultant correlations are large. However, we interpreted the differences between the mean correlations to identify the laps with the strongest relative relationship to performance. The lack of temporal lap data limits to some degree the interpretation of the correlations in the first lap. Lower correlations in the first lap could reflect larger individual variation in the quality of the dive start; however, the pattern of correlations is similar for the semi-finalists and finalists and in backstroke events that start in the water. Future research using this modelling approach should incorporate temporal race data to evaluate the relationship of the swimming and non-swimming components to performance, and provide further information to the coach on where improvements within each lap could be made.

In this study, we have modelled the pattern of pacing adopted by elite swimmers in international competition and determined improvements in performance associated with an achievable change in lap time. The magnitude of these improvements are similar ($\sim 1\%$) to an energy flow model used in track cycling (de Koning et al., 1999), and the statistically non-significant (0.8%) improvement in final time observed in a positively (102%) paced breaststroke trial (Thompson, MacLaren, Lees, & Atkinson, 2004). Coaches and sport scientists should look to address improvements in fitness or technique in the laps that will result in the greatest performance gain; however, the similarity in pattern of lap times for the fastest and slowest swims implies that the overall pattern of lap times should be maintained. Further experimental evaluation of small manipulations in the pattern of pacing is warranted to confirm the magnitude of potential gains in final time and improvements in placing for an individual swimmer.

Conclusion

Substantial gains in swimming performance are possible by improving the laps that have the strongest relationship with final time: the final lap in sprints and the middle two laps of 200- to 400-m events. However, the similarity in pattern of lap times for the top 16 swimmers in each event and the best and worst swims for an individual swimmer, suggests any improvements in lap time should be made without disrupting the overall pattern of pacing.

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