Pacing profiles and competitive performance of elite female 400-m freestyle swimmers

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Running head: Pacing strategy and competitive performance

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ABSTRACT

Pacing can impact competitive endurance performance. The objective of this study was to determine relationships between pacing parameters and competitive performance of elite female 400-m freestyle swimmers. Publicly available websites provided 50-m split and final times for 381 swims of 20 elite female swimmers in over 150 national and international competitions between 2004 and 2016. Most pacing profiles displayed negative quadratic curvature, with the fifth of the eight laps being the median slowest. The mean times for the first and last laps were faster than predicted by the quadratic by 5.6% and 1.9% respectively, and lap-to-lap variability was 0.65%. Scatter plots of each swimmer's final time often showed no obvious relationships with their pacing parameters, suggesting that swimmers compensated for changes in one parameter with changes in another. However, some plots showed a U shape or linear trend that allowed tentative identification of optimum values of the pacing parameters. In these plots it was apparent that about half the swimmers might make small to moderate improvements (up to ~1%) by changing the slope or curvature of their pacing profile or by changing time in the first or last laps. This approach for characterizing pacing profiles to identify possible improvements might be appropriate to assess pacing in other sports with multiple laps, frequent competitions and relatively constant environmental conditions.

Key Words: *pace, lap time, competition, improvement, variability*

INTRODUCTION

It is widely recognized that an athlete's pacing strategy, or how the athlete distributes and manage power output throughout a race, can have a substantial impact on performance (1,11). The effect of different pacing strategies on performance has been considered broadly in several sports, including cycling (13,4,5,7), running (26,12,29,3,6,16,30) speed skating (17,27) and rowing (14,23,15).

Olympic distance swimming (from 400-m to 1500-m) is a good sport to study pacing, owing to the large number of laps and the nearly constant environmental conditions between venues. However, race analysis in international swimming competitions has focused on starts, turns and stroke biomechanics (e.g., 37,36,38,39), and only a few authors have characterized pacing profiles in swimming (9,22,33). Researchers have already reported that the speed profile of 800- and 1500-m freestyle swimmers is generally parabolic (9), with U-shaped or reverse-J variants (1). Others observed that swimmers in the 400-m events adopt either a similar profile or another one, where after a faster first 50-m lap the remaining laps are swum evenly (fast-start-even) (22,33). We have shown that the pacing profile of 800- and 1500-m swimmers can be characterized with slope and curvature parameters of a quadratic (20,21). Additional parameters were required to specify the time for the first and last lap, which were swum faster than predicted by the quadratic. Random and systematic deviations of the time of each of the other laps from the quadratic curve were also summarized with the standard error of estimate. Ours are the only studies in which authors have explicitly addressed the relationship between changes in pacing parameters and competitive performance.

There were insufficient swims in our study of 800-m female swimmers to establish clear relationships between performance time and each pacing parameter (20), but our further research on 1500-m male swimmers, with more swims for each swimmer, showed that almost half the swimmers could make some improvement in their mean performance by changing values of pacing parameter (21). The 400-m freestyle swimming event is one of the most popular, with many female world records broken in last few years, but the effect of pacing parameters on performance time in this event is unknown. Thus the main aim of the present study was to characterize pacing and identify values of its parameters for optimal performance in 400-m freestyle female swimmers.

METHODS

Experimental Approach to the Problem

In our previous 1500-m male swimmers study we found that changing of pacing parameters was a potential avenue to enhance competitive performance for more than half of analyzed swimmers. Unfortunately the world record on that distance was broken only three times during last 15 years, while the world record in the female 400-m freestyle swimming events was broken nine times in last 10 years, whereas a record for the male 400-m swimming was broken once. We therefore opted to study females 400-m freestyle swimming, because change in pacing might have account for some of the improvements. The observational study, involving liner modelling of lap time, was the same as in our two previous studies (20,21).

Subjects and Events

Official 50-m lap and race times for 400-m female freestyle swimmers in international and national competitions were downloaded in September 2016 from the swimrankings.net site. Informed consent and ethical approval were not required, as all data were available in the public domain but our study was approved by the Scientific Board at Institute of Sport – National Research Institute. To focus on swims where the athletes were strongly motivated to perform at their best or near best, each swimmer's last swim in a given competition was included in the analysis, along with their fastest swim, if it occurred in a heat. The final dataset consisted of final and lap times for 381 swims of 20 elite female swimmers in 216 competitions between 1st of January 2004 and 31st of August 2016. Each swimmer provided between 13 to 28 swims (21.4 ± 4.9, mean ± SD). The swimmers' minimum age ranged from 15.0 to 23.1 years, while their maximum age ranged from 19.1 to 29.1 (18.3± 2.2 and 24.5 ± 2.6; mean ± SD, respectively) and they were in the top 24 of the best female 400-m freestylers based on FINA world ranking between 2004 and the Rio Olympics in 2016. We decided to include swimmers whose personal best time was shorter than 4:03.85, as it was the current world record in 2004. Four swimmers from 11th, 15th, 19th and 23th place in FINA world ranking were excluded from the final dataset, owing to a small number of swims (<8 races) with lap times for every 50 m. The remaining swimmers had at least 13 swims with 50-m lap times for all swims. Of the 381 analyzed swims, 84 were from Olympic Games and World Championships, 41 were from European Championships, Pan-Pacific Championships or Commonwealth Games, seven were from universiades, 189 were from international meetings including Olympic Trials, and 61 were from national championships.

Procedures

We have shown previously (20) that the pacing profile of each swim can be characterized with five parameters derived by multiple linear regression: linear and quadratic coefficients for the effect of lap number, reductions from the predicted time for the first and last laps, and the residual standard error of the estimate summarizing random and systematic deviations from the model (Figure 1). The linear coefficient represents the predicted last-lap time minus the predicted first-lap time; the quadratic coefficient was expressed as the amount of curvature (the quadratic contribution to the predicted middle minus first or last lap, or 0.25

times the usual quadratic coefficient). The log of lap time was the dependent variable, and parameters were back-transformed to percent units (Figure 1). All analyses were performed both for all swims of each swimmer and for the best swim of each swimmer in dataset.

Figure 1 about here

Scatter plots of final time versus each pacing parameter for each swimmer were used to evaluate the optimal value of the pacing parameter for best performance. Our previous study (21) showed that optimal value for a given parameter would be revealed by a quadratic trend in the scatter plot; therefore a quadratic was fitted to the points in each plot. When the quadratic had a minimum within the range of the values of the parameter, we estimated the difference between the mean and the value at the minimum, along with the corresponding difference in performance (illustrated in Figure 2).

Figure 2 about here

Some scatter plots lots did not show a turning-point minimum within the range of parameter values, but there was a reasonably clear trend towards an optimum at one or other end of the range of values (Figure 3A), allowing differences between the mean and optimum to be estimated. Finally some quadratics showed a maximum turning point with no clear optimum at either end of the range (Figure 3B).

Figure 3 about here

Statistical Analyses

Simple statistics for final time and the pacing parameters were derived from a linear mixed model. Analyses were performed with Proc Mixed in the Statistical Analysis System (version 9.4, SAS Institute, Cary NC). Final time was log transformed for its analysis, but pacing parameters were already log transformed. Standard deviations and effects from the mixed model were back-transformed to percent units. A fixed effect estimated linear trend in the mean over the years of the competitions, expressed as the change per decade, while random effects in the model accounted for differences between athlete means and; for variability within swimmers between years; and between calendar months. The residual estimated within-swimmer variability within calendar months. Variances of the random effects were combined to calculate the between-athlete standard deviation across all competitions and to estimate intraclass correlation coefficients (ICCs) representing the correlations of the swimmers' values between competitions less than 5 wk. Confidence limits for the ICCs were generated with a bootstrap method, in which the independent standard errors of the variances provided by the mixed model were combined with random normal deviates to generate bootstrap samples. Reliability analyses were also performed using change scores between consecutive competitions as the dependent variable in a mixed model that produced separate estimates for variation between competitions separated by <5, 5 to 49, and 50 to 88 wk.

Owing to lack of any quantifiable relationship between the pacing parameters and swimming performance, the means and trends in each pacing parameter were evaluated using magnitude based inference and standardization, with thresholds for small, moderate and large given by 0.2, 0.6 and 1.2, of the between-swimmer standard deviation of the parameter, respectively. Magnitude thresholds for the decade trend in final time were given by 0.3, 0.9 and 1.6 of the within-swimmer within-month standard deviation of final time, as small, moderate, large effects, respectively. This latter refers to chances of winning a medal for change in top athlete's competition time or distance (18). Intraclass correlations for the pacing parameters were interpreted with the usual scale for Pearson correlations (0.1, 0.3, 0.5, 0.7 and 0.9 for low, moderate, high, very high, and nearly perfect, respectively), while the magnitude of the ICC for final time was evaluated with the thresholds of Smith and Hopkins (34); 0.14, 0.36, 0.54, 0.69, and 0.83, respectively). Finally scatter plots of final time versus each parameter for each swimmer were inspected and evaluated qualitatively to find the value of the parameter for optimal performance (see Procedures section).

RESULTS

Table 1 presents the simple and reliability statistics for final time and the pacing parameters. The mean values of the linear and quadratic parameter represent a swim with negative curvature, similar in shape to that shown in Figure 1. The fifth lap was the median slowest for the individual swims showing negative curvature (85% of 381 swims). Relative to their between-swimmer standard deviations, the linear and quadratic coefficients were moderate and clear (likely substantial). Mean times for the first and last lap were shorter than the time predicted from each swimmer's quadratic profile, the differences being extremely large and moderate, both clear.

Table 1 about here

The linear improvement in final time over a decade was clear and moderate, while the trends in other parameters represented clear trivial reductions in first-lap and last-lap time. Lap-to-lap variability (error of the estimate) showed also trivial but unclear reduction over a decade. Race-to-race variability (represented by within-swimmer SD) from the analysis of change scores for final time showed an expected increase with 5-49 wk between competitions compared with <5 wk, although competitions separated by 50-88 weeks (usually Olympic or Continental/World championships) showed an intermediate value. Race-to-race variability for pacing parameters did not appear to change in any consistent way and represented similar SD, although values of race-to-race variability for the first-lap time and linear parameter in competitions separated by >50 weeks were the biggest.

The within-month race-to-race variability from the model used to estimate ICCs was similar (0.73; ×/÷1.16%) to that derived from the analysis of change scores (0.71; ×/÷1.14% for competitions held in less than 5 weeks; 0.81; ×/÷1.08% for competitions held between 5-49 weeks; and 0.66; ×/÷1.30% for longer period between competitions, up to 88 weeks) . Only the ICC for final time represented a high correlation, according to the thresholds of Smith and Hopkins (34), whereas correlations for pacing parameters were low.

In the analysis of the best swims of each swimmer, the profiles of the second through seventh laps all represented a linear small reduction in pace with negative quadratic curvature and with the fifth lap being the median slowest. The standard deviations for the linear and quadratic parameter show that individual profiles could vary substantially from positive to negative in slope and curvature. In her best swim, the best swimmer (Kathleen Ledecky, who broke three 400-m world records in last three years) had the most curvature (16%, expressed as the "depth" of the quadratic parameter: the contribution to the predicted middle minus the predicted first or last lap), the slowest first lap parameter (-3.3%) and the lowest lap-to-lap variability (0.20%) of all her swims. Her pacing parameters were similar to those of previous world record holders (Pellegrini and Manadou) on average and in their best swims: slower first lap, more curvature and less lap-to-lap variability in comparison with less successful swimmers.

There were at best only weak relationships between each parameter and final time. However, visual inspection of scatter plots of final time against each pacing parameter for each swimmer revealed some U shapes or linear trends, allowing tentative identification of optimum values of the pacing parameters (as exemplified in Figure 2). From these plots we determined that about half the swimmers might make some improvements in performance by changing pacing parameters (Table 2), because the optimum value of the parameter was substantially different from their mean value. Moderate improvements might be made by changing the curvature of their pacing profile, and small to moderate improvements might also be possible by swimming slower or faster in the first and last laps by ~1.0%. Only two swimmers could make a substantial improvement by reducing their lap-to-lap variability.

Table 2 about here

DISCUSSION

We showed previously that linear modeling is a potentially useful approach to characterize pacing profiles of 800-m and 1500-m swimmers (20,21), and the approach appears to have been successful with these 400-m swimmers. The shape of the pacing profiles was parabolic, which was generally similar to profiles for this distance described previously by other researchers (22,33) and for longer distances in our previous studies (20,21). First and last laps were swum faster than predicted by the quadratics, reflecting the effects of the dive start and the sprint for the finish. The percent reductions in time of the first and last laps were smaller than for the longer distances in our previous studies, presumably because the speed of the dive start and sprint finish represent smaller percents of the faster pace of the 400-m race.

Previous researchers (28,8,2) have reported gradual improvements in swimming performance greater than our estimate of 0.8% per decade. In our comparable studies of 800-m female and 1500-m male swimmers, the improvements were also greater (1.1% and 2.1% respectively). The percent changes in the first and last laps were trivial (unclear and likely, respectively) and could not contribute directly to the percent improvement in final time, so the small improvement in final time must have been due to an increase in swimming speed, as reported by Mytton et al. and Robertson et al. (31,25). The 10-year linear trend for the quadratic parameter showed that swimmers generally lost curvature of pacing profile, but surprisingly the slope represented by the linear parameter increased over the decade. Evidently, swimmers are now opting to go faster from the outset of the race and gradually incur fatigue, although they still speed up a little for the last lap.

The race-to-race variability for final time of 400-m swimmers was similar to that observed in our study of 800-m female swimmers (20) but overall a little less than the ~1.0% observed in previous studies (31,8,2,24); the difference can be explained by the generally lower level of performance of swimmers in those studies. The observed substantial reduction in race-to-race variability for competitions one year apart, in comparison to races separated by 5 to 49 weeks, was also similar to what we observed in our previous study of 800-m female swimmers (20), presumably reflecting greater consistency when swimmers did not compete during the year between important events (e.g., Olympic or World Championships).

The intraclass correlations of the pacing parameters ranged from low to high. Our findings are generally consistent with those of Skorski et al. (33), although our pacing parameters are not strictly comparable. The least consistent parameter (lowest ICC) was the error of the estimate, which indicates that there is a fundamental variability in lap-to-lap time that differs little between these top swimmers.

Analysis of the pacing parameters of the best swims showed that the lap-to-lap variability was the lowest for the best swims of the record holders, who also displayed slower first and faster last laps. Mytton at al. (25) also reported that in 400-m freestyle swimming, the best strategy for top swimmers includes a relatively slower first lap and faster last lap, with low lap-to-lap variability.

Changes in the pacing profile may lead to performance enhancement, hence the main aim of present study: to characterize pacing profile with a sufficient number of swims for each swimmer to allow for identification of optimum values of the parameters. We found that about half the swimmers might improve performance by changing the first- or last-lap parameter by ~1%. The change in performance due directly to the change in the first or last lap time itself would be negligible, so the enhancements would be associated with faster swimming in the other laps. Some authors found that slowing or speeding up the first lap of 400-m swimmers was unsuccessful on average, but that some swimmers might benefit (32,33). We also showed that about one-third of swimmers might obtain moderate improvement by changing the slope and curvature parameters. The fact that Kathleen Ledecky's best swim showed extreme quadratic curvature along with minimum lap-to-lap variability is consistent with the possibility that there is an optimum profile for each swimmer that differs considerably between swimmers, perhaps dictated by contributions of aerobic and anaerobic power.

The proportions of swimmers who could improve were smaller than in our 1500-m study, probably because pacing must become less important as the duration of the event decreases and the intensity approaches maximal effort throughout the race. We would expect similar findings with 400-m freestyle male swimmers.

CONCLUSIONS AND PRACTICAL APPLICATION

We have used straightforward linear modeling to characterize pacing of 400-m freestyle female swimmers with parameters derived from analysis of the lap times. Scatter plots of performance time vs each pacing parameter showed that some swimmers might improve their mean performance by changing values of some parameters, although the proportion of swimmers who could make such improvements was smaller than in longer swimming distances. Our method might also be useful for coaches in other sports with multiple laps or splits and relatively constant environmental conditions, such as running, cycling, speed skating, kayaking or rowing. However, data from at least 20 competitions will be needed to establish relationships between pacing parameters and performance, and to identify a potentially optimum pacing strategy. Once identified, the strategy would need to be rehearsed in time trials or minor competitions; it would not be improved by strength or conditioning exercise, but obviously such exercise could also improve performance by decreasing lap time throughout a race.

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FIGURE CAPTION

Figure 1. Lap time and lap number for a single swim (the fastest in the data set – current world record) illustrating the parameters characterizing the pacing profile.

Figure 2. An example of a plot of final time versus first-lap parameter (left section). The mean of the swimmer's all final times is rescaled to a mean of zero. The curve is best-fitting quadratics. Long dashed line is at the mean value of the first-lap parameter; short is at the optimal value of the parameter. Right section is enlargement of middle part of the plot, illustrating the method of identifying the optimal value of the parameter and the possible improvement in final time.

Figure 3. Two further examples of plots of final time versus value of pacing parameters for two swimmers. The dashed line are at the mean value of the parameters. Left-hand figure (A) illustrates optimum with no clear turning point. Right-hand figure (B) illustrates no optimum.

Table 1. Statistics from reliability analyses of 400-m race time and pacing parameters derived from the eight 50-m laps of 360 swims by 20 elite female swimmers. All data are percents, with the exception of race-to-race time (weeks), mean race time (s), and intraclass correlations.

	Race-to-race time (wk)	Final time	Pacing parameters: First lap	Last lap	Linear parameter[a]	Quadratic parameter[b]	Error of the estimate
Mean[c]	-	245 s	-5.7	-2.0	2.0	-1.3	0.65
Calendar linear trend; 90%CL	-	-0.81; ±0.45**	-0.14; ±0.49	-0.03; ±0.60	1.42; ±1.07*	0.58; ±0.61*	-0.00; ±0.11
Between-swimmer SD[d]	-	1.2	1.4	1.8	2.9	1.6	0.33
Within-swimmer SD[e]	<5 (n=83)	0.71	1.1	1.6	2.2	1.3	0.31
	5-49 (n=256)	0.81	1.2	1.4	2.5	1.4	0.31
	50-88 (n=21)	0.66	1.6	1.4	2.9	1.4	0.37
Race-to-race ICC; 90%CL	<5	0.63; ±0.13 high	0.32; ±0.21 small	0.24; ±0.19 low	0.38; ±0.19 small	0.31; ±0.19 small	0.16; ±0.20 low

90%CL: 90% confidence limits.

*small, likely substantial; **moderate, very likely substantial; trends of first lap and last lap were trivial clear, error of estimate was trivial unclear.

[a]Predicted last-lap time minus predicted first-lap time.

[b]Expressed as the quadratic contribution to the predicted middle minus first (or last) lap.

[c]Predicted on 13 August 2016 (middle of Rio Olympics). 90%CL = ~±0.20 ×/÷ (between-swimmer SD). Means of pacing parameters were all clear; for magnitudes see text.

[d]The SD of all swimmers' values, after adjustment for the linear trend; 90%CL all ~×/÷1.2.

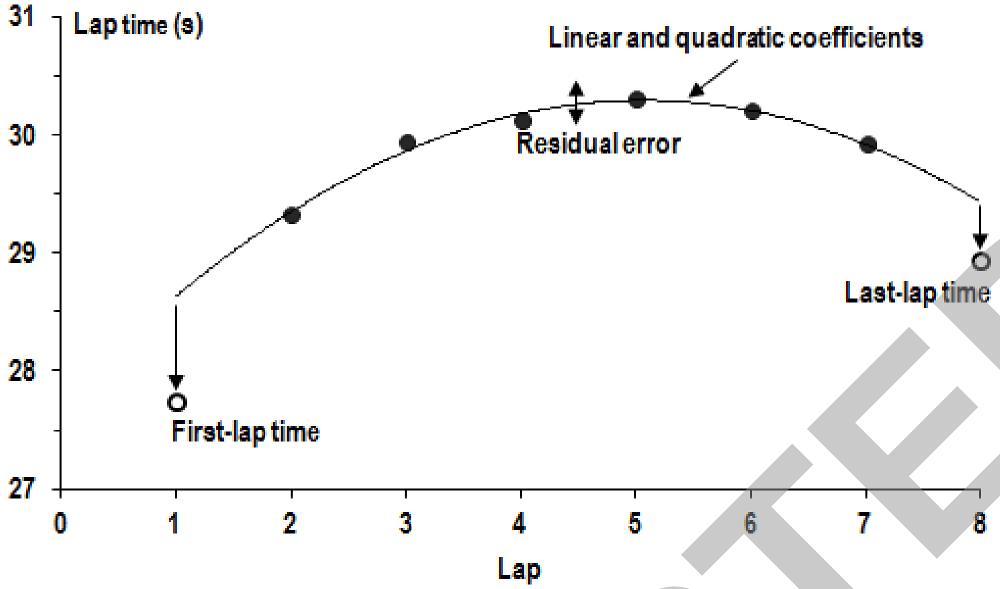
[e]Number of change scores contributing to the estimates of within-swimmer SD is shown in parentheses. 90%CL of SD are ×/÷1.14 (<5 weeks), ×/÷1.08(5-49 weeks), ×/÷1.30 (50-88 weeks).

Table 2. Pacing parameters of all 400-m swimmers and of a sub-group whose mean values of the parameters were not optimal. Also shown for the sub-group are the optimum values and the difference (improvement) in final time between the mean and optimal values of each parameter. Data are either mean ± SD or proportions, all in percent units.

	Linear parameter	Quadratic parameter	First lap	Last lap	Error of the estimate
Means of all swimmers (n=20)	1.4 ± 1.4	-1.6 ± 0.8	-5.8 ± 0.7	-2.0 ± 1.0	0.64 ± 0.12
Means of sub-group with sub-optimal means	2.0 ± 2.3	-2.4 ± 0.9	-5.7 ± 0.7	-1.6 ± 1.1	0.66 ± 0.01
Optimal values of the sub-group	2.1 ± 3.3	-0.5 ± 1.4	-6.1± 1.7	-0.7 ± 0.9	0.35 ± 0.07
Possible improvement in final time	1.1 ± 0.5	1.0 ± 0.5	0.7 ± 0.4	0.8 ± 0.3	1.3 ± 1.1
Proportion of swimmers in the sub-group	25	20	35	25	10

Parameters were derived from the 8 50-m lap times of each of 360 swims.

Figure 1.



Lap time (s)
31
30
29
28
27
Linear and quadratic coefficients
Residual error
Last-lap time
First-lap time
0
1
2
3
4
5
6
7
8
Lap

Figure 2.

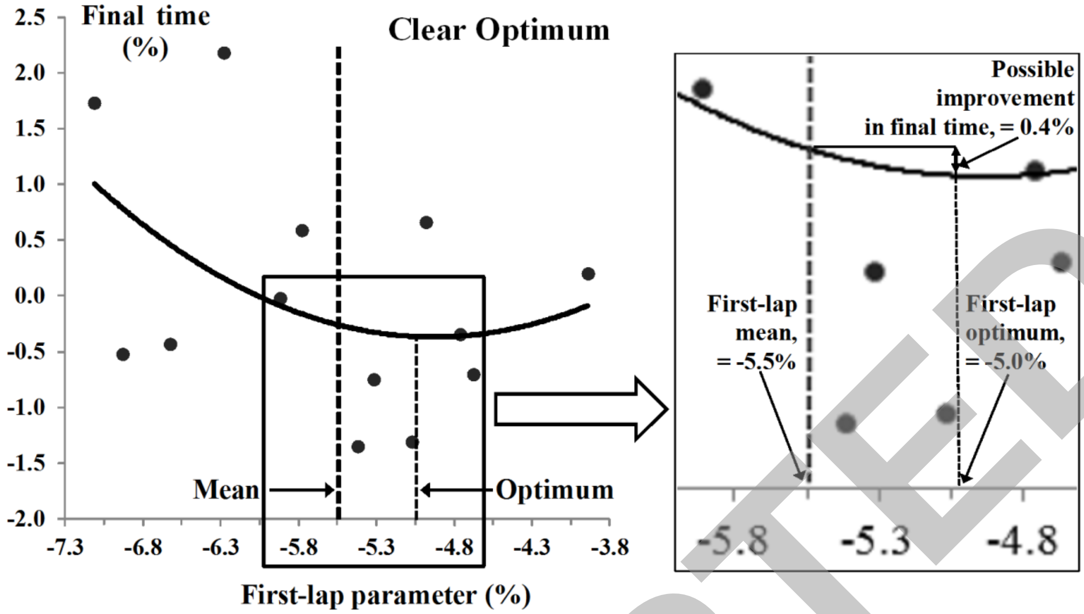
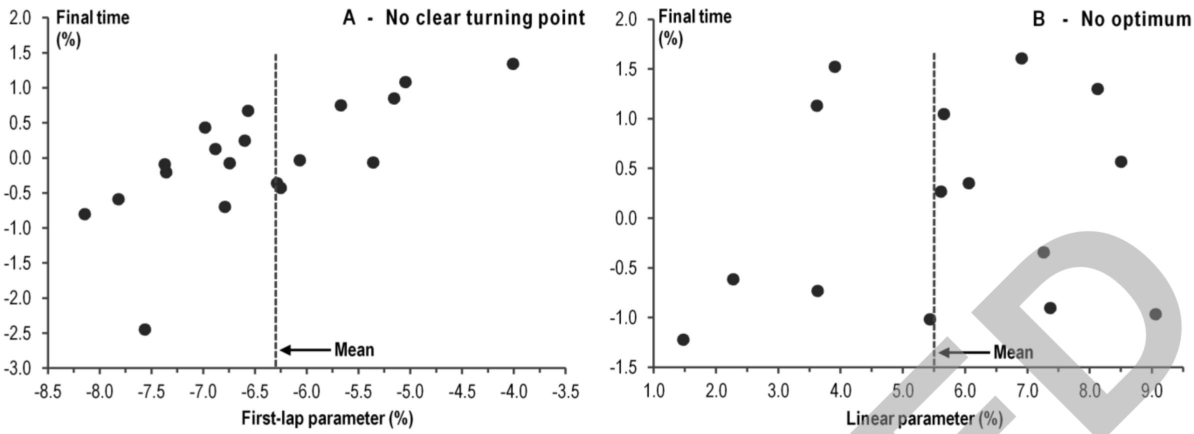

Final time (%)
Clear Optimum
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
Mean
Optimum
-7.3
-6.8
-6.3
-5.8
-5.3
-4.8
-4.3
-3.8
First-lap parameter (%)
Possible improvement in final time, = 0.4%
First-lap mean, = -5.5%
First-lap optimum, = -5.0%
-5.8
-5.3
-4.8

Figure 3.


Final time (%)
A - No clear turning point
Mean
First-lap parameter (%)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-8.5
-8.0
-7.5
-7.0
-6.5
-6.0
-5.5
-5.0
-4.5
-4.0
-3.5
Final time (%)
B - No optimum
Mean
Linear parameter (%)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0