A MODEL OF SWIMMING ECONOMY DURING INCREMENTAL EXERCISE

Gregory Wells[1], James Duffin[2], and Michael Plyley[3]
[1]Graduate Department of Exercise Sciences, [2]Departments of Physiology and Anesthesia, and [3]Faculty of Physical Education and Health. University of Toronto, Toronto, Ontario, Canada

The responses of swimming economy (distance stroke-' (DPS) and stroke rate (SR)) to incremental exercise were examined in 20 highly trained competitive swimmers to derive parameter estimates to model swimming economy during incremental exercise. As the swimmer's velocity increased, DPS was first steady at a maximal value, and then decreased linearly beyond a breakpoint. Conversely, we observed a constant linear increase in SR that did not exhibit a breakpoint or steady state. We defined the maximal DPS as DPS_{max} (m·stroke^{-1}), the breakpoint as $DPS_{threshold}$ (m·stroke^{-1}), and the linear decrease as DPS_{dec} (m·stroke^{-1}·velocity^{-1}). These results were incorporated into a two segment linear fit of the individual responses. The SR response was described by a regression line and was defined as SR_{inc} (strokes·min^{-1}·velocity^{-1}).

KEY **WORDS:** swimming economy, technical efficiency, training, modelling performance

INTRODUCTION: The concept of swimming economy (swimming velocity is the product of distance travelled per stroke and stroke rate) was first published by Craig and Pendergast (1979). Analysis of swimming economy parameters has been performed on elite athletes during competition (Craig, et al. 1985; Chengalur & Brown, 1992). This research has shown that velocities are achieved by using unique combinations of distance per stroke and stroke rate. Research has also indicated that improvements in velocity over the course of a season (Hay and Guimaraes, 1983) and in Olympic results between 1976, 1984, and 1988 (Craig, et al. 1985; Chengalur & Brown, 1992) occurred almost exclusively due to corresponding improvement in distance per stroke. More recently Wakayoshi et al. (1995) presented evidence describing the relationship between velocity and distance stroke-'. They found that high performance swimmers had a greater distance stroke-' than lower performance swimmers at a given velocity. Given the importance of swimming economy as a determinant of performance, it is important that coaches and researchers be able to easily and accurately evaluate changes in swimming economy parameters. Thus, the purpose of this study was to develop a model of swimming economy response to incremental exercise that could be used to measure a swimmer's technical efficiency.

METHODS: Sample Characteristics. The athlete group consisted of 20 highly trained competitive swimmers (11 females and 9 males) from four swim clubs in the Greater Toronto Area. These athletes ranged in age from 15 to 22, with a mean of 16.9 ± 2.0 years (Table 1). All swimmers had achieved a performance within 5% of Canadian National Championship qualification times.

Data Collection. Swimming tests were conducted in a long course (50 m) pool. The participants performed the swimming test using the freestyle stroke. Each swim test consisted of a set of progressive effort 5 x 200 m swims followed by a maximal effort 1 x 150 m freestyle swim. The 200 m swims were targeted at speeds that resulted in heart rates within ± 10 b.m^{-1} of 140, 150, 160, 170, and 180 b.m^{-1} (Treffene, 1980). The final times, the number of strokes taken on the third length and post-exercise heart rates for were recorded.

Data Analysis. The data (velocity, distance per stroke, stroke rate, and heart rate) from each 5x200 m, 1x150 m tests were analyzed graphically to determine several parameters of swimming economy. The data analysis was accomplished using a spreadsheet (Microsoft Excel) specifically designed for this purpose. Curve fitting was accomplished using weighted least squares regression analysis. The R^2 values for both distance per stroke vs. velocity and stroke rate vs. velocity plots are reported in Table 1. Both distance per stroke and stroke rate data were plotted vs. velocity. The distance per stroke data exhibited a biphasic response, and as such was analyzed by fitting a model composed of two intersecting linear segments. The first segment was a horizontal straight (i.e., indicative of a maintained distance per stroke at a maximal value. The second segment was a straight line that decreased in a linear fashion. The intersection of the two lines yields a breakpoint. Figure 1 shows an example of this fit using a commercial fitting program (Sigma Plot, SPSS Inc.) that simultaneously calculates the maximal value, the breakpoint and the slope of the decrease in distance per stroke as velocity increases. The stroke rate vs. velocity data exhibited a steady increase, and as such were analyzed by fitting the data with a linear regression line. From these fitting procedures, estimates for the maximal distance per stroke (DPS), the threshold beyond which distance per stroke begins to decrease ($DPS_{threshold}$), the rate at which distance per stroke decreases as velocity increases (DPS_{dec}), and also the rate at which stroke rate increases as velocity increases (SR_{inc}).

RESULTS: The results of the swimming test varied slightly between subjects. Table 1 presents the results for each swimmer. The results of the swimming test and analysis for a representative subject are presented in Figure 1.

Table **1** Subject Characteristics and Swimming Test Results*

Subject	Age	Sex	Event	DPSmax	DPSdec	DPSthr	Srinc	DPS R^2	SR R^2
1	17	F	Sprint	1.19	-1.07	1.07	98.74	0.81	0.97
2	16	F	Distance	1.43	-1.14	1.22	95.08	0.99	0.97
3	19	F	Sprint	1.53	-0.95	1.19	87.43	0.97	1.00
4	22	M	Distance	1.45	-0.96	1.44	83.42	0.96	0.98
5	15	M	Sprint	1.56	-1.46	1.18	46.28	1.00	0.97
6	16	F	Distance	1.14	-0.33	1.38	63.06	0.69	0.97
7	21	F	Sprint	1.28	-0.98	1.31	75.32	0.92	0.96
8	15	M	Distance	1.47	-1.58	1.24	103.84	0.93	0.94
9	18	M	Sprint	1.56	-1.21	1.37	70.92	1.00	0.96
10	15	F	Distance	1.35	-1.11	1.30	57.11	0.78	0.94
11	16	M	Distance	1.28	-0.71	1.30	89.52	0.90	0.97
12	16	F	Sprint	1.29	-0.28	1.16	63.49	0.66	0.97
13	17	F	Sprint	1.39	-1.26	1.14	93.06	0.95	0.98
14	18	F	Distance	1.22	-0.73	1.13	87.12	0.95	0.98
15	14	F	Distance	1.25	-0.64	1.16	79.53	0.72	0.97
16	15	F	Distance	1.33	-0.92	1.03	99.96	0.95	0.99
17	18	M	Sprint	1.67	-1.05	1.21	81.69	0.95	0.98
18	17	M	Distance	1.43	-0.89	1.32	95.89	0.98	1.00
19	17	M	Sprint	1.79	-0.83	1.37	67.10	0.87	0.90
20	16	M	Distance	1.26	-1.00	1.36	84.54	0.76	0.98
Mean	16.90			1.39	-0.95	1.25	81.15	0.89	0.97
SD	2.02			0.17	0.32	0.11	15.67	0.11	0.02

• DPS_{max} is the maximal distance per stroke, DPS_{dec} is the rate of decline of distance per stroke in the second phase, DPS_{thr} is the distance per stroke at the breakpoint, and SR_{inc} is the increase in stroke rate with increasing velocity. DPS R^2 and SR R^2 are the weighted least squares regression values for each variable.

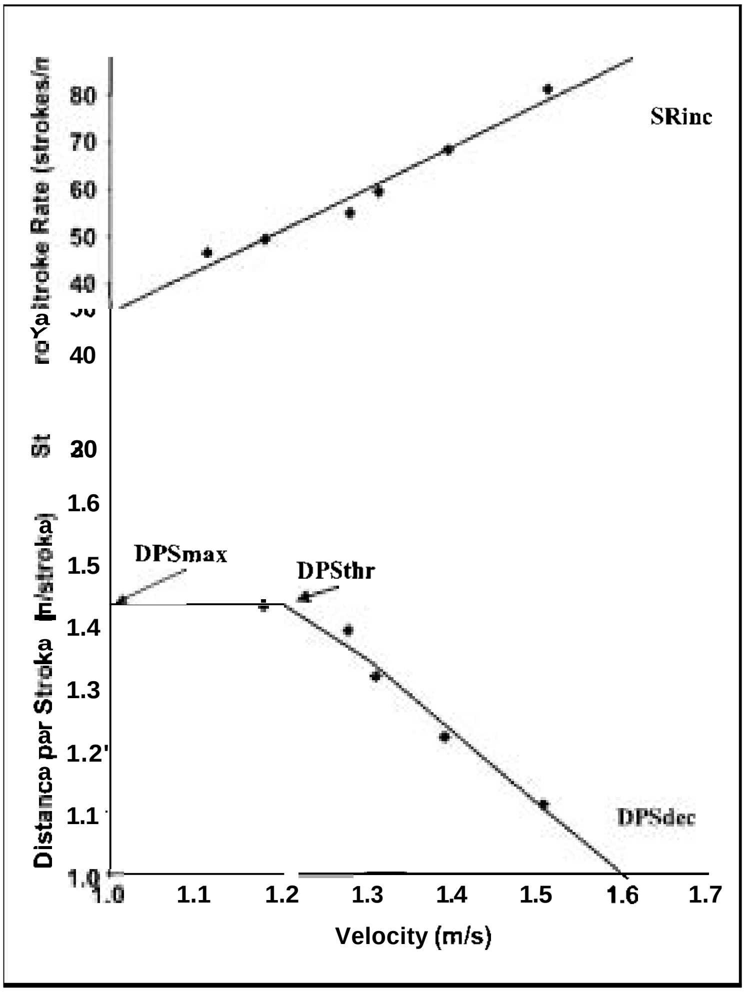

Figure **1 -** Results of an incremental velocity swimming economy test for one subject. $\mathbf{DPS_{max}}$ is the maximal distance stroke^{-1}, $\mathbf{DPS_{dec}}$ is the rate of decline of distance stroke^{-1} in the second phase, $\mathbf{DPS_{thr}}$ is the distance stroke^{-1} at the breakpoint, and $\mathbf{SR_{inc}}$ is the increase in stroke rate with increasing velocity.

DISCUSSION: The objective of the current study was to develop a simple model that can be used to assess and describe the swimming economy response to incremental exercise for typical high-level competitive swimmers. The model proved to be reliable, yielding mean goodness of fit values for DPS (R^2=0.89) and SR (R^2=0.97). The model, based upon previous research and physiological assumptions, agrees with published data on swimming economy. Swimming velocity (V, m.s^{-1}), is the product of the stroke rate (SR, strokes.s^{-1}), and distance per stroke (DPS, m.stroke^{-1}), that is, V=(SR)(DPS) (Craig and Pendergast, 1979). Changes in velocity result from changes in one, or both, of stroke rate and distance per stroke (Craig, et al. 1985).

We chose to examine a range of velocities that were consistent with typical training programs for elite level athletes. The parameter results varied between swimmers; the observed results may reflect the effects of gender, distancelsprint background, anthropometry, and technical aspects of stroke mechanics and the turn.

Several researchers have proposed physiological justifications for the observed changes in swimming economy that occur as swimming velocity increases. Wakayoshi, et al. (1995) indicated that there could be an optimal combination of distance per stroke and stroke rate for

each swimmer, and that this optimal combination involved considerations of technique, local muscle power and muscular endurance. Craig, et al. (1985) have suggested that the improvement in various measures of distance per stroke may occur due to an improved swimming efficiency, an improved metabolic capability, and adaptations of the nervous system. Analysis of the length-by-length profiles of the velocities during the 200, 400, 800, and 1500 m events (Chengalur & Brown, 1992) showed that as fatigue developed, the distance per stroke decreased. Fatigue was thought to be related to a decreasing ability to develop the force necessary to overcome the resistance to forward movement. This would be reflected in the decrease in distance per stroke that is observed as velocity increases.
Analysis of swimming economy parameters with changes in velocity may provide valuable information on a) resistance to fatigue, b) the ability of the athlete to generate and maintain the required power output, and c) the technical characteristics of the swimmer. Having an accurate measure of swimming economy, when combined with other physiological feedback, will enable scientists, coaches and athletes to assess various abilities and to design appropriate training programs.

CONCLUSIONS: A simple and accurate method of examining changes in distance per stroke and stroke rate that occurred with increasing velocity was developed using a group of elite swimmers. This method, based on a strong foundation of previously published research and physiological assumptions, represents an important advance for evaluating the technical characteristics of competitive swimmers. The method is suitable for use by both coaches and researchers interested in examining the effectiveness of various stroke techniques and training paradigms.

REFERENCES:
Chengalur, S. N., & Brown, P.L. (1992). An analysis of male and female Olympic swimmers in the 200-meter events. Canadian Journal of *Sport* Science, **17**(2), 104-9.
Craig, A. B., & Pendergast, D.R. (1979). Relationships of stroke rate, distance per stroke, and velocity in competitive swimming. Medicine and Science in Sports and Exercise, **11**(3), 278-83.
Craig, A. B., Skehan, P.L., et al. (1985). Velocity, stroke rate, and distance per stroke during elite swimming competition. Medicine and Science in Sports and Exercise, **17**(6), 625-34.
Hay, J.G., & Guimaraes, A. (1983). A quantitative look at swimming biomechanics. Swimming Technique, **20**(2), 11-17.
Treffene, R.J., Dickson, R., Craven, C., Osborne, C., Woodhead, K., & Hobbs, K. (1980). Lactic acid accumulation during constant speed swimming at controlled relative intensities, 20 (3), 244-54.
Wakayoshi, K., et al. (1995). Relationship between oxygen uptake, stroke rate and swimming velocity in competitive swimming. International Journal of Sports Medicine, **16**(1), 19-23.

ACKNOWLEDGMENTS:
This research was supported by a fellowship from the University of Toronto Department of Exercise Sciences. We thank the members of the Respiratory Research Group at the University of Toronto for helpful discussion. We also thank the dedicated coaches and athletes who volunteered their time and participated in the research.