The use of Critical Velocity in Swimming. A place for Critical Stroke Rate.

Jeanne Dekerle[1,2]
[1] Human Movement Studies Laboratory, University of Lille 2, France
[2] Chelsea School, University of Brighton, United Kingdom

For any swimmer, a hyperbolic relationship links velocity (*v*) and stroke rate (SR) to time to exhaustion (*t*). The asymptotes of these relationships are called Critical Velocity (CV) and Critical Stroke Rate (CSR). Both could be maintained, at least in theory, indefinitely. This review presents the origins of these two concepts, their physiological / biomechanical underpinnings to emphasis their usefulness for training. Coaches should appreciate the ease in using the CV model to set training loads, monitor training effects, and predict performance. The CSR concept is very recent and should be further investigated. However, current available knowledge suggests there is merit in using the two parameters for training.

INTRODUCTION

Understanding that physiological assessment of athletes is inherent to a good training process, laboratory testing in Sports and Exercise Science are becoming more and more accessible to athletes and a wide range of testing procedures are today recommended in the literature for cyclists (15) and runners (26). Physiological assessment should be sport-specific (3), but routine measurements are technically limited in swimming (41), assessing the physiological potential of a swimmer remains challenging. A number of 'field' tests have been developed. Smith et al. (41) acknowledge, in a review on the physiological and psychological tools used in the evaluation of swimmers, that the first-level of evaluation should be the competitive performance itself. The use of the individualised swimming speed versus time performance 'curve' based on a series of criterion effort has appeared attractive and appealing for physiological assessment in swimming (41). The 'critical swimming velocity' concept could provide the basis to analyse the effects and trends brought about through training, predict future competitive performance, and provide recommendations for continued directional training. Alongside the critical velocity concept (CV), a critical stroke rate (CSR) concept has been proposed in swimming (11). The purpose of this review is to address the usefulness of CV and CSR for swimming training. Because of a lack of evidence concerning the validity and reliability of the second parameter that can be derived from the CV concept (the Anaerobic Distance Capacity, ADC), its usefulness for training is not presented in the present review.

ORIGINS OF THE CONCEPTS: THE CRITICAL POWER CONCEPT

The CV and CSR concepts are extensions of the critical power concept originally introduced by Monod and Scherrer fifty years ago (35). Attempting to improve the understanding of the local work capacity of one muscle or one synergistic muscle group, these authors highlighted that local work (*W*) and time to exhaustion (*t*) were linearly related (Equation 1). The slope of the relationship, called Critical Power (CP), was defined as a 'threshold of local fatigue' while the y-intercept (a) was corresponding to a reserve of energy.

Equation 1: $W = a + CP.t$

CP can also be derived from the *P-t* relationship. The higher the power, the lower the time to exhaustion so that the *P-t* relationship is hyperbolic, with CP being its asymptote. Indeed, when time tends to the infinity, power tends to CP. CP is therefore mathematically defined as the power that can be maintained indefinitely.

The 2-parameter model has been one of the first physiological models applied to human endurance (1). Indeed, it was used few years later to model world records dating from 1965 in swimming, running, speed skating, and cycling (14). The aims were to predict performances and to explain the limits of human endurance. A *d-t* relationship (Equation 2) equivalent to equation 1 of Monod and Scherrer (35) was proposed. The y-intercept of the relationship (Anaerobic Distance Capacity, ADC; (23)) was therefore a distance in meters which could be run on oxygen reserves and the energy supplied by anaerobic metabolism, while the slope (CV; (23)) was interpreted as a maximal rate of synthesis of these reserves by aerobic metabolism. This application of the CP concept to cyclic activities is not without assumptions that are better detailed in Dekerle et al. (8).

Equation 2: *d= ADC + CV.t*

In the latter stage of the 20th century, most of the works on the models of Monod and Scherrer (35) and Ettema (14) were conducted to affine the methodology used to plot the *W-t* and *d-t* relationship, and better define the physiological meanings of the different constants. The numerous *post hoc* interpretations of the slope and the y-intercept of the *d-t* and *W-t* relationships these last 50 years have permitted a better understanding of the physiological meanings of the above-mentioned parameters.

CRITICAL VELOCITY IN SWIMMING.

Methodology and reliability.

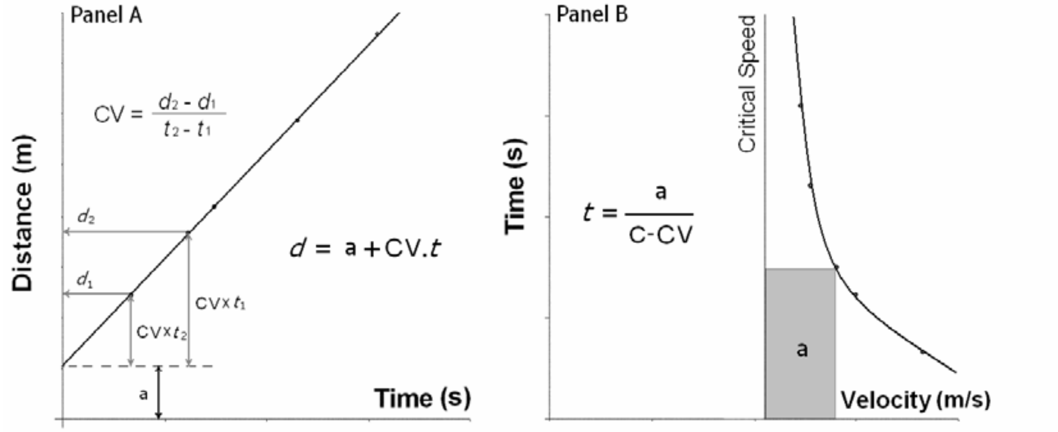
Three equivalent models can be used to calculate Critical Velocity in swimming (CV). Indeed, CV is represented by the slope of the *d-t* relationship (Equation 2; Panel A, Figure 1), the asymptote of the *v-t* relationship (Panel B, Figure 1), and the y-intercept of the *v*-1/*t* relationship. The relationship the most used in swimming to derive CV is the linear *d-t* one (Panel A, Figure 1). This is certainly due to its easy application from the plot of two or more swimming performances over time.

Performances recorded on several events allow critical velocity to be determined (Figure 1, Panel A). It is however important to remember that the value of this slope is dependent on the exhaustion times used to plot the relationship (8, 13) (influence of the energetic cost in swimming). It is therefore recommended to include in the model tests or races that enable VO_2max to be reached (between 2 and 15 min). Competitive distances ranging from 200 to 1500m can be advised in swimming (33, 49). According to these requirements, and in a wish to make the determination of critical speed easy and rapid for coaches, the suggestion of Wakayoshi et al. (47) and Dekerle et al. (11) to base this determination on only two performances (200m and 400m) seems today pertinent.

However, using only two performances to derive CV would decrease its level of reliability. This has to be considered when using the *d-t* relationship to predict performance or monitoring effects of periods of training. It can be noticed that CV determination has been shown to be reliable even if exhaustion times are variable (21,

44) and physiological responses at CV have also been shown in swimming, to be reproducible (4).

Figure 1: illustration of two different but equivalent representations of the 2-parameter CV model.



Definition and validity.

According to its mathematical definition, CV has firstly been thought to correspond to a sustainable intensity and has been compared to parameters such as the maximal lactate steady state (MLSS; highest intensity that can be maintained without any drift in the blood lactate concentration ([La])) or the onset of blood lactate accumulation (OBLA; intensity corresponding to a 4-mmol.L^{-1} of [La] during an incremental test). Wakayoshi et al. (47) and Brickley et al. (4) obtained steady [La] values during several 400-m blocks performed at CSV (around 3-4 mmol.L^{-1}). But the 30-45 sec of rest enabling blood samples to be taken between the blocks could have helped the swimmer keeping his motivation, limiting the drift of [La] and maintaining a 'relatively' good efficiency. Stroking parameters have indeed been shown to change, with progressive stroke rate increases and stroke length decreases within and between the 400-m blocks (4). Most authors today agree that CV does not correspond to a sustainable intensity. In fact, swimmers can hardly maintain their CSV for longer than 30-40 min (unpublished data from our laboratories) and CV has been shown to be close to the velocity of a 30-min test (11) and higher than MLSS (10) and OBLA (12, 40, 47, 48). Similar responses and exhaustion times have been recorded on treadmill and ergocycle (5, 7, 17, 22, 34, 36, 39).

CV is today defined as the upper limit of the heavy intensity domain, i.e. the highest intensity that does not allow VO_2max to be attained during a constant load exercise (19). Below CV, progressive drifts of blood [La], heart rate and VO_2 ('slow component') are observed but maximal values are not reached. The slow component of VO_2 is not great enough for VO_2max to be attained. Capillary blood [La] can attain 8-10 mmol.L^{-1}. These speeds can be maintained from an hour (exhaustion times usually recorded at MLSS) to 30-40 min. High inter-individual variations were also reported (Brickley et al., 2002). In swimming, CV would refer to a 2000-m performance.

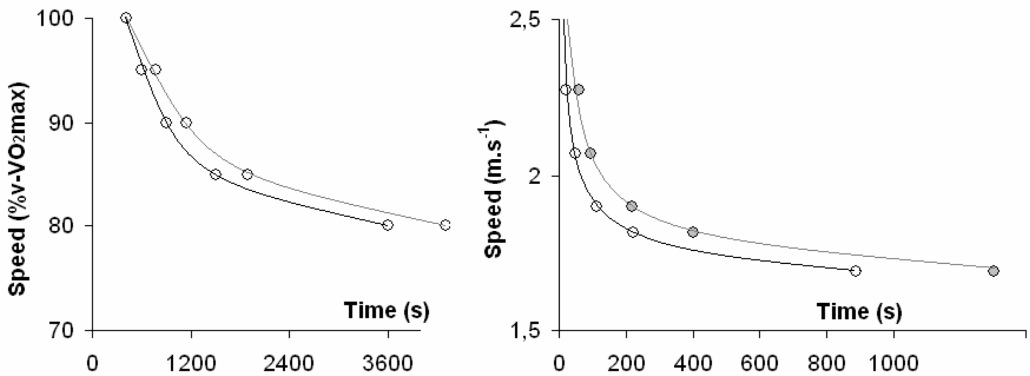
Above CV, because of the slow component phenomena, VO_2max should be elicited. The work of Hill and collaborators (19, 20) corroborates this definition in running and cycling but this has not yet been directly verified in swimming. However, it is in line with several findings reported in the literature. CV has been shown in swimming to be a good indicator of the capacity of the aerobic energy system (43). Several studies confirmed this finding in young swimmers (6, 42). CV is lower than the end velocity of an incremental test, traditionally identified as the maximal aerobic velocity (around 92-96% of the 400-m velocity in trained swimmers (4'15 up to 4'45)). It is highly correlated to OBLA (45, 47, 48), the average 400-m velocity (45, 47, 48), and MLSS (10). The first belief that CV was sustainable for a very long period of time was a misinterpretation of the mathematical (and not physiological) definition of CV, i.e. the intensity that can be maintained "in theory" indefinitely.

THE USE OF CRITICAL VELOCITY IN SWIMMING?

Setting training intensities

CV allows demarcating two different intensity domains and should be used as a reference to set training intensities. The 400-m pace is usually used by coaches for this purpose. However, two swimmers with similar performances on 400 m can have different aerobic potentials (Figure 2). One can swim a 1500 m quicker than the other one (and so on, for short races). The physiological stress to exercise of long duration will be different for the two swimmers. It is important to properly individualise training loads to optimise the physiological adaptations while avoiding overtraining especially when accuracy in the definition of the training loads is required as higher levels of performance.

Figure 2: Schematic of the speed-time relationship of two different swimmers having different aerobic potentials.



Using CV for aerobic training programs offers great potential. It allows better setting of continuous, long and short interval training for each. Continuous training (2000-3000m) and long interval training at and below CV would induce great lactic acid production leading to accumulation of H^+ that would be buffered and La^- that would be oxidised in different body cells. An example of long interval training could be 6 to 10 x 400m swum at CV with 15-sec rest. Indeed, several 400-m blocks performed at CV can be swam with steady [La] values (around 3-4mmol.L^{-1}) when separated by 30-40s of rest (4). Among all acute adaptations, we could expect a great improvement of the buffering capacity and oxidative potential of several body cells on top of the muscular ones (18). This increase in the buffering capacity has been shown to well explain the improvement of performance of trained athletes (30).

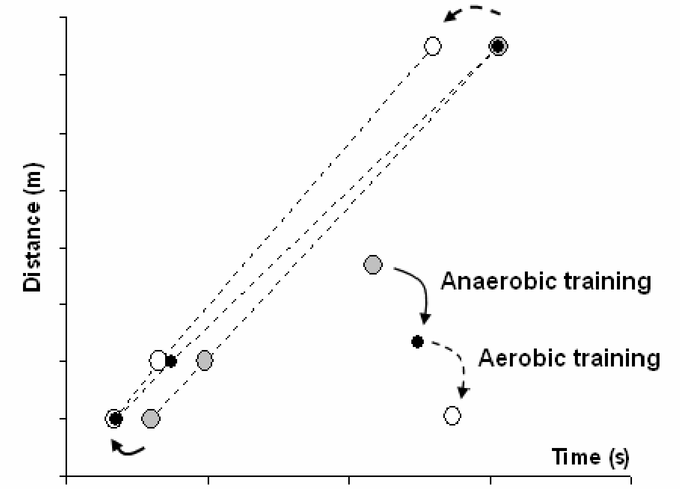
The other interest in swimming above CV relies on the hypothesis that to improve the VO_2max of trained athletes, VO_2max has to be solicited, and thus for a long time (2). Short interval training could then appear as one of the most interesting forms of training since it enables the time spent at VO_2max to be up to threefold those recorded during a continuous training. Short interval training presents other interests: 1) since the fifties, it is used by long and middle distance runners to train at speeds close to competitive ones (2). In swimming, it therefore enables to swim at stroke length and stroke rate ratio close to the competitive ones. 2) It induces a greater lipid solicitation for a given work done compared to continuous training (for example, 15 sec at 100% of VO_2max, 15 sec rest, compared to an hour at 50% of VO_2max). Consequently, greater physiological adaptations (especially a greater oxidative capacity of the type 2 muscle fibres; lower muscular glucose and glycogen and greater lipid reliance for a given intensity after training). It has even been evocated that in highly trained population, performances can 'only' be envisaged using short interval training (2, 30). On top of the improvements of the aerobic capacity and power, increase in anaerobic capacities has also been observed after a period of short interval training in trained athletes (2, 30). Adequate long and short interval training above CV (20-30 x 100m at 110% CV, 30-s rest; 1min at 120% CV, 1min rest for 20 min) would therefore enable VO_2max (very high heart rate and stroke volume) to be solicited and maintained for a very long time.
Central and peripheral adaptations occur with training performed around CV but it can be expected that the peripheral adaptations induced by swimming at and below CV would be less predominant with the increase in the intensity, the central adaptations becoming even more important.
Interval training swum around CV has been mentioned to be of great interest for improving aerobic and anaerobic potentials of swimmers. On top of these physiological adaptations, this kind of training allows swimming at high race paces while challenging the aerobic potential (200- up to 1500-m pace in this case). Training at race pace is important, especially in swimming where swimming coordination (42), energetic cost (6), and technical efficiency are changing depending on the velocity. Short interval training would enable to focus on the swimming techniques whose swimmers should attempt to maintain efficient while fatigue progressively develops during such long aerobic work performed around CV.

Monitoring training effects and predicting performance

A few studies conducted in laboratories have shown the 2-parameter model to be affected by training (24, 25). Aerobic training has a positive effect on CV (32). In swimming, MacLaren and Coulson (31) reported an increase and steady state in CV determined from the performances over a 50, 100, 200, and 400-m race, after a 8-week aerobic training period and a 3-week anaerobic training period, respectively. The results concerning the intercept of the *d-t* relationship were not reported as consistent.
Recently, Dekerle and Carter (in press) analysed the changes in CV during the last century of swimming Olympic performances. The greater improvements of long distance performance compared to shorter ones between two Olympic Games induced an explainable increase of CV. Plotting the *d-t* relationship would enable to monitor the effects of training on CV over a season (Figure 3) but further investigations are required to clarify the methodology that has to be used (number of performances required to plot the *d-t* relationship). Regarding the findings concerning the intercept of the *d-t*

relationship, we would suggest being prudent when interpreting its value and change over time.

Figure 3: Effects of aerobic and anaerobic training on the *d-t* relationship.



As shown in rowing (27) and running (16), when knowing the equation of the *d-t* relationship, it is possible to predict performance. Again, this should be confirmed or infirmed in swimming by further research. However, because of the good linearity of the relationship, coaches can try to predict performance as long as they are ranging between around 2 and 30 min (8).

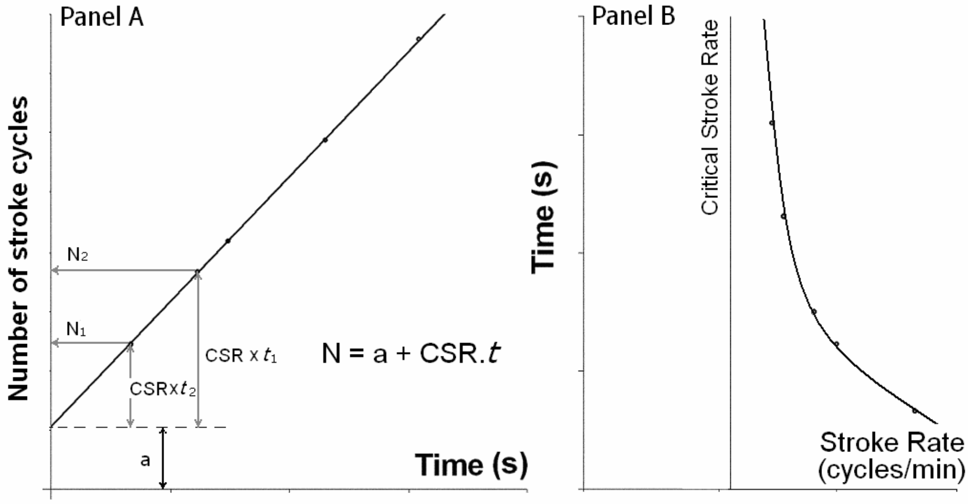
A PLACE FOR CRITICAL STROKE RATE?

Alongside the endurance-time relationship, the CP concept has recently been extended in swimming to characterise the stroke rate (SR) – *t* relationship (11). Several studies have illustrated the hyperbolic SR – velocity curve (9, 28, 29, 37, 46). Indeed, when attempting to swim faster, a swimmer will increase his SR. This increase in SR will be detrimental to the stroke length (SL) above a given sub-maximal intensity (MLSS or OBLA (9, 28, 29, 37)). Consequently, the longest the race is, the lowest the speed is, and the lowest the SR is. Dekerle et al. (11) suggested that the SR-*t* relationship could be modelled using a hyperbolic model, the asymptote being called Critical Stroke Rate (CSR). CSR is mathematically defined as the highest SR that can be maintained indefinitely, i.e. for a very long period of time.

The determination of CSR does not required extra-tests to be performed compared to the CV determination. It relies on the record of the SR of each performance. The hyperbolic SR-*t* relationship can then be modelled (Figure 4, Panel B). To simplify the modelling, Dekerle et al. (11) proposed another model equivalent to the hyperbolic SR-*t* one. This procedure enables a quick and easy determination of CSR by using a simple linear regression method. Indeed, CSR is also represented by the slope of the "number of stroke cycles" (N=SR x *t*) – *t* relationship (Figure 4, Panel A).

No study has yet tested the reliability of the CSR concept and further investigations should also focus on its validity. However, Dekerle et al. (11) reported regression line coefficient of 0.99-1 when modelling the N-*t* relationship (performances over a 50, 100, 200, and 400m swim). CSR was not significantly different and was highly correlated to the average SR of a 30-min test. Moreover, when swimming at CV, the nine participants spontaneously adopted SR values similar to CSR. Similarly, when having to swim at the imposed CSR, participants swum at CV.

Figure 4: illustration of two different but equivalent representations of the 2-parameter CSR model.



It is today acknowledge that SR/SL ratio should be monitored during training in order to control and even improve stroke efficiency. When preparing a repetition, alongside the set of distance/duration, intensity, number of repetitions, and duration and form of the recoveries, coaches should control the SR/SL ratio in order to preserve a good technical gesture. When considering the results of Dekerle et al. (11), it could even be suggested that a given SR could be imposed during training repetitions rather than the usual time "allowed" to cover a given distance. Because training is just about "pushing the limits of the swimmer", the aim in aerobic swimming training performed at CV could consist in maintaining CV with a lower SR than CSR, or maintaining CSR while swimming faster than CV. This would require higher SL to be adopted and maintained.

As explained above, it is known that training at race pace is of importance for technical aspects of the strokes. Therefore, this training strategy relying on the multiple combinations linking the stroke parameters ("task constraint" strategy) should be performed at any velocity of the race spectrum. The SR-*t* relationship that supports the CSR concept could then represent a very useful tool for coaches.

CONCLUSION

The actual knowledge on the application of the CV concept seems sufficient to underlie its interests for training. The *d-t* relationship is a useful tool for setting training intensities, monitoring training effects, and predicting performances. However, "luckily" for researchers, further research is required to confirm its meaningfulness in swimming (responses at and above CV) and usefulness for training (among all, effects of training at intensities around CV, effects of training on the *d-t* relationship, kicking *vs* full stroke CV, prediction of performance). Almost all the studies conducted on the CV have been conducted on trained swimmers whose 400-m performance ranged from 72-84% of the world record. Published data on elite international swimmers will help to create strong performance indicators. More work on the Critical Stroke Rate concept is needed that incorporates an input from coaching, biomechanics, motor control, and physiology.

REFERENCES

1. Billat LV, Koralsztein JP, Morton RH. (1999). Time in human endurance models. From empirical models to physiological models. Sports Med, 27: 359-79

2. Billat VL, Slawinksi J, Bocquet V, Chassaing P, Demarle A, Koralsztein JP. (2001). Very short (15s-15s) interval-training around the critical velocity allows middle-aged runners to maintain VO2 max for 14 minutes. Int J Sports Med, 22: 201-8

3. Bosquet L, Leger L, Legros P. (2002). Methods to determine aerobic endurance. Sports Med, 32: 675-700

4. Brickley G, Carter H, Dekerle J, Clark S (2004). Physiological responses to exercise at critical swimming velocity. In: *9th Annual Congress of the European College of Sport Science*. Clermont-Ferrand: 2004,

5. Brickley G, Doust J, Williams CA. (2002). Physiological responses during exercise to exhaustion at critical power. Eur J Appl Physiol, 88: 146-51

6. Coelho Greco C, Denadai BS. (2005). Relationship between Critical Speed and endurance Capacity in Young Swimmers: Effect of Gender and Age. Pediatric Exercise Science, 17: 353-63

7. Dekerle J, Baron B, Dupont L, Vanvelcenaher J, Pelayo P. (2003). Maximal lactate steady state, respiratory compensation threshold and critical power. Eur J Appl Physiol, 89: 281-8

8. Dekerle J, Brickley G, Sidney M, Pelayo P (2006). Application of the critical power concept in swimming? In: *Biomechanics and Medicine in Swimming X* edited by Vilas-Boas JP, Alves F,Marques A. Porto: Portuguese Journal of Sport Sciences, 2006,

9. Dekerle J, Nesi X, Lefevre T, Depretz S, Sidney M, Marchand FH, Pelayo P. (2005). Stroking parameters in front crawl swimming and maximal lactate steady state speed. Int J Sports Med, 26: 53-8

10. Dekerle J, Pelayo P, Clipet B, Depretz S, Lefevre T, Sidney M. (2005). Critical swimming speed does not represent the speed at maximal lactate steady state. Int J Sports Med, 26: 524-30

11. Dekerle J, Sidney M, Hespel JM, Pelayo P. (2002). Validity and reliability of critical speed, critical stroke rate, and anaerobic capacity in relation to front crawl swimming performances. Int J Sports Med, 23: 93-8

12. Denadai BS, Greco CC, Teixeira M. (2000). Blood lactate response and critical speed in swimmers aged 10-12 years of different standards. J Sports Sci, 18: 779-84

13. di Prampero PE. (1999). The concept of critical velocity: a brief analysis. Eur J Appl Physiol Occup Physiol, 80: 162-4

14. Ettema JH. (1966). Limits of human performance and energy production. Int F für Angew Physiol Einschl Arbeitphysiol, 22: 45-54

15. Faria EW, Parker DL, Faria IE. (2005). The science of cycling: physiology and training - part 1. Sports Med, 35: 285-312

16. Florence S, Weir JP. (1997). Relationship of critical velocity to marathon running performance. Eur J Appl Physiol Occup Physiol, 75: 274-8

17. Gaesser GA, Wilson LA. (1988). Effects of continuous and interval training on the parameters of the power-endurance time relationship for high-intensity exercise. Int J Sports Med, 9: 417-21

18. Hawley JA, Myburgh KH, Noakes TD, Dennis SC. (1997). Training techniques to improve fatigue resistance and enhance endurance performance. J Sports Sci, 15: 325-33

19. Hill DW, Ferguson CS. (1999). A physiological description of critical velocity. Eur J Appl Physiol Occup Physiol, 79: 290-3
20. Hill DW, Poole DC, Smith JC. (2002). The relationship between power and the time to achieve .VO(2max). Med Sci Sports Exerc, 34: 709-14
21. Hinckson EA, Hopkins WG. (2005). Reliability of time to exhaustion analyzed with critical-power and log-log modeling. Med Sci Sports Exerc, 37: 696-701
22. Housh DJ, Housh TJ, Bauge SM. (1989). The accuracy of the critical power test for predicting time to exhaustion during cycle ergometry. Ergonomics, 32: 997-1004
23. Hughson RL, Orok CJ, Staudt LE. (1984). A high velocity treadmill running test to assess endurance running potential. Int J Sports Med, 5: 23-5
24. Jenkins DG, Quigley BM. (1992). Endurance training enhances critical power. Med Sci Sports Exerc, 24: 1283-9
25. Jenkins DG, Quigley BM. (1993). The influence of high-intensity exercise training on the Wlim-Tlim relationship. Med Sci Sports Exerc, 25: 275-82
26. Jones AM, Carter H. (2000). The effect of endurance training on parameters of aerobic fitness. Sports Med, 29: 373-86
27. Kennedy MD, Bell GJ. (2000). A comparison of critical velocity estimates to actual velocities in predicting simulated rowing performance. Can J Appl Physiol, 25: 223-35
28. Keskinen KL, Komi PV (1988). Interaction between aerobic/anaerobic loading and biomechanical performance in free style swimming. . In: *Swimming V, International series on Sport Sciences*, edited by Ungerechts BE, Wilke K,Reische K. Champaign: Human Kinetics, 1988, p. 285-93
29. Keskinen KL, Komi PV (1988). The stroking characteristics in four different exercises in freestyle swimming. , : . In: *Biomechanics XI-B*, edited by de Groot G, Hollander AP, Huijing PA,van Ingen Schenau GJFree University Press, 1988, p. 839-43
30. Laursen PB, Jenkins DG. (2002). The scientific basis for high-intensity interval training: optimising training programmes and maximising performance in highly trained endurance athletes. Sports Med, 32: 53-73
31. MacLaren DPM, Coulson M (1999). Critical swim speed can be used to determine changes in training status. In: *Biomechanics and medicine and swimming VIII*, edited by Keskinen KL, Komi PV,Hollander AP. Jyväskylä: Grummerus Printing, 1999, p. 227-32
32. MacLaren DPM, Coulson M (1999). Crticial swim speed can be used to determine changes in training status. In: *Biomechanics and Medicine in swimming VIII*, edited by Keskinen KL, Komi PV,Hollander AP. Jyvaskyla: Grummerus printing, 1999, p. 227-32
33. Martin L, Whyte GP. (2000). Comparison of critical swimming velocity and velocity at lactate threshold in elite triathletes. Int J Sports Med, 21: 366-8
34. McLellan TM, Cheung KS. (1992). A comparative evaluation of the individual anaerobic threshold and the critical power. Med Sci Sports Exerc, 24: 543-50
35. Monod H, Scherrer J. (1965). The work capacity of a synergic muscular group. Ergonomics, 8: 329-38
36. Moritani T, Nagata A, deVries HA, Muro M. (1981). Critical power as a measure of physical work capacity and anaerobic threshold. Ergonomics, 24: 339-50
37. Nomura T, Shimoyama Y (2002). The relationship between stroke parameters and physiological responses at the various swim speeds. In: *Biomechanics and medicine in swimming IX*, edited by Chatard JC. Saint Etienne: Universite de Saint-Etienne, 2002, p. 355-60

38. Nomura T, Shimoyama Y (2003). The relationship between stroke parameters and physiological responses at various swim speeds. In: *Biomechanics and Medicine in Swimming IX*, edited by Chatard JC. Saint-Etienne: University of Saint-Etienne, 2003, p. 355-60
39. Pringle JS, Jones AM. (2002). Maximal lactate steady state, critical power and EMG during cycling. Eur J Appl Physiol, 88: 214-26
40. Rodriguez FA, Moreno D, Keskinen KL. (2003). Validity of a two-distance simplified testing method for determining critical swimming velocity. In: Chatard JC (Ed.). Biomechanics and Medicine in Swimming IX. Saint- Etienne: University of Saint Etienne, 385-90
41. Smith DJ, Norris SR, Hogg JM. (2002). Performance evaluation of swimmers: scientific tools. Sports Med, 32: 539-54
42. Toubekis AG, Douda HT, Tokmakidis SP. (2005). Influence of different rest intervals during active or passive recovery on repeated sprint swimming performance. Eur J Appl Physiol, 93: 694-700
43. Toussaint HM, Wakayoshi K, Hollander AP, Ogita F. (1998). Simulated front crawl swimming performance related to critical speed and critical power. Med Sci Sports Exerc, 30: 144-51
44. Vandewalle H, Vautier JF, Kachouri M, Lechevalier JM, Monod H. (1997). Work-exhaustion time relationships and the critical power concept. A critical review. J Sports Med Phys Fitness, 37: 89-102
45. Wakayoshi K, Ikuta K, Yoshida T, Udo M, Moritani T, Mutoh Y, Miyashita M. (1992). Determination and validity of critical velocity as an index of swimming performance in the competitive swimmer. Eur J Appl Physiol Occup Physiol, 64: 153-7
46. Wakayoshi K, Yoshida T, Ikuta Y, Mutoh Y, Miyashita M. (1993). Adaptations to six months of aerobic swim training. Changes in velocity, stroke rate, stroke length and blood lactate. Int J Sports Med, 14: 368-72
47. Wakayoshi K, Yoshida T, Udo M, Harada T, Moritani T, Mutoh Y, Miyashita M. (1993). Does critical swimming velocity represent exercise intensity at maximal lactate steady state? Eur J Appl Physiol Occup Physiol, 66: 90-5
48. Wakayoshi K, Yoshida T, Udo M, Kasai T, Moritani T, Mutoh Y, Miyashita M. (1992). A simple method for determining critical speed as swimming fatigue threshold in competitive swimming. Int J Sports Med, 13: 367-71
49. Wright B, Smith DJ. (1994). A protocol for the determination of critical speed as an index of swimming endurance performance. In: Myashita M, Mutoh Y,Richardson AB (Ed.). Medicine Science in Aquatic Sports. Karger: Basel, 55-59

ACKNOWLEDGEMENTS

Jeanne Dekerle's post and this collaboration is funded by the EU programme 'Interreg IIIa'