

1 **An updated methodology to estimate Critical Velocity in Front Crawl Swimming:**
2 **a scoping review**

3 **Une méthodologie mise à jour pour estimer la vitesse critique en crawl: une revue**
4 **cadrage**

5

6 **Abstract**

7 *Objectives:* Critical velocity and its related total distance covered above critical velocity
8 can be used to evaluate and monitor the training and competition performance in
9 athletes. While it is well researched in sports such as cycling and running, the literature
10 on critical velocity in swimming is less available. Therefore, the objectives of this
11 review are (i) to methodologically evaluate the protocols used to obtain critical velocity;
12 and (ii), eventually, to provide a standard operating procedure to evaluate critical
13 velocity in front crawl swimming.

14 *Prospects and projects:* The review followed Preferred Reporting Items for Systematic
15 Reviews and Meta-Analyses Extension for Scoping Reviews guidelines. PubMed, Web
16 of Science, and Scopus were used to find original studies written in English. No
17 exclusion criteria were adopted for the country of origin. The results were analysed
18 through a narrative synthesis.

19 *News:* A total of 41 studies were included. Sixteen different protocols were adopted
20 with different physiological thresholds as comparators with critical velocity.

21 *Conclusion:* critical velocity evaluation presents different testing protocols, making this
22 performance marker potentially inaccurate. As a consequence, we propose a standard
23 operating procedure.

24 **Keywords:** critical speed, critical power, front crawl swimming, standard operating
25 procedure, SOP

26 **Resume**

27 Objectifs: La vitesse critique et la distance totale parcourue au-dessus de vitesse critique
28 peuvent être utilisées pour évaluer les performances d'entraînement et de compétition
29 chez les athlètes. Bien qu'elle soit bien documentée dans des sports comme le cyclisme
30 et la course à pied, la littérature sur la vitesse critique en natation est plus rare. Par
31 conséquent, les objectifs de cette revue sont (i) d'évaluer méthodologiquement les
32 protocoles utilisés pour obtenir vitesse critique; et (ii) de fournir un mode opératoire
33 standard pour évaluer vitesse critique en crawl.

34 Perspectives et projets: La revue a suivi les directives Éléments de rapport préférés pour
35 les examens systématiques et extension de méta-analyses pour une revue cadrage.
36 PubMed, Web of Science et Scopus ont été utilisés pour trouver des études originales
37 rédigées en anglais. Aucun critère d'exclusion n'a été adopté pour le pays d'origine. Les
38 résultats ont été analysés à travers une synthèse narrative.

39 Actualités: Au total, 41 études ont été incluses. Seize protocoles différents ont été
40 adoptés et différents seuils physiologiques ont été utilisés pour comparer avec vitesse
41 critique.

42 Conclusion: L'évaluation de vitesse critique présente différents protocoles de test, ce qui
43 rend ce marqueur de performance potentiellement inexact. En conséquence, nous
44 proposons un mode opératoire standard.

45 Mots clés: vitesse critique, puissance critique, crawl, mode opératoire standard

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47

48 **1. Introduction**

49 Critical Velocity (CV) can be used to evaluate and monitor swimming performance (1).
50 ~~It is commonly referred to the analogous term of~~ derives from the “Critical Power”
51 (CP), a concept introduced by Monod and Scherrer in 1965 (2) and it corresponds to the
52 power that can be sustained without a progressive loss in metabolic steady state (3). CV
53 is extrapolated by the equation (eq. 1):

54

55
$$D = a + b \times T \tag{1}$$

56

57 In which CV (b) is given by the slope of the regression line obtained from tests
58 distances (D) and the respective time (T) to cover it; a (D') is the y-interception which
59 represents the total distance covered above CV ~~until task failure (m)~~ (4). The equation
60 to obtain CV to be create, requires the completion, as quickly as the athletes can, of four
61 swimming distances (50-100-200-400 meters) (4). Critical velocity evaluates aerobic
62 endurance (5) while the y-interception (D') is related to anaerobic indices (6).
63 Consequently, the anaerobic work capacity (D') as in the CP concept, is the work that
64 can be performed using the energy stored within the working muscles (7, 8).

65 Over the years, the CP ~~concept~~ has become popular in ~~sports such as~~ cycling (9) and the
66 concept has been adopted, named as CV or Critical Speed, in other sports such as
67 running (10), rowing (11) and swimming (1, 8). The importance of this performance
68 parameter is for both, the training and competition planning and performance
69 monitoring (12, 13). Critical Velocity ~~can also be used as a “fatigue threshold” (3)~~, it is
70 a direct method to determine aerobic endurance (14), and it is a ~~valid and~~ practical
71 parameter that it lends itself to the comparison with commonly employed physiological

72 performance tests ~~measuring for example~~ such as blood lactate concentrations
73 evaluation methods, also adopted to assess aerobic and anaerobic thresholds (5).
74 Examples of such physiological thresholds used in comparison to CV are the lactate
75 turning point (LTP) (15), the V4 (swimming velocity at 4 mmol) (16), the onset of
76 blood lactate accumulation (4), the anaerobic threshold (17), and the maximal lactate
77 steady state (MLSS) (18). ~~Consequently,~~ ~~–~~In contrast to the LTP, V4, OBLA, and
78 MLSS, the determination of CV is attractive to coaches and athletes alike, indeed, it
79 does not requires ~~rely on performing a prolonged sub-maximal constant intensity or an~~
80 ~~incremental exercise task~~ (19). ~~Furthermore coaches and investigators do not have to~~
81 collect repeated blood lactate samples, making this test simple, fast, and non-invasive
82 (5, 19), even if the protocol should have to be follow accurately. ~~Finally, no differences~~
83 ~~exist between CV evaluated in the laboratory (i.e. in a swimming flume) and directly in~~
84 ~~the field (i.e. in a swimming pool)~~ (1) adding to the attractiveness of this parameter as
85 ~~an applied training and performance marker~~. Interestingly, Costa et al. (2009) proposed
86 to determine CV using swimming times obtained from competitions (20), which gives
87 the option to attain the value without a regular test.

88 Some confusion and conflicting information with respect to the accuracy of CV in
89 swimming still exists (19). Indeed, it is unclear if CV is a valid alternative to blood
90 lactate based thresholds, with some evidence suggesting that test results are comparable
91 (5, 16, 20, 21), and others suggesting the opposite (15, 22, 23). Considering these
92 conflicting results and the importance of this topic, the objectives of this review are (i)
93 to provide methodological indication and evaluate the protocols adopted to obtain CV in
94 front crawl swimming; and (ii), eventually, to provide a detailed and reliable step by
95 step process, the so called standard operating procedure (SOP) (24). Consequently, a

96 point by point analysis of each part of the protocols (i: adopted equation; ii: use of
97 swimming distances; iii: number of swim trials; and iv: length of the swimming pool)
98 used in published research in relation to the determination to CV and D' and front crawl
99 swimming will be discussed and a SOP consequently proposed.

100

101 **2. Materials and Methods**

102 This scoping review was conducted in agreement with the principles outlined by the
103 Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for
104 Scoping Reviews (PRISMA-ScR) checklist and explanation (25). It was decided to
105 perform a scoping review due to the high heterogeneity of retrieved findings. In more
106 details, after the pre-screening, it was decided not to perform a systematic review or a
107 meta-analysis due to the: (i) wide variety of testing procedures and methods to obtain
108 CV and D' ; (ii) the differences in the physiological parameters protocols ~~measured~~ used
109 in the studies and the impossibility to compare them between studies ~~and with CV and~~
110 ~~D'~~ (26); (iii) the diversity of participants recruited (young and older adults, amateur and
111 elite, Olympic level athletes). ~~Unfortunately, the International Prospective Register of~~
112 ~~Systematic Review (PROSPERO) rejected the protocol and it was not registered before~~
113 ~~the revision of the literature.~~

114

115 *2.1 Eligibility criteria*

116 Population, Intervention, Comparison, Outcomes, and Study design (PICO-S) criteria
117 were followed during the data collection of this review. The population comprised
118 swimmers, with the exclusion of additional activities practiced (i.e. triathletes or water
119 polo) and any mental (i.e. neurodegenerative disease or intellectual disability),

120 psychological (i.e. personality disorder or somatic symptom disorder), motor (i.e.
121 akinesia, bradykinesia or dystonia), or physical (i.e. injury to muscles, tendons,
122 ligaments or bones) disorders.

123 As only ~~pre-intervention data~~ baseline CV and physiological values were considered,
124 any type of intervention was included in the search (i.e. training intervention or
125 performance analysis). Another inclusion criteria was that the CV evaluation had to be
126 adopted (outcomes). ~~Consequently, protocols evaluating only the anaerobic component~~
127 ~~were excluded.~~ Finally, front crawl was the swimming technique examined. Only
128 original and peer-reviewed papers that used cross-sectional, longitudinal, case-control,
129 correlational, randomized, non-randomized controlled or quasi randomized papers
130 written in English were included. Reviews, meta-analyses, commentary, opinion
131 articles, books, book reviews, abstracts, citations, scientific conference abstracts,
132 statements, editorials, and non-peer reviewed journal articles were excluded.

133

134 *Search strategy*

135 Studies published through June 07th, 2021 were included. The electronic search was
136 performed through the databases PubMed, Scopus, and Web of Science using the
137 keywords swim, critical velocity, critical power, endurance exercise capability,
138 ventilatory threshold, anaerobic threshold, and aerobic threshold. The following strings
139 were used: Swim* and critical velocity; Swim* and critical power; Swim* and critical
140 speed; Swim* and endurance exercise capability; Swim* and ventilatory threshold;
141 Swim* and anaerobic threshold; Swim* and aerobic threshold.

142

143 *Data collection synthesis and analysis*

144 To identify duplicates, research papers were imported into EndNote software (EndNote
145 version X8; Thompson Reuters, New York, USA) to find duplicates. Two independent
146 investigators performed the selection process. A first screening was performed by titles,
147 then abstracts, and, lastly, considering the full-length articles. In case of disagreement in
148 the selection of the papers, another investigator was involved and provided the tie-
149 breaking decision. Investigators were not blinded to the authors or associated
150 institutions during the selection process. The following data were extracted from each
151 included study and inserted into a Microsoft Excel (Microsoft Corp, Redmond,
152 Washington) spreadsheet: lead author, year of publication, sample size, samples' age
153 (range or mean \pm standard deviation), gender, swim background, swimming-pool
154 characteristics (50 or 25 m length), CV and D' protocol, equation adopted to obtain CV
155 and D' in the different studies, physiological evaluation, and swimming technique
156 studied. All the data were summarized descriptively with tables and graphs and
157 analysed through a descriptive narrative synthesis.

158

159 **Results**

160 *Included studies*

161 A total of 5,396 studies were selected following the databases search. After the
162 duplicates selection, the studies left for screening against the eligibility criteria were
163 3,103. After the inclusion/exclusion criteria application, a final number of 41
164 manuscripts were included. A flow diagram summarized the selection process (Fig 1).

165

166 [Fig 1. Flow diagram]

167 Fig 1. Flow Diagram representing selection process of manuscripts.

168

169 *Participant characteristics*

170 A total of 1535 participants were included in the qualitative synthesis, with 37.3 %
171 women (572), 59.8 % men (918), and 2.9 % non-specified gender (45), with an average
172 (standard deviation) age of 16.5 (2) years. The results are summarized graphically in
173 table 1.

174

175 [table 1]

176

177 *Individual study characteristics*

178 The length of the swimming-pool adopted to perform the test by the majority of the
179 authors (41.5 %) was 25 m, while only 31.7 % of the authors used a 50 m swimming-
180 pool. The remaining part of the studies (26.8 %) did not provide any information
181 regarding the pool length. The most frequently adopted protocols comprised 200-800 m
182 (17.1 %), ~~protocol, comprising,~~ and 200-400 m (17.1 %), 50-100-200-400 m (9.8 %)
183 and 50-400 m (9.8 %). All protocols used in the studies, such as results and additional
184 information are provided in table 1.

185 CV expressed as the slope of the regression line between swimming distance and
186 corresponding time as employed in swimming by Wakayoshi and colleagues (1) was
187 used most frequently (43.9 %). Studies that adopted other equations are reported in table
188 1. While the D' of CV ~~parameter,~~ given by the y-intercept of the regression line, was
189 adopted in only nine articles (table 2).

190

191 [table 2]

192

193 Differences were noted in the number of ~~data~~ points taken ~~into account~~ to create the
194 slope of the equation. This number ranged between two to six ~~data~~ points ~~protocols~~. The
195 protocol most frequently used comprised of two ~~data~~-points (63.4 %) which was
196 followed by four or more points protocols (26.8 %) and by three-points protocols (26.8
197 %). Information related to the start of the test were provided by a limited number of
198 authors, with some asking athletes to start in the water (26.8 %), others opted for a dive
199 start (2.4 %), while most of the authors did not provided this information.

200 A comparison of CV with other physiological markers was performed in twelve studies.
201 These adopted comparators were the MLSS (13.5%), V4 (10.8 %), and LTP (8.1 %).
202 Nine of these works (table 3) suggested that it is possible to use CV interchangeably
203 with the physiological marker investigated. Arsoniadis and colleagues (27) suggested
204 that V4 is ~~provides a higher precision~~ more sensitive to detect than CV. Minganti and
205 colleagues (16) stated CV, measured with the inclusion of the 400 m, is well correlated
206 with V4 even if the CV values are higher. Three authors (28-30) suggested CV to be
207 higher than the MLSS. Three authors (table 3) recommended not to adopt CV because
208 the agreement between the physiological marker in question and CV was too low.

209 Related to D' (table 2), five of the nine studies that investigated this parameter, stated
210 that this value in swimming presents either great variability and low accuracy (31), or
211 low validity (32), that it is unreliable (33), and that it is not correlated with lactate
212 thresholds (34). Two studies (29, 35) adopted this parameter but no conclusion with
213 respect to its validity or reliability were stated. Two studies (36, 37) suggest to adopt D'
214 only in sprinter swimmers. Finally, Zacca and colleagues (38, 39) suggested, to increase
215 the accuracy of D' , to use a three- or four-parameter models instead of the two-
216 parameter model.

217

218 [Insert table 3]

219

220 **Discussion**

221 The results of the present review underline the existence of a methodological issue in
222 ~~that~~ the assessment of CV in front crawl swimming, indeed, this parameter was
223 proposed adopting different protocols different by the first CV of Wakayoshi and
224 colleagues (1). This, consequently, might have resulted in an inaccurate determination
225 of the performance marker. Furthermore, new findings suggest to update CV protocol
226 making it accurate and more attractive.

227 Although a number of authors suggest that CV is comparable to physiological markers
228 such as V4, MLSS, LTP, others stipulated CV to overestimate MLSS or V4 (table 3)
229 and therefore CV cannot be considered as synonymous. It is to consider that the
230 physiological markers were evaluated with different methodologies making the
231 comparison not accurate, if the determination criteria are not followed, CV results are
232 not replicable and comparable. To resolve the issue related to the variety of CV
233 protocols used in the literature and different by the first proposed by Wakayoshi and
234 colleagues (1), such standardized testing method in form of a SOP is proposed (table 4).

235

236 [table 4]

237

238 The first point of the SOP is related to the equation used, which determines CV (i) and
239 the liner regression proposed by Wakayoshi and colleagues (1), ~~where CV is the slope~~
240 ~~of the regression line obtained from swim trial distances and the respective time to~~
241 ~~cover it,~~ , which is the first and adopted in majority of research examined (table 1),

242 should be adopted. Instead, related to the D' , due to the low accuracy of this parameter
243 in swimmers (31-34, 40), it is not suggested to considered as an anaerobic performance
244 indicator.

245 The major question raised from the reviewed studies is the distances chosen for the test
246 (ii). The equation of Wakayoshi and colleagues (1) suggest to adopt distances from 50
247 to 400 m but swimmers compete in distances that range between 50 m and 1500 m. It is
248 important to consider that the slope gradient is a function of the trial duration (33).
249 Indeed, shorter distances can lead to an overestimation of CV values while longer
250 distances can lead to an underestimation (21). According to Muniz-Pumares et al. (41),
251 the duration of the exercise bouts used for the CP testing should range between 2 and 15
252 minutes. Consequently, the distance of 50 m ~~and 100 m~~ due to the extremely short trail
253 duration should be exclude. Similarly, the 1500 m distance, that only Olympics athletes
254 can swim under fifteen minutes, should be avoided. Anyway, a relatively short (100 or
255 200 m) and long (800 m) distances should have to be included so the regression line
256 will result better balanced. While in other swimming techniques (backstroke,
257 breaststroke or butterfly), where the longest competitive distance is maximally 200 m,
258 ~~should also not use longer testing distances as a) the athletes are not used to swim these~~
259 ~~and b) as results might be invalid but potentially also irrelevant.~~ CV should be not
260 adopted, for the front crawl, instead, it is possible to adopt a protocol that includes
261 further and longer distances which can range between 100 and 800 m. ~~Furthermore, the~~
262 ~~protocol for the front crawl should be adapted according to the swimming~~
263 ~~characteristics of the athletes.~~ Therefore, generally, the test ~~that~~ should include 200-400
264 m ~~should be proposed~~ because CV extrapolated from the performance of these two
265 distances is highly reliable (40) but an 800 m trial should be added to make CV more

266 accurate. ~~To be more specific, the sprint athletes should perform shorter distances (200-~~
267 ~~400 m) and endurance athletes should include longer distances (400-800 m).~~

268 Regarding the number of ~~data~~ points (iii) needed, various trial numbers were used,
269 which can affect CV values (20). Wakayoshi and colleagues (1) used four-points in
270 their equation, but this is time consuming. The decision to adopt a two-points equation
271 requires less time ~~and therefore energy~~ but, as the literature suggests (20) it is more
272 prone to error as values of standard error of estimate cannot be calculated. In contrast,
273 more than two points permits to obtain a more precise CV ~~parameter~~ (20), but it is more
274 time ~~and energy~~ consuming. Consequently, we propose the two-points approach during
275 the season to more crudely evaluate athletes' performance, while adopting at least three-
276 points if a more precise information is required, as for CV values to adopt during races
277 or for scientific studies. This proposal is supported by pertinent research in particular
278 when using well-trained athletes such as runners (42).

279 One final important factor of the SOP that has to be considered is the pool length (iv),
280 as CV obtained in a 25 m swimming pool it is not comparable to a CV obtained in a 50
281 m swimming pool (43) or to open-water swimming with no turns and other variables
282 such as weather and water conditions being of relevance. Consequently, coaches should
283 adopt proper CV conversions technique in-between different swimming-pool lengths to
284 monitor training or competition performances.

285 Generally, the sample in the present review, similarly to a previous study (5) was
286 composed of different levels of athletes, which ranged between amateur and elite and
287 youth and adult. This, as a contributing factor for the conflicting findings with respect to
288 the agreement between CV and physiological values, can also be speculated. Indeed, the
289 blood lactate thresholds used to identify the aerobic and anaerobic domains are different

290 according to the training level (44, 45). Consequently, a 4 mmol/l blood lactate
291 concentration adopted as a standard threshold does not always correspond to the “true”
292 anaerobic threshold (AnT) of the person examined (44) and it has also been suggested
293 in front crawl swimmers that the AnT corresponds to a blood lactate concentration of
294 3.5 mmol/l (46). Considering that CP and CV are thresholds that can be maintained
295 between 20 and 40 min (47) and different studies asserted that this parameter is an
296 useful threshold to determine the anaerobic and the aerobic domain in different sports
297 (14), probably, CV in swimmers should be study independently of other physiological
298 parameters. Implementing SOP would allow researchers to gain a better understanding
299 of the relationship between CV with traditionally used physiological markers.

300 The aim of this study was to provide information on the accuracy of incorporating CV
301 calculations derived in front-crawl swimming and to provide guidelines to coaches and
302 exercise scientists. Limitations to consider include the differences in age, skill and
303 training levels and the testing methodology employed. Furthermore, water polo players,
304 triathletes or other population have not been considered in this review limiting the
305 findings only to one sport. Future studies should have to consider also the protocols
306 adopted in other sports. Lastly, one important parameter adopted in swimmers and
307 comparable to CV, it is the continuous 30 min swimming test (48), future studies should
308 have to focalize the attention on the relationship between CV and this field test.

309 In conclusion, from the first CV protocol proposed in 1992 by Wakayoshi and
310 colleagues (1), a number of different CV estimations have been proposed ~~in front crawl~~
311 ~~swimmers~~ but also some interesting findings suggested to update the procedure. This
312 had lead to inconsistent and potentially inaccurate results. Our proposed SOP minimizes
313 this variability by recommending to adopt (i) the equation of Wakayoshi and colleagues

314 (1) to calculate CV; (ii) the distances 200-400-800 m; (iii) a two-points based CV
315 calculation for coaches during general training and a three-points CV calculation for
316 specific race preparation and research; (iv) CV values should be evaluated according to
317 the competition and the swimming pool characteristics.

318

319

320 **Disclosure of interest**

321 The authors declare that they have no competing interest.

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