

Northumbria Research Link

Citation: Foster, Carl, de Koning, Jos, Hettinga, Florentina, Barroso, Renato, Boulosa, Daniel, Casado, Arturo, Cortis, Cristina, Fusco, Andrea, Gregorich, Halle, Jaime, Salvador, Jones, Andrew M., Malterer, Katherine R., Pettitt, Robert, Porcari, John P., Pratt, Cassie, Reinschmidt, Patrick, Skiba, Phillip, Splinter, Annabel, Gibson, Alan St Clair, Mary, Jacob St, Thiel, Christian, Uithoven, Kate and van Tunen, Joyce (2023) Competition Between Desired Competitive Result, Tolerable Homeostatic Disturbance and Psychophysiological Interpretation Determines Pacing Strategy. *International Journal of Sports Physiology and Performance*, 18 (4). pp. 335-346. ISSN 1555-0265

Published by: Human Kinetics

URL: <https://doi.org/10.1123/ijsp.2022-0171> <<https://doi.org/10.1123/ijsp.2022-0171>>

This version was downloaded from Northumbria Research Link:
<https://nrl.northumbria.ac.uk/id/eprint/51024/>

Northumbria University has developed Northumbria Research Link (NRL) to enable users to access the University's research output. Copyright © and moral rights for items on NRL are retained by the individual author(s) and/or other copyright owners. Single copies of full items can be reproduced, displayed or performed, and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided the authors, title and full bibliographic details are given, as well as a hyperlink and/or URL to the original metadata page. The content must not be changed in any way. Full items must not be sold commercially in any format or medium without formal permission of the copyright holder. The full policy is available online: <http://nrl.northumbria.ac.uk/policies.html>

This document may differ from the final, published version of the research and has been made available online in accordance with publisher policies. To read and/or cite from the published version of the research, please visit the publisher's website (a subscription may be required.)



Competition Between Desired Competitive Result, Tolerable Homeostatic Disturbance and Psychophysiological Interpretation Determines Pacing Strategy

Journal:	<i>International Journal of Sports Physiology and Performance</i>
Manuscript ID	IJSPP.2022-0171.R1
Manuscript Type:	Brief Review (Invited Only)
Date Submitted by the Author:	22-Nov-2022
Complete List of Authors:	<p>Foster, Carl; University of Wisconsin-La Crosse, Department of Exercise and Sport Science de Koning, Jos; Vrije Universiteit-Amsterdam, Department of Human Movement Sciences; University of Wisconsin-La Crosse, Exercise and Sport Science Hettinga, Florentina; Northumbria University, Sport, Exercise and Rehabilitation Barroso, Renato; University of Campinas, School of Physical Education; Boullosa, Daniel; Federal University of Mato Grosso Casado, Arturo; Rey Juan Carlos University Cortis, Cristina; Università degli Studi di Cassino e del Lazio Meridionale, Human Sciences, Society and Health Fusco, Andrea; University of Cassino and Lazio Meridionale, Department of Human Sciences, Society and Health Gregorich, Halle Jaime, Salvador; University of Wisconsin-La Crosse, Exercise and Sports Science Jones, Andrew; Exeter University, Sport and Health Sciences Malterer, Katherine; Mayo Clinic Pettitt, Robert; Force Science Ltd Porcari, John; University of Wisconsin-La Crosse, Department of Exercise and Sport Science Pratt, Cassie; University of Wisconsin-La Crosse Reischmidt, Patrick; University of Wisconsin-La Crosse Skiba, Philip; Advocate Lutheran General Hospital, Sports Medicine Splinter, Annabel ; Vrije Universiteit Amsterdam Faculteit der Betawetenschappen St Clair Gibson, Alan; University of Hull St Mary, Jacob; University of Wisconsin-La Crosse Thiel, Christian; Hochschule fur Gesundheit Uithoven, Kate; Medtronic Inc van Tunen, Joyce; VU University Amsterdam, Research Institute Move</p>
Keywords:	fatigue, pacing, homeostasis

SCHOLARONE™
Manuscripts

1 *Invited Brief Review IJSPP.2022-0171-R1*

2 **Competition Between Desired Competitive Result, Tolerable Homeostatic Disturbance and**
3 **Psychophysiological Interpretation Determines Pacing Strategy**

4 Carl Foster¹, Jos J. de Koning^{1,2}, Florentina J Hettinga³, Renato Barroso⁴, Daniel Boullosa⁵,
5 Arturo Casado⁶, Cristina Cortis⁷, Andrea Fusco⁷, Halle Gregorich¹, Salvador Jaime¹, Andrew M.
6 Jones⁸, Katherine R Malterer¹, Robert Pettitt⁹, John P. Porcari¹, Cassie Pratt¹, Patrick
7 Reinschmidt¹, Phillip Skiba^{8,12}, Annabel Splinter², Alan St Clair Gibson¹⁰, Jacob St Mary¹,
8 Christian Thiel¹¹, Kate Uithoven¹, Joyce van Tunen²

9

10 ¹ University of Wisconsin-La Crosse, USA

11 ² Vrije Universiteit-Amsterdam, The Netherlands

12 ³ University of Northumbria, UK

13 ⁴University of Campinas, Brazil

14 ⁵ Universidad Leon, Spain

15 ⁶ Rey Juan Carlos University, Spain

16 ⁷ University of Cassino & Lazio Meridionale, Italy

17 ⁸ University of Exeter, UK

18 ⁹ Force Science Ltd, USA

19 ¹⁰ Hull University, UK

20 ¹¹ Hochschule für Gesundheit, Bochum, Germany

21 ¹²Advocate Lutheran General Hospital, USA

22 Correspondence: Carl Foster, Ph.D.

23 Department of Exercise and Sport Science

24 University of Wisconsin-La Crosse

25 La Crosse, WI 54601 USA

26 Phone 608 792 2170

27 E-mail cfosteruwl@gmail.com

28 [Word Count: 4987 Abstract Length: 191](#)

29 [Figures: Tables: 8: 0](#)

30 Abstract

31 Scientific interest in pacing goes back >100 years. Contemporary interest, both as a feature of
32 athletic competition and as a window into understanding fatigue, goes back >30 years. Pacing
33 represents the pattern of energy use, designed to produce a competitive result while managing
34 fatigue of different origins. Pacing has been studied both against-the-clock and during head-to-
35 head competition. Several models have been used to explain pacing including the
36 teleoanticipation model, the central governor model, the anticipatory-feedback-RPE model, the
37 concept of a learned template, the affordance concept, the integrative governor theory and as an
38 explanation for “falling behind”. Early studies, mostly using time trial exercise focused on the
39 need to manage homeostatic disturbance. More recent studies, based on head-to-head
40 competition have focused on an improved understanding of how psychophysiology, beyond the
41 gestalt concept of RPE, can be understood as a mediator of pacing and as an explanation for
42 falling behind. More recent approaches to pacing have focused on the elements of decision
43 making during sport and have expanded the role of psychophysiological responses including
44 sensory-discriminatory, affective-motivational and cognitive-evaluative dimensions. These
45 approaches have expanded the understanding of variations in pacing, particularly during head-to-
46 head competition.

47 Index terms: pacing, homeostasis, fatigue

48 Introduction

49 The concept of pacing, i.e distributing energetic resources over the duration of a task, is not new.
50 Historical examples remind us of the necessity for pacing, ranging from Aesop's fable of the
51 tortoise and the hare; Emil Zatopek asking Jim Peters (1952 Olympic marathon) in mid-race if
52 "they were running fast enough"; Vladimir Kuts (1956 Olympic 5 & 10-km) using an interval
53 pacing pattern to defeat WR holder Gordon Pirie; Kipchoge Keino using a "go out fast" strategy
54 in the altitude of Mexico City to defeat WR holder Jim Ryun (1968 Olympic 1500m); David
55 Wottle, coming from 20-m behind after the first 200-m to win (1972 Olympic 800-m); and to
56 WR holder Steven Jones (European Championships marathon, 1986), 2-min ahead of the field at
57 20-miles, who faded and finished 13th place. In all these cases, pacing (good or bad) helped
58 define the competitive result.

59

60 Pacing is the process of using the resources available at the start, in an anticipatory manner based
61 on experience ¹, or in response to internal and external stimuli ², to achieve the desired result.
62 Often the goal is to finish as quickly as possible, particularly against-the-clock rather than head-
63 to-head. Pacing represents the balance between energy availability, technique, and fatigue.
64 Energy availability depends on energy producing systems, which depend on physiologic capacity
65 and the duration and mode of the event. Technique depends on neuromuscular performance,
66 which is of modest importance in running, but crucial in other activities (skating, cycling, cross-
67 country skiing, rowing, swimming), and may deteriorate with fatigue. For example, in cycling
68 and skating athletes are able to continue to glide or roll toward the finish even after considerable
69 losses of power output, whereas in running and swimming there is a rapid deceleration with loss
70 of power output. Fatigue, which has become better understood ³⁻⁶ depends upon either the
71 depletion of substrates (adenosine triphosphate, creatine phosphate, glucose, glycogen), the
72 accumulation of metabolites (inorganic phosphate and hydrogen ions) and heat, and functioning
73 as control processes via afferent nerves, as well as the interpretation of what these changes mean.

74 Historical Evidence of Interest in Pacing

75 The concept of pacing is not new. The first report was by Tripplet in 1898.⁷ He evaluated why
76 drafting improved performance. While describing performance improvements when following a
77 pacer, he reported distance-velocity relationships which anticipated the critical speed
78 (CS)/critical power (CP) concept.⁸ He also developed theories (suction, shelter, encouragement,
79 hypnotic suggestion) anticipating concepts of reduced wind resistance ⁹ and the ergogenic
80 effect of a competitor riding just a little faster than an athlete's personal best.¹⁰ Other studies by
81 Kennelly ¹¹ and Hill ¹², performed a century ago, described the distance-velocity relationship
82 (for running, walking, cycling, and skating). The classical study of Robinson et al.¹³, perhaps the
83 first experimental study of pacing, showed that $\dot{V}O_2$, O_2 deficit and [blood lactate] favored an
84 even pace. Thus, by ~65 years ago we knew that: 1) there was a regular distance-velocity
85 relationship that anticipated the CS/CP concept, 2) there were differences in the absolute
86 dimensions related to the mode of ambulation, 3) drafting was advantageous and 4) for tasks of

87 longer than ~3 minutes, there was an advantage to even pacing. Today we are better at
88 explaining the science behind pacing, but early concepts have endured,

89 **The Concept of Pacing Strategy Emerges**

90 The first contemporary studies of pacing emerged from groups in the Netherlands and the
91 USA.¹⁴⁻¹⁹ These studies demonstrated that: 1) there was a range of advantageous pacing
92 strategies in cycling events of 1000-4000-m (or even longer), 2) an all-out strategy was better in
93 shorter events, 3) longer events favored a brief high intensity start which was then “dialed back”
94 after ~10-15s, and, 4) more even, or U shaped, pacing patterns were seen in longer events. These
95 studies, particularly the frequent observation of an end-spurt, also established the concept that
96 high speed at the finish was essentially wasted kinetic energy that might have been better used to
97 go faster earlier and arrive at the finish sooner. Trying to improve performance (particularly in
98 events <4 min required an athlete to take a “calculated risk” of starting faster than normal, in
99 order to achieve a performance that they had never previously achieved.²⁰

100 **Teleoanticipation Model**

101 By the mid-1990's the first conceptual model of pacing emerged. Ulmer¹ suggested that energy
102 output was governed by central control mechanisms designed to: 1) avoid early fatigue, 2) not
103 waste time with a slow start, 3) use learned behavior as a template for current activity and 4)
104 anticipate the time required to finish. Thus, the *teleoanticipation model* was conceptualized as a
105 closed-loop, feedback dependent, anticipatory regulation of energetic output. About this same
106 time, evidence emerged of a replicable pattern of pacing strategy and that elite athletes used the
107 same pacing as recreational athletes.²¹ Beyond single efforts, there was evidence of pacing in the
108 Grand Tours of cycling, in which General Classification competitors would only exert
109 themselves heavily on the days when significant time gains were possible.²² On other days,
110 teammates would keep them near the front of the peloton. These findings reinforced Ulmer's
111 concept of anticipating stresses across an entire event. Less than a decade later, evidence
112 emerged of a consistent pattern in the pacing of races where the goal was to defeat other
113 competitors head-to-head.²³⁻²⁴ It also became evident that pacing displayed a consistent pattern,
114 evolving toward less of the fast-slow-slower-fast pattern observed in early 20th century.²³⁻²⁴ The
115 concept also emerged that the pacing strategy, in attempts to improve best performance, was
116 consistent over time.²⁵ Supporting Ulmer's concept, there was evidence that different events had
117 unique pacing patterns, suggesting that the anticipation of muscular power output was very
118 strongly grounded.²⁶⁻²⁹

119 **Pacing Versus Fatigue (Central Governor Model)**

120 Early concepts of fatigue were based on observations of the progressive reduction in force/power
121 output (to near zero values) in isolated skeletal muscle despite supramaximal stimulation.³⁰ It
122 was thought that muscle failure was related to factors including level of stimulation, blood flow,
123 availability of O₂ and the ability to buffer changes in pH. Observations by Noakes et al.³¹ that
124 humans rarely exercise to the point of total muscular failure suggested that fatigue was not solely
125 related to absolute levels of muscular substrates or metabolites. While there is evidence that
126 homeostatic disturbances are profound during severe exercise, and that exercise end-points

127 occurred at similar levels of homeostatic disturbance regardless of the task³²⁻³⁵, complete
128 muscle, cardiac or organ system failure rarely occurred. This evolved to the understanding that
129 fatigue acts to prevent cellular damage related to severe homeostatic disturbance.³⁶ Even
130 demanding tasks such as the Wingate test (30-s in duration), can be extended to as long as 3-min,
131 with the power output only falling as low as the CP.³⁷ These data suggested the presence of
132 bidirectional signaling between the efferent neural output and afferent signals from peripheral
133 receptors, rather than unidirectional unresponsiveness by the muscle. Noakes, St Clair Gibson
134 and Lambert³⁸⁻⁴⁰ called this bidirectional signaling the *central governor model*. This concept
135 was expanded by St Clair Gibson and Foster⁴¹ suggesting that pacing involved competition
136 between the psychological drive to perform a task and managing homeostatic disturbances. Thus,
137 although catastrophic collapses of ambulatory ability are possible, they are comparatively rare.⁴²
138 Studies of exercise in the presence of afferent blockade⁴³ supported the role of afferent signaling
139 as an obligatory feature in pacing. Evidence in support of bidirectional signaling was provided
140 by studies where warm-up was manipulated to induce fatigue before a time trial.⁴⁴ The lesson
141 from the Central Governor model was that pacing, far from being an epiphenomenon of athletic
142 competition, was a window into how fatigue was experienced and managed.

143 **Patterns of Pacing Strategy**

144 Much of the early pacing research was dominated by observations during athletic competitions.
145 Abbiss and Laursen⁴⁵ identified basic pacing strategy variants. Subsequent work from a number
146 of laboratories^{14-19,21,22,27-29,45-72}, identified physiological responses during variations in pacing
147 strategy. These studies demonstrated that pacing could be understood in terms of the power
148 balance model of van Ingen Schenau et al.^{18,19}, with power production depending on the
149 summation of aerobic and anaerobic energy provision and power losses related to summated
150 resistive forces. The first clear evidence that pacing was related to homeostatic disturbances,
151 primarily related to substrate (creatine phosphate³²⁻³⁴ and glycogen⁴⁶⁻⁴⁸ depletion, and/or
152 metabolite accumulation³²⁻³⁵ and hyperthermia⁴⁹⁻⁵¹ appeared during this time period.

153

154 Pacing strategy follows general rules related to the distance/ time taken to complete a task, and
155 displays differences related to the nature of the task, particularly the retarding medium.⁵² There is
156 evidence of “reserve” built into pacing strategy^{53,54} that can be disrupted by deception regarding
157 distance feedback and influenced by another competitor (or avatar) that is slightly faster than an
158 athlete's previous performances⁶⁰⁻⁶⁵, but hindered if the other competitor is too much faster.⁶⁵⁻⁶⁹
159 These findings suggest that the reserve during exercise tasks can be manipulated, either by
160 time/distance deception or the meaningfulness of the competition (club race vs Olympic final), .
161 Further, the most predictable strategy to improve performance is a faster than normal start.
162 However, only about 50-80% of fast start experiences will lead to improved performance.<sup>65-
163 69,73,73,76</sup> Head-to-head racing against a much superior opponent can lead to both an
164 inappropriately rapid increase in Rating of Perceived Exertion (RPE), and a negative affect and
165 loss of self-efficacy during the race, leading to reductions in speed/power output (i.e. letting go
166 of the leading competitors).⁷³⁻⁷⁵

167

168 The structure of the pacing pattern (Figure 1), at least against-the-clock has been conceptualized
169 as a “landscape” where the interaction of race distance and percent of the race completed define
170 momentary power output, regardless of whether power output is attributable to aerobic or
171 anaerobic energetic sources.^{77,78}

172

Insert Figure 1 About Here

173

Rating of Perceived Exertion

174 Several studies have shown that RPE grows in a systematic manner in relation to the percent of a
175 task completed.^{25,28,29,79-89} This suggests a scaling of RPE to the overall level of homeostatic
176 disturbance, regardless of the precise nature of the disturbance. The rate of RPE growth during
177 an event appears to be tightly regulated, as blinded changes in inspired [O₂] cause a rapid change
178 in muscular power output while the rate of RPE growth barely changes.^{80,89-91} Similarly, while
179 changes in pre-exercise muscle glycogen exert a consequential influence on power output, the
180 growth of RPE normalized to endurance time hardly changes.⁹²

181 The overriding importance of RPE as a way to express the sensation of both intensity and
182 progressive fatigue is so powerful that the third major conceptual model of pacing, the
183 *anticipatory-feedback-RPE* model^{93,94} proposes that power output is regulated based on prior
184 experience, anticipated completion time and rate of growth of RPE. If the rate of growth of RPE
185 is discordant with that anticipated, then power output is either up- or down-regulated to return
186 RPE to the anticipated growth curve (Figure 2). This concept has been supported in studies
187 where power output was increased by mid-race tactical decisions^{81,91} or deception regarding the
188 distance remaining.^{60,64}

189

Insert Figure 2 About Here

190 The growth of RPE relative to the percent of an event remaining has been combined into a
191 derived variable called the Hazard Score (momentary RPE x fractional distance remaining)
192 which seems to be able to inform athletes when to change power output during an event.^{82,84,95,96}
193 An extension of this technique, the summated Hazard Score, has been shown to allow
194 appreciation of how taxing an event feels.⁹⁶

195 For as important as the RPE has been to understanding pacing, it has been recognized that RPE is
196 a gestalt of a number of sensory inputs which reflect how a given power output, progress through
197 an event and homeostatic disturbance is interpreted. As such, RPE has been criticized as a less
198 than ideal psychophysiological marker, with other measures being regarded a potentially more
199 discriminatory. Do Carmo et al.⁶⁶ and Renfree et al.^{97,98} have demonstrated that another
200 psychophysiological construct, the affect (or valence) toward a task (degree to which momentary
201 effort is viewed as pleasant or unpleasant) is more explanatory of when an athlete is having a
202 good or bad performance, despite identical RPE growth. Thus, affect appears superior to RPE in
203 the heuristic type of decision-making processes which athletes often use. Given the importance
204 of head-to-head competition in augmenting performance^{68,97-100}, the ability of athletes to solve
205 the performance challenges raised by their own physiology, the capacity and tactics of their

206 opponents and challenges presented by the course and environment requires a more granular
207 psychophysiological tool than RPE.

208 Venhorst, Micklewright and Noakes⁷³⁻⁷⁵ have shown that affect (valence) and RPE grow
209 differently during head to head competition and reflect of the degree to which an athlete is
210 “winning” or “losing” a competition. In particular, changes in affect (valence) reflect the point
211 in a competition when athletes first begin to fall behind and then “disengage” from their
212 competitors (action crisis).⁷³⁻⁷⁵ They suggest that psychophysiological regulation of exercise
213 behavior can be viewed in three dimensions. The first is perceived physical and mental strain,
214 reflecting sensory-discriminatory processes akin to homeostatic disturbances. The second is
215 affect and arousal reflecting the interpretation of effort as pleasant-unpleasant, and the
216 momentary level of arousal. This can be viewed as interpreting whether increasing level of
217 discomfort is worth continued effort. The third is cognitive-evaluative process, what they term
218 as an “action crisis” or “letting go” of their opponent in mid race. Their model accounts for
219 traditional homeostatic challenges provided by a task, how pleasant or unpleasant the task is, and
220 how willing they are to continue to compete.

221 **The Pacing Template (self-regulation model)**

222 One striking element of pacing is how difficult it is to disrupt freely chosen patterns. Monetary
223 incentives to improve performance by going out faster have little effect.¹⁰¹ Conscious pre-race
224 decisions to select different strategies have small effects on the actual pacing pattern used, at
225 least in against-the-clock events.^{81,91} Pairing with a faster opponent can improve performance,
226 but only when the opponent/avatar is seen as a realistic “rival” and “within reach” of the best
227 current performance.⁶⁸⁻⁷² Otherwise, the riders “let the superior rider go”. This corresponds to
228 the action crisis described by Venhorst et al.⁷³⁻⁷⁵ Apparently, the magnitude of “reserve” within
229 pacing strategy can be revised by changing the focus from anticipatory-internal monitoring
230 (against the clock) to relative positional-external monitoring (head-to-head) so long as
231 homeostatic changes are not ignored.

232

233 Within race experimental manipulations, such as exposing participant to sudden onset episodes
234 of hypoxia and hyperoxia, can rapidly change the pattern of power output.^{28,80,89,90,102} However,
235 blinded exposure to simulated altitude in the minutes immediately before the start of an event
236 does little to change the early pattern of power output.^{89,90} Even exposure to simulated altitude
237 during the warm-up period, sufficient to result in increases in heart rate, blood [lactate] and RPE,
238 does little to influence power output during the opening segment of time trials (Figure 3).

239 Beyond this initial phase, with opportunity for afferent feedback to express itself, there is a large
240 negative effect consistent with that expected in hypoxia.¹⁰² There is a large negative effect of
241 pre-race glycogen depletion in events ranging from 1500m (~2 min) to 4000m (~5 min)¹⁰²
242 (Figure 3) to 1-hour.⁴⁸ Power output in the early stages of a time trial is only modestly affected
243 by glycogen depletion (Figure 4). During warm-up, there is an increased heart rate, decreased
244 blood [lactate] and increased RPE, expected with glycogen depletion. Similarly, strategies
245 designed to increase muscle glycogen content, resulting in improved performance, do not exert

246 an effect until later within an event.^{46,47} Evidence supports the presence of a pre-exercise
247 template, which is a learned behavior, specific to competitive circumstances.¹⁰³ Learning may
248 take several trials, and typically evolves as a faster early pace (e.g. less “reserve”). In time trial
249 events, this learned strategy seems very hard to override, despite conditions in the warm-up that
250 might be expected to reset the template.¹⁰⁷ In head-to-head competitions it is possible to reset the
251 template. This supports data regarding the development of pacing strategies in youth athletes of
252 the need for experience to develop self-regulating strategies.^{105,106}

253 **Insert Figure 3-4 About Here**

254 In fit people, with minimal time trial experience, there is evidence of modifications in the
255 template with repeated time trials¹⁰³, that may take ≥ 6 trials. In athletes attempting to improve
256 their best performance, the pacing pattern is more or less similar, with the exception that the
257 opening segment is slightly faster, suggesting that improved performance is more attributable to
258 improved physiologic capacity than to pacing.²⁵ Empirical evidence suggests that competitive
259 performance may improve when novel pacing strategies are employed during practice or less
260 important competitions, in order to reset the template.¹⁶

261

262 Specific attempts to influence the pacing strategy, such as by mid-race “break away” efforts^{81,91}
263 support the concept of a template, in that upward speed departures from a normal template in 10-
264 20 km time trials are marked by a subsequent reduction of power output until homeostatic
265 disturbances (heart rate, blood [lactate], RPE, muscle O₂ saturation) return toward normal, at
266 which time the template is resumed (Figure 5). Similarly, attempts to force starting ~5% faster
267 or slower over the first 30% of a time trial show a rapid return to the “best race” template as soon
268 as the experimental constraints are removed.⁹⁶

269 **Insert Figure 5 About Here**

270 **Pacing Strategy vs Racing Strategy**

271 Early research on pacing was mostly conducted on events where performance was against the
272 clock, the competitive pattern in pursuit cycling, one-hour cycling, metric style speed skating and
273 swimming. Many events where pacing might be important are decided based on relative placing
274 rather than absolute time, leading to a more stochastic pacing pattern.¹⁰⁷⁻¹¹³ These events
275 demonstrate evidence of variations in starting strategy and of an end-spurt. Additionally, they
276 display evidence of intentional variations in speed or power output. Within a single elite athlete,
277 WR or best performances are often characterized by small variations in momentary speed (e.g.
278 low coefficient of variation). Championship races are often characterized by frequent, potentially
279 pre-planned, variations in momentary speed and high speed during the end-spurt, high coefficient
280 of variation Variations in pacing seem designed to drop weaker competitors from the leading
281 group and reduce the number of competitors in contention before the end-spurt occurs.¹⁰⁷⁻¹¹³

282

283 Hettinga et al.⁶⁸ discussed the role of opponents in pacing, using ecological principles and the
284 affordance hypothesis. They explored mechanisms of interactive behavior, proposing a pacing
285 framework to understand head-to-head competition in which both internal (e.g. fatigue) and
286 external (e.g. opponent) factors interact. Support for this model was obtained through a series of
287 laboratory and field studies^{67,68} pacing behaviors of other exercisers⁶⁹ and different competitive
288 circumstances. In addition to a preplanned template, interactions with competitors and other
289 environmental aspects play roles that have been described as the *affordance concept*, wherein
290 the actions of the opponents afford the athlete with a range of possibilities to modify pre-planned
291 strategies.^{67-69,76}

292
293 St Clair Gibson, Swart and Tucker¹¹⁴ proposed the *Integrative Governor Theory* proposing a
294 continuous oscillation between psychological drives (e.g. competitive goals) and homeostatic
295 disturbances that serves to regulate momentary power output. Both concepts highlight the
296 complexity of the processes regulating momentary power output, and highlights the
297 meaningfulness of competition and actions of opponents are drivers of competitive strategy.
298 Additionally, since slower starting strategies reduce feelings of effort during competition⁹⁶, there
299 is a tendency in head-to-head competition to start slower than the best performance strategy,
300 insert competitive “surges”, and recovery sections, and rely on the end-spurt to win the race. This
301 is true unless the athlete perceives that their own end-spurt might be inadequate to match other
302 competitors, whereupon higher intensity segments might be inserted to neutralize the end-spurt
303 of other athletes, or to force them to drop off mid-race. This is an example of the *concept of*
304 *affordances*. Head-to-head races use best performance strategy, until the actions or perceived
305 capabilities of opponents afford the opportunity to use stochastic pacing. This is particularly true
306 in aerodynamic (cycling, speed skating) or hydrodynamic (rowing, swimming) events where the
307 cost of locomotion can be influenced by pacing, or where the pacing of teammates (cycling, pack
308 style skating or team pursuit skating) or adversaries (Grand Tours, open water swimming) can
309 influence energy cost. It is even possible that an athlete may go to the front, with the intention of
310 slowing the pace, if they perceive that they cannot effectively complete the pace their opponents
311 have adopted. In other words, starting with the best performance strategy as a default, pacing in
312 head-to-head competitive events can be modified almost infinitely depending on the real or
313 potential behavior of competitors. However, the overriding need to limit the magnitude of
314 homeostatic disturbances remains, causing competitors to change from the externally monitored
315 competitive strategy back to the internally monitored best performance (e.g. survival) strategy.
316 Opponents have thus been called social placebo’s/nocebos, influencing expectations regarding
317 successful/unsuccessful pacing and performance.¹¹⁵

318

319 **Critical Speed and Pacing**

320 Critical Speed (CS) or Power (CP) is the speed /power associated with highest sustainable
321 metabolic rate.⁸ This is derived from the asymptote for the hyperbolic speed-time or power-time
322 relationship, recognized for nearly 60 years^{7,8}, and anticipated before the turn of the 20th
323 century.¹¹ Although not exactly the same, CS/CP approximates the physiological intensity of the
324 maximal lactate steady state (MLSS), the 2nd ventilatory threshold (VT2) or the 2nd lactate
325 threshold (LT2).^{8,116} CS/CP is at least as explanatory of endurance performance as VO₂max and
326 VT. If the CS/CP explains the upper limit of sustainable aerobic power, the concept of D’ (or
327 W’) representing the curvature constant of the speed-time or power-time relationship, accounts

328 for additional non-oxidative energetic capacity during exercise above CS/CP. The momentary
329 balance of W'/D' can explain the likelihood of needing to decrease power output during severe
330 exercise or the ability to increase power output in service of competitive goals.^{117,118} This
331 “anaerobic” energy can be used as needed to sustain metabolic rates in excess of CS/CP in
332 shorter events (<15 min), to make mid-race surges, or during the end-spurt. Using direct
333 measurement of anaerobically attributable energy supply, there is evidence^{78,120,121} that, within an
334 individual, the magnitude of anaerobically attributable energy (e.g. D'), after adjustment for
335 changes in gross efficiency, may be more or less constant.⁸⁰ There is evidence supporting the
336 concept that the D'/W' may be reconstituted if, during the middle of an event, the speed/power
337 output decreases below CS/CP.^{117,118} Examining the pacing of elite runners during 10-km
338 competitions, it is evident that WR performances are performed close to CS, whereas important
339 races (Olympic finals) are contested with an average speed <CS, but with tactical bursts above
340 CS (Figure 6).^{107,121} Pacing in groups of runners (first 3, middle 3 and last 3) in an Olympic final,
341 shows that better runners run much of the early part of the event <CS, preserving D' for the end-
342 spurt, whereas less good runners run the early part of the event > CS in order to stay with the
343 early pace, thus limiting energetic reserve (D') to contest the last laps (Fig 7). This concept has
344 been called the D' balance¹¹⁸. On this basis, it would be expected that the D' balance would fall
345 to very low values near the end of a race. Recent evidence from WR 1-mile races (entirely >CS)
346 and high level 800-m swimming races^{120,121} supports this expectation (Figure 8). Additional
347 evidence from the 2008 Olympic men’s 10-km race indicates that the CS/ D' balance could
348 predict how high-level races unfolded, including evidence that the 80% of athletes falling out of
349 contention before the end-spurt do so, often by mid race, when D' reaches critically low levels
350 and that D' often increases during the remainder of the race as they are running <CS (e.g.
351 survival mode). However, in the 20% remaining in contention until the last 400-m, the
352 magnitude of D' falls to very low values only at the end of the race (Figure 8).¹²¹ Recent
353 evidence suggests that the magnitude the end-spurt was related to how well runners were able to
354 preserve D' until the last 400-m and that superior athletes might win or lose competitions based
355 on good or poor management of D' .¹¹⁰

356 **Insert Figure 6 About Here**

357 **Insert Figure 7 About Here**

358 **Insert Figure 8 About Here**

359 The CS/CP and D'/W' seem to be as definitional of performance level and pacing strategy as
360 were prior candidates such as VO_2 max, LT/VT and the O_2 cost of running.^{8,122,123} While these
361 metrics are still powerful predictors of the ability to move at a certain pace, the concept of an
362 anaerobic capacity¹²⁴, and how it is deployed during the course of an event, represented by the
363 concept of D' is useful for analysis of performance, for explaining why some athletes drop off
364 the leading group during mid-race, and why some athletes have particularly effective end-
365 spurts.¹¹⁰

366 The CS/CP may also explain, at least in part, athletes’ predisposition to use a fast start strategy
367 during shorter, high-intensity events. There is evidence that such an approach speeds VO_2

368 kinetics, leading to a greater aerobic contribution in the early phase of exercise, thereby sparing
369 D'/W' . This effect of a fast start strategy on VO_2 kinetics also increases CP compared to that
370 established using constant-work-rate protocols. The pattern of D'/W' use during short-duration
371 exhaustive exercise, where W' starts at 100% and finishes near 0 %, will also be altered by a U-
372 shaped (relatively fast start and finish) compared to more even pacing. The regularly-adopted U-
373 shaped pacing strategy may be a behavioral evolution not only because it is likely to be
374 performance enhancing, but also because it would result in a higher W'/D' over a large fraction
375 of the mid-race, potentially making the exercise feel more tolerable.

376 **Neuromuscular Factors**

377 Since the paper by Paavolainen et al.¹²⁵, it is well-accepted that “muscle power factors”
378 contribute to performance. The contribution of neuromuscular factors to pacing in endurance
379 events has been scarcely addressed. Damasceno et al.¹²⁶ documented that improvements in
380 strength influenced the last 2.8-km of 10-km races. This finding agrees with cross-sectional
381 studies reporting positive influences of diverse neuromuscular performances on pacing in
382 endurance athletes. Intervention studies have suggested potentiation effects of strength exercises
383 during warming up on the first laps of short time trials in runners¹²⁷⁻¹³⁰, cyclists¹³¹ and rowers
384¹³², without improving overall performance. Conversely, impaired neuromuscular function after
385 static stretching¹³³ reduced the starting speed of 3-km running trials without affecting the final
386 time. Therefore, current evidence suggests that neuromuscular function and post-activation
387 performance enhancement would allow optimal pacing behaviors while counteracting the effects
388 of fatigue.¹³⁴

389

390 One of the most consistent and striking findings in the pacing literature is the near universal
391 presence of the end-spurt in events of >2-3 min duration, particularly in head-to-head
392 competition. Presumably this evidence of “reserve” in the pattern of energetic expenditure is
393 hard-wired into exercise patterns by virtue of evolutionary history as hunter-gatherers, who
394 needed to preserve reserve until “closing in for the kill”.¹³⁵ It can be argued that the interaction of
395 muscle fiber type, lactate accumulation, preservation of anaerobic reserve (D') can act to define
396 pacing. Athletes with a higher %Type II motor units are predisposed to have more top-end power
397 or speed.^{136,137} However, since higher % Type II motor units have a lower muscle respiratory
398 capacity and lactate threshold (a surrogate of CS¹³⁸), it is likely that the consistent pattern of
399 runners with a higher %Type I fibers attempt to “burn off” lesser runners¹⁰⁷ is representative of
400 the need to remove the inherently better sprinters before the competitively critical moment of the
401 race. Certainly, the best evidence is that the athletes winning in the final sprint are those who
402 have best preserved their anaerobic capacity (D').¹¹⁰ Thus, the essential pacing decision within an
403 event is whether natural sprinters (high %Type II motor units, high D') can remain in contact
404 with more endurance-oriented athletes (high % Type I motor units, high muscle respiratory
405 capacity, high CS).

406 **Conclusion**

407 Pacing strategies have been of interest to exercise physiologists for at least the last 30-years.
408 Several models have emerged through the years attempting to predict the optimal pattern to
409 finish an event without excess fatigue or excess remaining energy at the finish. These models
410 have shown that pacing reflects a complex relationship between environmental stressors,
411 physiological feedback, and psychological drive with a default pattern of a relatively “even”
412 pacing strategy with a brief “fast start” to optimize time-centric vs head-to-head competition.
413 These templates are robust even in the face of conditions that predictably would change them
414 (hypoxia, glycogen depletion, etc.). Athletes revert to the baseline template unless there is
415 conscious effort to change for tactical reasons. However, templates may have progressive
416 modifications through repeated performances. Once an “ideal” pacing template is achieved, the
417 athlete may use the “concept of affordances” to modify pacing based on events occurring within
418 an event. Although progressive growth of RPE is characteristic of pacing, more subtle
419 psychodynamic factors such as affect (valence) appear to be more discriminatory than RPE on
420 whether an athlete remains with competitors or “lets go” part way through an event.

421 **Practical Applications**

422 Pacing, the way an athlete expends energy during a competition, depends on several factors.
423 Although the term pacing strategy is widely used, the term is probably too broad, as “strategy”
424 encompasses the overall race plan, the tactics used to accomplish the strategy, and the highly
425 responsive pattern of energy expenditure, are all designed to achieve competitive outcome. The
426 first is the competitive result (best performance vs defeating competitors). This will lead to
427 whether the pattern of energetic output is smooth and based on the time-distance characteristics
428 of the event or stochastic, where energetic output is focused on “dropping” competitors or
429 preserving energy for the end-spurt. To accomplish these goals, an athlete needs to have a sense
430 of their own capacity and be able to interpret internal feedback indicating the magnitude of
431 homeostatic disturbances. They also need to have a good sense of their competitor’s capabilities
432 and be able to interpret signals from their competitors, in order to vary their tactics. Thus, while
433 pacing strategy is not likely to discriminate between athletes of widely varying ability, it may be
434 critical to achieving a desired competitive result in a tolerable physiological state.

435

436 **References**

- 437 1. Ulmer H-V. Concept of an extracellular regulation of muscular metabolic rate during
438 heavy exercise in humans by psychophysiological feedback. *Experienta*. 1996; 52: 416-
439 420.
- 440 2. Smits B, Pepping GJ, Hettinga FJ. Pacing and decision-making in sport and exercise: On
441 the roles of perception and action in the regulation of exercise intensity. *Sports Med*.
442 44(6) (2014) 763-75.
- 443 3. Enoka RM, Duchateau J. Translating fatigue to human performance. *Med Sci Sports*
444 *Exerc*. 2016; 48: 2222-2238.
- 445 4. Marcora SM, Staiano W. The limit to exercise tolerance in humans: mind over muscle?
446 *Eur J Appl Physiol*. 2010; 109: 763-770.
- 447 5. Marcora SM. Do we really need a central governor to explain brain regulation of exercise
448 performance. *Eur J Appl Physiol*. 2008; 104: 929-931.
- 449 6. Edwards AM, Polman RCJ. Pacing and awareness: Brain regulation of physical activity.
450 *Sports Med*. 2013; 43: 1057-1064.
- 451 7. Triplett N. The dynamogenic factors on pacemaking and competition. *Am J Psychol*.
452 1898; 9: 507-533.
- 453 8. Vanhatalo A, Jones AM, Burnley M. Application of critical power in sport. *Int J Sports*
454 *Physiol Perf*. 2011; 6: 128-136.
- 455 9. Pugh, L.G.. The influence of wind resistance in running and walking and the mechanical
456 efficiency of work against horizontal or vertical forces. *The Journal of Physiology*. 1971;
457 213, 255–276.
- 458 10. Konings MJ, Hettinga FJ. Pacing decision making in sport and the effects of
459 interpersonal competition: A critical review. *Sports Med*. 2018; 48: 1829-1843.
- 460 11. Kennelly AE. An approximate law of fatigue in the speeds of racing animals. *Proc Am*
461 *Acad Arts Sci*. 1906; 42: 275-331.
- 462 12. Hill AV. The physiological basis of athletic records. *Lancet*. 1925; Sept 5: 481-486.
- 463 13. Robinson S, Robinson DL, Mountjoy RJ, Bullard RW. Influence of fatigue on the
464 efficiency of men during exhausting runs. *J Appl Physiol*. 1958; 12: 197-201.
- 465 14. Van Ingen Schenau GJ, de Koning JJ, de Groot G. The distribution of anaerobic energy
466 in 1000 and 4000 metre cycling bouts. *Int J Sports Med*. 1992; 13: 447-451.
- 467 15. Foster C, Snyder AC, Thompson NN, Green MA, Foley M, Schragger M. Effect of pacing
468 strategy on cycle time trial performance. *Med Sci Sports Exerc*. 1993; 25: 383-388.
- 469 16. Foster C, Schragger M, Snyder AC, Thompson NN. Pacing strategy and athletic
470 performance. *Sports Med*. 1994; 17: 77-85.
- 471 17. De Koning JJ, Bobbert MF, Foster C. Determination of optimal pacing strategy in track
472 cycling with an energy flow model. *J Sci Med Sport*. 1999; 2: 266-277.
- 473 18. De Koning JJ, de Groot G, van Ingen Schenau GJ. A power equation for the sprint in
474 speed skating. *J Biomech*. 1992; 25: 573-580.
- 475 19. Van Ingen Schenau GJ, de Koning JJ, de Groot G. A simulation of speed skating
476 performances based on a power equation. *Med Sci Sports Exerc*. 1990; 22: 718-728.
- 477 20. Roelands B, de Koning JJ, Foster C, et al. Neurophysiological determinants of theoretical
478 concepts and mechanisms of pacing. *Sports Med*. 2013; 43: 301-311.

- 479 21. Foster C, de Koning JJ, Hettinga F, et al. Pattern of energy expenditure during simulated
480 competition. *Med Sci Sports Exerc.* 2003; 35: 826-831.
- 481 22. Foster C, Hoyos J, Earnest C, Lucia A. Regulation of energy expenditure during
482 prolonged athletic competition. *Med Sci Sports Exerc.* 2005; 37: 670-675.
- 483 23. Noakes TD, Lambert MI, Hauman R. Which lap in the slowest? An analysis of 32 world
484 record performances. *Br J Sports Med.* 2009; 43: 760-764.
- 485 24. Foster C, de Koning JJ, Thiel C. Evolutionary patterns of improved 1-mile running
486 performance. *Int J Sports Physiol Perf.* 2014; 9: 715-719.
- 487 25. Foster C, de Koning JJ, Thiel, et al. Beating yourself: How do runners improve their own
488 records? *Int J Sports Physiol Perf.* 2020; 15: 437-440.
- 489 26. Foster C, de Koning JJ, Hettinga F, Lampen J, Dodge C, Bobbert M, Porcari JP. Effect of
490 competitive distance on energy expenditure during simulated competition. *Int J Sports
491 Med.* 2004; 25: 198-204.
- 492 27. De Jong J, van der Meijden L, Hamby S, et al. Pacing strategy in short cycling time trials.
493 *Int J Sports Physiol Perf.* 2015; 10: 1015-1022.
- 494 28. Joseph T, Johnson B, Battista RA, et al. Perception of fatigue during simulated
495 competition. *Med Sci Sports Exerc.* 2008; 40: 381-386.
- 496 29. Foster C, de Koning JJ, Bischel S, et al. Pacing strategies for endurance performance. In:
497 *Endurance Training: Science and Practice*, Mujika I (ed), Victoria Gasteiz, 2012.
- 498 30. Halperin I, Aboodarda SV, Basset FA, et al. Pacing strategies during repeated maximal
499 voluntary contractions. *Eur J Appl Physiol.* 2014; 114: 1413-1420.
- 500 31. Noakes TD. Fatigue is a brain-derived emotion that regulates the exercise behavior to
501 ensure the protection of whole body homeostasis. *Front Physiol.* 2012; 3: 1-13.
- 502 32. Karlsson J, Saltin B. Lactate, ATP and CP in working muscle during exhaustive exercise
503 in man. *J Appl Physiol.* 1970; 29: 598-602.
- 504 33. Jones AM, Wilkerson DP, Di Menna F, Fulford J, Poole DC. Muscle metabolic
505 responses to exercise above and below the “critical power” assessed using 31P MRS. *Am
506 J Physiol Regul Intergr Comp Physiol.* 2008; 294: R585-R593.
- 507 34. Vanhatalo A, Fulford J, Di Menna FJ, Jones AM. Influence of hyperoxia on muscle
508 metabolic responses and the power-duration relationship during severe-intensity exercise
509 in humans: a 31P magnetic resonance spectroscopy study. *Exptl Physiol.* 2010; 95: 528-
510 540.
- 511 35. Laurencio TF, Nunes LAS, Martins LEB, Brenzikovfer R Macedo PV. The performance
512 in 10km races depends on blood buffering capacity. *J Athl Enhancement* 2019; 8:1-7.
- 513 36. Black MI, Jones AM, Blackwell JR, et al. Muscle metabolic and neuromuscular
514 determinants of fatigue during cycling in different intensity domains. *J Appl Physiol.*
515 2017; 122: 446-459.
- 516 37. Vanhatalo A, Doust JH, Burnley M. Determination of critical power using a 3-min all-out
517 cycling test. *Med Sci Sports Exerc.* 2007; 39: 5465-555.
- 518 38. St Clair Gibson A, Noakes TD. Evidence for complex system integration and dynamic
519 neural regulation of skeletal muscle recruitment during exercise in humans. *Br J Sports
520 Med.* 2004; 38: 797-806.

- 521 39. Lambert EV, St Clair Gibson A, Noakes TD. Complex systems model of fatigue:
522 integrative homeostatic control of peripheral physiological systems during exercise in
523 humans. *Br J Sports Med.* 2005; 39: 52-62.
- 524 40. Noakes TD, St Clair Gibson A, Lambert EV. From catastrophe to complexity: a novel
525 model of integrative central neural regulation of effort and fatigue during exercise in
526 humans: summary and conclusions. *Br J Sports Med.* 2005; 39: 120-124.
- 527 41. St Clair Gibson A, Foster C. The role of self talk in the awareness of physiological state
528 and physical performance. *Sports Med.* 2007; 12: 1029-1044.
- 529 42. St Clair Gibson A, de Koning JJ, Thompson KG, et al. Crawling to the finish line: Why
530 do endurance runners collapse? *Sports Med.* 2013; 43: 413-424.
- 531 43. Amann M. Central and peripheral fatigue: Interaction during cycling exercise in humans.
532 *Med Sci Sports Exerc.* 2011; 43: 2039-2045.
- 533 44. Burnley M, Doust J, Jones AM. Effects of prior warm-up regime on severe intensity
534 cycling performance. *Med Sci Sports Exerc.* 2005; 37:830-845.
- 535 45. Abbiss CR, Laursen PB. Describing and understanding pacing strategies during athletic
536 competition. *Sports Med.* 2008; 238-252.
- 537 46. Karlsson J, Saltin B. Diet, muscle glycogen and endurance performance. *J Appl Physiol.*
538 1971; 31: 203-206.
- 539 47. Bergstrom J, Hermansen L, Hultman E, Saltin B. Diet, muscle glycogen and physical
540 performance. *Acta Physiol Scand.* 1967; 71: 140.150.
- 541 48. Rauch GGL, St Clair Gibson A, Lambert EV, Noakes TD. A signaling role for muscle
542 glycogen in the regulation of pace during prolonged exercise. *Br J Sports Med.* 2005; 39:
543 36-38.
- 544 49. Gonzalez-Alonso J, Teller C, Anderson SL, et al. Influence of body temperature on the
545 development of fatigue during prolonged exercise in the heat. *J Appl Physiol.* 1999; 86:
546 1032-1039.
- 547 50. Crew H, Tucker R, Noakes TD. The rate of increase in the Rating of Perceived Exertion
548 predicts the duration of exercise to fatigue at a fixed power output in different
549 environments. *Eur J Appl Physiol.* 2008; 103: 569-577.
- 550 51. Levels K, de Koning JJ, Broekhuijzen I, et al. Effects of radiant heat exposure on pacing
551 pattern during a 1150km cycling time trial. *J Sports Sci.* 2013; doi
552 10.1080/02640414.2013.86283.
- 553 52. De Koning JJ, Foster C, Lucia A, et al. Using modeling understand how athletes in
554 different disciplines solve the same problem: swimming vs running vs speed skating. *Int*
555 *J Sports Physiol Perf.* 2011; 6: 276-280.
- 556 53. Swart J, Lamberts RP, Lampert MI, Lambert EV, Woolrich RW, Johnson S, Noakes TD.
557 Exercising with reserve: exercise regulation by perceived exertion in relation to duration
558 of exercise and knowledge of endpoint. *Br J Sports Med.* 2009; 43:775-781.
- 559 54. Swart J, Lamberts RP, Lambert MI, St Clair Gibson A, Lambert EV, Skowno J, Noakes
560 TD. Exercising with reserve: evidence that the central nervous system regulates
561 prolonged exercise performance. *Br J Sports Med.* 2009; 43:782-788.

- 562 55. Hettinga FJ, de Koning JJ, Schmidt LJI, Wind NAC, MacIntosh BR, Foster C. Optimal
563 pacing strategy: from theoretical modeling to reality in 1500-m speed skating. *Br J*
564 *Sports Med.* 2011; 45: 30-35.
- 565 56. De Koning JJ, Foster C, Lampen J, Hettinga F, Bobbert MF. Experimental evaluation of
566 the power balance model of speed skating. *J Appl Physiol.* 2005; 98: 227-233.
- 567 57. Azevedo RA, Milioni F, Morias JN, Bertucci R, Millet GY. Dynamic changes of
568 performance fatiguability and muscular O₂ saturation in a 4-km cycling time trial. *Med*
569 *Sci Sports Exerc.* 2021; 613-623.
- 570 58. Casado A, Hanley B, Jimenez-Reyes P, Renfree A. Pacing profiles and tactical behavior
571 of elite runners. *J Sport Health Sci.* 2021; 10: 532-549.
- 572 59. Mickelwright D, Kegerreis S, Raglin J, Hettinga FJ. Will the conscious-unconscious
573 pacing quagmire help elucidate the mechanisms of self-paced exercise: New
574 opportunities in dual process theory and process tracing mechanisms. *Sports Med.* 2017;
575 47: 1231-1239.
- 576 60. Albertus Y, Tucker R, St Clair Gibson A, Lambert EV, Hampson DB, Noakes TD.
577 Effect of distance feedback on pacing strategy and perceived exertion during cycling.
578 *Med Sci Sports Exerc.* 2005; 37: 461-468.
- 579 61. Jones HS, Williams EL, Bridge CA, Merchant D, Midgley AW, Mickelwright D, Mc
580 Naughton LR. Physiological and psychological effects of deception on pacing strategy
581 and performance. *Sports Med.* 2013; 43: 1243-1257.
- 582 62. Stone MR, Thomas K, Wilkerson M, Jones AM, St Clair Gibson A, Thompson KG.
583 Effect of deception on exercise performance: Implications for determinants of fatigue in
584 humans. *Med Sci Sports Exerc.* 2012; 44: 534-541
- 585 63. Stone MR, Thomas K, Stevenson E, St Clair Gibson A, Jones AM, Thompson KG.
586 Exploring the performance reserve: Effect of different magnitudes of power output
587 deceptions on 4000-m cycling time-trial performance. *PLoS ONE* 2017; 12:e0173120.
- 588 64. Schallig W, Veneman T, Noordhof DA, Rodriguez-Marroyo JA, Porcari JP, de Koning
589 JJ, Foster C. The role of Rating of Perceived Exertion template in pacing. *Int J Sports*
590 *Physiol Perf.* 2018; 13:367-373.
- 591 65. Do Carmo EC, Renfree A, Vieira CYN, Ferreira DIS, Truffi GA, Barroso R. Effects of
592 different goal orientation and virtual opponents' performance level on pacing strategy
593 and performance in cycling time trials. *Eur J Sports Sci.* 2021;
594 doi.org/10.1080/1746391.2021.1880645.
- 595 66. Do Carmo EC, Barroso R, Renfree A, de Silva R, Gil S, Tricoli V. Affective feelings
596 and perceived exertion during a 10-km time trial and head-to-head running race. *Int J*
597 *Sports Physiol Perf.* 2020; 11: 736-741.
- 598 67. Konings M, Hettinga FJ. Objectifying tactics: Athlete and race variability in elite short
599 track speed skating. *Int J Sports Physiol Perf.* 2018; 13: 170-175.
- 600 68. Hettinga FJ, Konings M, Pepping GJ. Regulation of exercise intensity in head-to-head
601 competition: the science behind racing against opponents. *Front Physiol.* 2017; 8:118.
- 602 69. Konings M, Foulsham T, Mickelwright D, Hettinga FJ. Pacing decision making in sports
603 and the effects of interpersonal competition: a review. *Sports Med.* 2018; 48: 1829-1843.

- 604 70. Losnegard T. Energy system contribution during competitive cross-country skiing. *Eur*
605 *J Appl Physiol.* 2019; 119:1675-1690.
- 606 71. Staunton CA, Colyey SL, Karlsson O, Swarece M, Ihalanen S, McGawley K.
607 Performance and micro-pacing strategies in a freestyle cross-country skiing distance race.
608 *Front Sport Act Living.* 2022; 4:834424
- 609 72. Do Carmo EC, Barroso R, Renfree A, Gil S, Tricoli V. Influence of an enforced fast
610 start on 10-km running performance. *Int J Sports Physiol Perf.* 2016; 11: 732-741.
- 611 73. Venhorst A, Mickelwright DP, Noakes TD. The psychophysiological determinants of
612 pacing behavior and performance during prolonged endurance exercise: a performance
613 level and competition outcome comparison. *Sports Med.* 2018; 48: 2387-2400.
- 614 74. Venhorst A, Mickelwright DP, Noakes TD. Towards a three-dimensional framework of
615 centrally regulated and goal directed exercise behavior: a narrative review. *Br J Sports*
616 *Med.* 2018; 52: 957-966.
- 617 75. Venhorst A, Mickelwright DP, Noakes TD. Modelling the process of falling behind and
618 its psychophysiological consequences *Br J Sports Med.* 2018; 52: 1523-1528.
- 619 76. Konings M, Schoelmakens PP, Walker A, Hettinga FJ. The behavior of an opponent alters
620 pacing decisions in 4-km cycling time trials. *Physiol and Behav.* 2015; 158: 1-5.
- 621 77. Hettinga FJ, de Koning JJ, Foster C. VO₂ response in supramaximal cycling time trials of
622 750-4000m. *Med Sci Sports Exerc.* 2009; 41: 230-236.
- 623 78. Mulder RCM, Noordhof DA, Malterer KR, et al. Anaerobic work calculated in cycling
624 time trials of different length. *Int J Sports Physiol Perf.* 2015; 10: 153-159.
- 625 79. Faulkner J, Parfitt G, Eston R. The rating of perceived exertion during competing running
626 scales with time. *Psychophysiol.* 2008; 45: 977-985.
- 627 80. Johnson B, Joseph T, Wright G, et al. Rapidity of responding to a hypoxic challenge
628 during exercise. *Eur J Appl Physiol.* 2009; 106: 493-499.
- 629 81. Cohen J, Reiner B, Foster C, de Koning JJ, Wright G, Doberstein S, Porcari JP. Breaking
630 away: Effects of non-uniform pacing on power output and growth of RPE. *Int J Sports*
631 *Physiol Perf.* 2013; 8: 352-357.
- 632 82. Baldasare R, Ieno C, Bonifozi M, Piacentini MF. Pacing and hazard score of elite open
633 water swimmers during a 5-km indoor pool race. *Int J Sports Physiol Perf.* 2021; 16:
634 796-801.
- 635 83. Mickelwright D, Papadopoulou E, Swart J, Noakes TD. Previous experience influences
636 pacing during 20-km time trial cycling. *Br J Sports Med.* 201; 44: 952-960.
- 637 84. De Ioannon G, Cibelli G, Mignardi S, et al. Pacing and mood changes while crossing
638 Adriatic sea from Italy to Albania. *Int J Sports Physiol Perf.* 2015; 10: 520-523.
- 639 85. Konings MJ, Parkinson J, Zijdewind I, Hettinga FJ. Racing an opponent: Alterations of
640 pacing, performance and muscle force but not RPE. *Int J Sports Physiol Perf.* 2018; 13:
641 283-289.
- 642 86. Swart J, Lindsay TR, Lambert MI, et al. Perceptual cues in the regulation of exercise
643 performance-physical sensations of exercise and awareness of effort interact as separate
644 cues. *Br J Sports Med.* 2012; 46: 42-48.

- 645 87. Veneman T, Schallig W, Eken M, et al. The physiological, neuromuscular and perceptual
646 response to even and variable paced 10-km cycling time trials. *Int J Sports Physiol Perf.*
647 2021; 16: 1408-1415.
- 648 88. Meyer H, Bruenig J, Cortis C, et al. Evidence that the Rating of Perceived Exertion
649 growth during fatiguing tasks is scalar and independent of exercise mode. *Int J Sports*
650 *Physiol Perf.* 2022 (in press); doi.org/10.1123/ijsp2031-0334.
- 651 89. Henslin-Harris KB, Foster C, et al. Rapidity of response to hypoxic conditions during
652 exercise. *Int J Sports Physiol Perf.* 2013; 330-335.
- 653 90. Nyberg K, Jaime S, Rodriguez-Marroyo JA, et al. Effect of disparities of feedback on
654 pacing in cycle time trials. *Proc ECSS 2012*; 17:528.
- 655 91. Jaime S, Pratt C, Reinschmidt P, et al. Muscle oxygenation patterns during a 20-km time
656 trial with intermediate sprints and recoveries. *Proc ACSM 2019*; abstract 1757.
- 657 92. St Mary J, Foster C, de Koning JJ, et al. Evidence for the robust nature of the pacing
658 template. *Med Sci Sports Exerc.* 2015; 46: S427.
- 659 93. Tucker R, Noakes TD. The physiological regulation of pacing strategy during exercise: a
660 critical review. *Br J Sports Med.* 2009; 43:e1.
- 661 94. Tucker R. The anticipatory regulation of performance: the physiological basis for pacing
662 strategies and the development of a perception-based model for exercise performance. *Br*
663 *J Sports Med.* 2009; 43: 392-400.
- 664 95. De Koning JJ, Foster C, et al. Bakkum A, Kloppenburg S, Thiel C, Joseph T, Cohen J,
665 Porcari JP. Regulation of pacing strategy during athletic competition. *PLoS ONE* 2011;
666 6:e15863.
- 667 96. Binkley S, Foster C, Cortis C, et al. Summated hazard score as a powerful predictor of
668 fatigue in relation to pacing strategy. *Int J Environ Res Pub Health.* 2021; 18: 1984.
- 669 97. Renfree A, West J, Corbett M, et al. Complex interplay between determinants of pacing
670 and performance during 20-km cycle time trials. *Int J Sports Physiol Perf.* 2012; 7: 121-
671 129.
- 672 98. Renfree A, Martin L, Mickelwright D, St Clair Gibson A. Application of decision making
673 theory to the regulation of muscular work rate during self-paced competitive endurance
674 activity. *Sports Med.* 2014; 44:147-150.
- 675 99. Jones HS, Williams EL, Marchant D, et al. Distance dependent association of affect with
676 pacing strategy in cycling time trials. *Med Sci Sports Exerc.* 2015; 47: 825-832.
- 677 100. Corbett J, Barwood MJ, Onzonuoglou A, et al. Influence of competition on
678 performance and pacing during cycling exercise. *Med Sci Sports Exerc.* 2012; 44: 509-
679 515.
- 680 101. Hulleman M, de Koning JJ, Hettinga FJ, Foster C. The effect of extrinsic
681 motivation on cycle time trial performance. *Med Sci Sports Exerc.* 2007; 39: 709-715.
- 682 102. Amann M, Eldridge MW, Lovering AT, et al. Arterial oxygenation influences
683 central motor output and exercise performance via effects on peripheral locomotor
684 fatigue. *J Physiol.* 2006; 575: 937-952.
- 685 103. Foster C, Hendrickson KJ, Peyer K, et al. Pattern of developing the pacing
686 template. *Br J Sports Med* 2009; 43: 765-769.

- 687 104. Hettinga FJ, Edwards AM, Hanley B. The science behind competition and
688 wining in athletics: Using world level competition data to explore pacing and tactics.
689 *Front Sports Active Living* 2019; 1: 11.
- 690 105. Elferink-Gemser M, Hettinga FJ. Pacing and self-regulation: Important for talent
691 development in endurance sport. *Int J Sports Physiol Perf.* 2017; 12: 830-835.
- 692 106. Micklewright D, Augen C, Suddaby J, et al. Pacing strategy in school children
693 differ with age and cognitive development. *Med Sci Sports Exerc.* 2012; 44: 362-369.
- 694 107. Thiel C, Foster C, Banzer W, de Koning JJ. Pacing in Olympic track races:
695 Competition tactics vs best performance strategy. *J Sports Sci* 2012; 30: 1107-1115.
- 696 108. Konings M, Hettinga FJ. Objectifying tactics; athlete and race variability in elite
697 short track speed skating. *Int J Sports Physiol Perf.* 2018; 13: 170-175.
- 698 109. Abbiss CR, Menaspa P, Villerius V, Martin DT. Distribution of power output
699 when establishing a breakaway in cycling, *Int J Sports Physiol Perf.* 2013; 8: 452-455.
- 700 110. Kirby BS, Wein BJ, Wilkerson BW, Jones AM. Interaction of exercise
701 bioenergetics with pacing behavior predicts track distance running performance. *J Appl*
702 *Physiol.* 2021; 131: 1532-1542..
- 703 111. Tucker R, Lambert M, Noakes TD. An analysis of pacing strategies during men's
704 world record performances in track athletics. *Int J Sports Physiol Perf.* 2006; 1: 233-245.
- 705 112. Hanley B. Pacing profile and pack running at the IAAF world half-marathon
706 championships. *J Sports Sci.* 2015; 33: 1189-1195.
- 707 113. Hanley B. Pacing, packing and sex-based differences in Olympic and IAAF
708 world championship marathons. *J Sports Sci.* 2016; 34: 1675-1681.
- 709 114. St Clair Gibson A, Swart J, Tucker R. The interaction of psychological and
710 physiological homeostatic drives and role of general control principles in the regulation
711 of physiological systems, exercise and fatigue processes: the Integrative Governor
712 Theory. *Eur J Sports Sci.* 2018; 18: 25-36/
- 713 115. Davis A, Hettinga FJ, Beedie C. You don't need to administer a placebo to elicit
714 a placebo effect: Social factors trigger neurobiological pathways to enhance sports
715 performance. *Eur J Sports Sci.* 2020; 302-312.
- 716 116. Galan-Rioja M, Gonzalez-Maahino F, Poole DC, Gonzalez-Rave JM. Relative
717 proximity of critical power and metabolic/ventilatory thresholds: Systematic review and
718 meta-analyses. *Sports Med.* 2020
- 719 117. Skiba PF, Chidnok W, Vanhatalo A, Jones AM. Modeling the expenditure and
720 reconstitution of work capacity above eh critical power. *Med Sci Sports Exerc.* 2012; 44:
721 1522-1532.
- 722 118. Skiba PF, Clarke D The W' balance model: mathematical and methodological
723 considerations. *Int J Sports Physiol Perf.* 2021; 11: 1561-1572.
- 724 119. Barroso R, Do Carmo EC, Foster C, et al. Longitudinal analysis of the 800-m
725 performances of the world's best female long distance pool swimmer: a case study using
726 critical speed. *Int J Sport Sci Coaching.* 2022; In Press.
- 727 120. Foster C., Gregorich H, Barroso R, et al. Pacing strategy in one-mile world
728 records as a test of the critical speed/D' hypothesis. *Med Sci Sports Exerc.* 2021; 54(8s):
729 46.

- 730 121. Foster C, Gregorich H, de Koning JJ, Skiba P. Depletion of D' in the critical
731 speed/d' model explains "dropping off" from the leading pack of elite runners. *Med Sci*
732 *Sports Exerc.* 2022; (In press)
- 733 122. Joyner MJ, Coyle EF. Endurance exercise performance: the physiology of
734 champions. *J Physiol.* 2008; 586: 35-44.
- 735 123. Sjodin B, Svedenhag J. Applied physiology of marathon running. *Sports Med.*
736 1985; 2: 83-99.
- 737 124. Noordhof DA, de Koning JJ, Foster C. The maximal accumulated oxygen deficit
738 method: A valid and reliable measure of anaerobic capacity? *Sports Med.* 2010; 40: 285-
739 302.
- 740 125. Paavolainen L, Hakkinen K, Hamalainen I, et al. Explosive-strength training
741 improves 5-km running time by improving running economy and muscle power. *J Appl*
742 *Physiol.* 1985; 86: 1527-1533.
- 743 126. Damasceno MV, Lima-Silva AE, Pasqua LA, et al. Effect of resistance training
744 on neuromuscular characteristics and pacing during 10-km running time trial. *Eur J Appl*
745 *Physiol.* 2015; 115: 1513-1522.
- 746 127. Del Rosso S, Barros E, Tonello L, et al. Can pacing be regulated by post-
747 activation potentiation? Insights from a self-paced 30-km trial in half-marathon runners.
748 *PLoS One* 2016; 11: e0150679.
- 749 128. Del Rosso S, Souza DP, Munoz E, et al. 10-km performance prediction by
750 metabolic and mechanical variables: influence of performance level and post-submaximal
751 running jump potentiation. *J Sports Sci.* 2021; 39: 1114-1126.
- 752 129. Bertuzzi R, Lima-Silva AE, Pires FO, et al. Pacing strategy determinants during a
753 10-km running time trial: contributions of perceived effort, physiological and muscular
754 parameters. *J Strength Cond Res.* 2014; 28: 1688-1696.
- 755 130. Boulosa D, Abad CC, Reis VP, et al. Effect of drop jumps on 1000-m
756 performance time and pacing in elite male and female endurance runners. *Int J Sports*
757 *Physiol Perf.* 2020; doi: 10.1123/ijsp.2019-0585.
- 758 131. Silva RAS, Silva-Junior FL, Pinheiro FA, et al. Acute prior heavy strength
759 exercise outs improve the 20-km cycling time trial performance. *J Strength Cond Res.*
760 2014; 28: 2513-2520.
- 761 132. Feros SA, Young WB, Rice AJ, Talpeg SW. The effect of including a series of
762 isometric conditioning contractions to the rowing warm-up on 1000-m rowing ergometer
763 time trial performance. *J Strength Cond Res.* 2012; 26: 3326-3334.
- 764 133. Damascou MV, Duarte M, Pasqua LA, et al. Static stretching alters
765 neuromuscular function and pacing strategy, but not performance during a 3-km running
766 time trial. *PLoS One* 2014; 9: e99238.
- 767 134. Boulosa D, Del Rosso S, Behm DG, Foster C. Post-activation potentiation in
768 endurance sports: a review. *Eur J Sports Sci.* 2018; 18:595-610.
- 769 135. Boulosa D, Abreu L, Varela-Sauz A, Mujika I. Do Olympic athletes train as in
770 the Paleolithic era? *Sports Med.* 2013; 43: 909-917.
- 771 136. Costill DL, Fink WJ, Pollock ML. Muscle fiber composition and enzyme
772 activities of elite distance runners. *Med Sci Sports Exerc.* 1976; 8: 96-100.

- 773 137. Costill DL, Daniels J, Evans W et al.. Skeletal muscle enzymes and fiber
774 composition in male and female track athletes. *J Appl Physiol.* 1976; 40: 149-154.
775 138. Ivy JL, Withers RT, van Handel PJ, Elger DH, Costill DL Muscle respiratory
776 capacity and fiber types as determinants of the lactate threshold. *J Appl Physiol.* 1980;
777 48: 523-527.

778

779

780

For Peer Review

781 Captions for Figures

782 **Figure 1:** Schematic of relative PO vs total distance and relative percent of a time trial
783 completed. The data resemble a “landscape” and show that in almost all distances that there is
784 an initial peak in PO at the start, and a terminal end-spurt in all but the shortest distances.^{29,77,78}

785 **Figure 2:** Schematic of the growth of RPE in relation to the percent of a task completed. Data
786 included are for ambulatory tasks such as walking, running and cycling, as well as for lifting
787 weights to failure with different levels of resistance.^{21,25,28,51,53,54,64,72,80,88,93-96}

788 **Figure 3:** Schematic responses of the degree to which changes in PO are used to regulate the
789 growth of RPE during heavy exercise. In one trial (upper panels) the subjects completed a 5-km
790 cycle time trial, either breathing room air throughout, or breathing a hypoxic mixture between 2-
791 4 km.²⁸ During hypoxia, the PO is rapidly reduced and then returns to normal when normoxia is
792 restored. However, the growth of RPE across the duration of the time trial is barely affected. In
793 another trial (lower panels) the subjects competed a 4-km time trial in either a control condition
794 or following an exercise/diet manipulation calculated to cause muscle glycogen depletion. In the
795 depleted condition there were profound decreases in PO, after the opening 400-m segment, but
796 only modest increases in RPE.⁹²

797 **Figure 4:** Schematic of the effect of glycogen depletion during time trials of 1.5 and 4.0-km. In
798 concert with the effect of a pre-exercise template there is no effect on PO at the beginning of the
799 time trial, but there is a rapid and progressive decrease in PO throughout the course of the
800 glycogen depleted time trial.⁸⁷

801 **Figure 5:** Schematic responses of 10-km (upper panels)⁷⁹ and 20-km (lower panels)⁸⁸ cycle
802 time trials where one or more bursts, as if the rider were trying to “break away from the peloton”
803 were inserted. In both cases, during the burst the RPE grew at a higher rate than in the control
804 (self-paced) trial, and slowly recovered after the burst, consequent to a reduction in PO. The
805 data demonstrate that the rate of growth of RPE is tightly controlled and that PO is adjusted to
806 maintain the expected rate of growth of RPE.

807 **Figure 6:** Speed profiles of Kenesa Bekele (ETH) during world record 5-km and 10-km races
808 and during Olympic gold medal races in the 2007-2008 time period. Note that the variation in
809 pace during the championship events is much larger (CV~3x greater). For reference, the Critical
810 Speed (dashed line), calculated from public record performances, approximates the velocity of
811 the 10 km world record.

812 **Figure 7:** Speed profiles of the first 3, middle 3 and last 3 runners in the men’s 5-km and 10-km
813 Olympic finals (Beijing 2008). The data are normalized to the individual values for Critical
814 Speed, which emphasizes that the first 3 runners are running at a physiologically easier pace
815 during the early part of the race. This may serve to preserve D’ and allow them to run at a
816 relatively higher percentage of their already higher CS during the closing stages of the race. A
817 better preserved D’ also increase the likelihood of producing a more effective end-spurt.^{114th}

818 **Figure 8** Top: Progressive depletion of D’, to essentially zero values, during the course of World
819 Record performances in the 1-mile run, based on historical data since ~1920. The CS was

820 subtracted from the observed speed during each 402-m lap, and the remaining distance was
821 subtracted from the D' (both CS and D' were computed based on published historical races for
822 that athlete).¹⁰⁷ Bottom: Progressive depletion of D' to near zero values in competitors in contact
823 with the leader with 400-m remaining in the men's 10-km final at the 2008 Olympics. In athletes
824 who dropped off the leader prior to 400-m remaining, D' decreased early, but then remained
825 constant or even increased during the remainder of the race.¹⁰⁸

826

827

828

829

830

831

832

For Peer Review

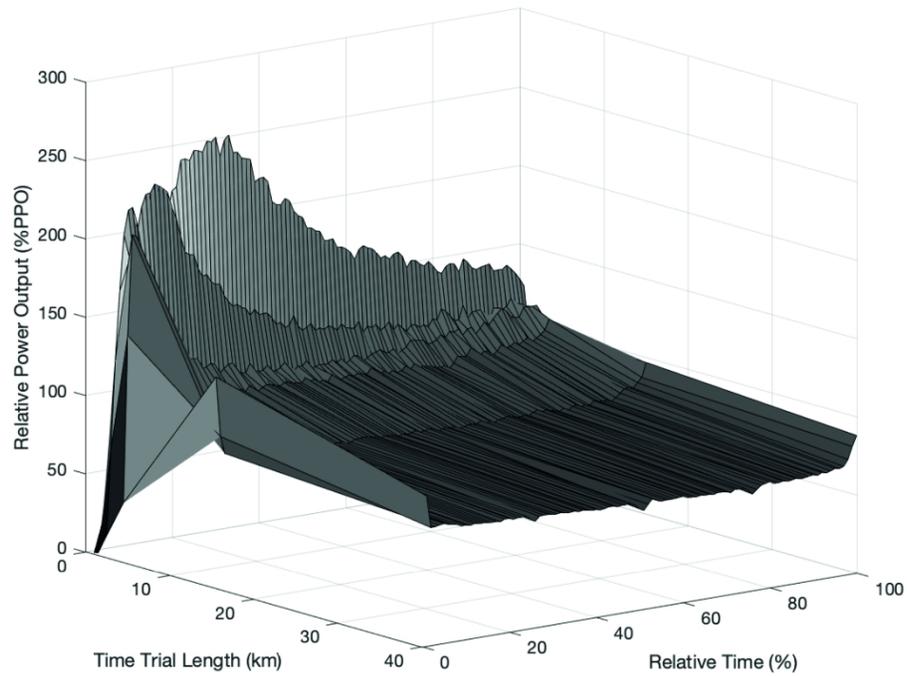


Figure 1: Schematic of relative PO vs total distance and relative percent of a time trial completed. The data resemble a "landscape" and show that in almost all distances that there is an initial peak in PO at the start, and a terminal end-sprint in all but the shortest distances.^{29,77,78}

202x173mm (300 x 300 DPI)

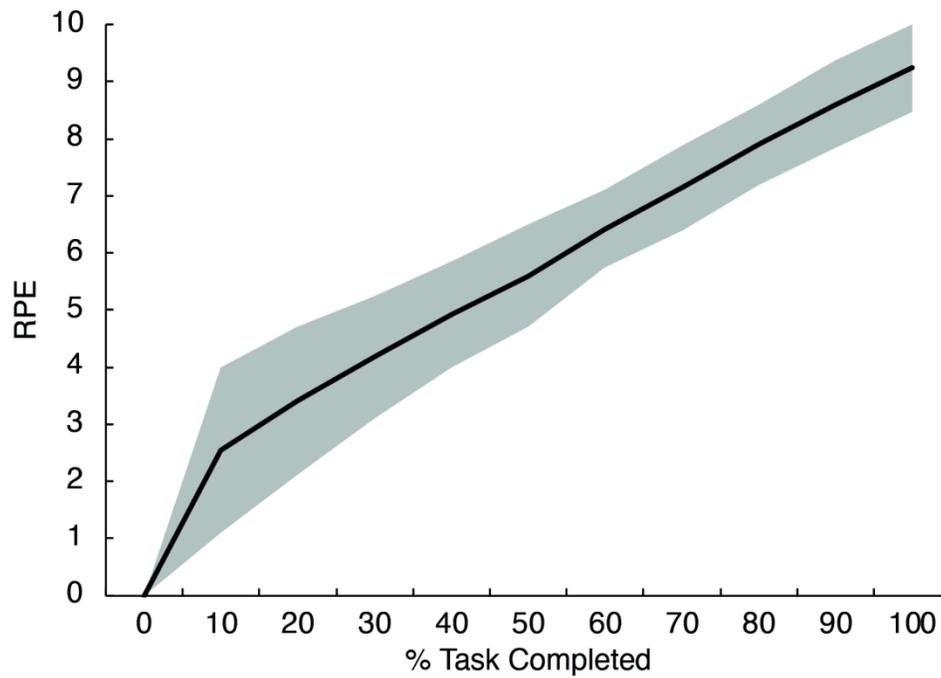


Figure 2: Schematic of the growth of RPE in relation to the percent of a task completed. Data included are for ambulatory tasks such as walking, running and cycling, as well as for lifting weights to failure with different levels of resistance.21,25.28.51.53.54.64.72.80.88.93-96

142x101mm (300 x 300 DPI)

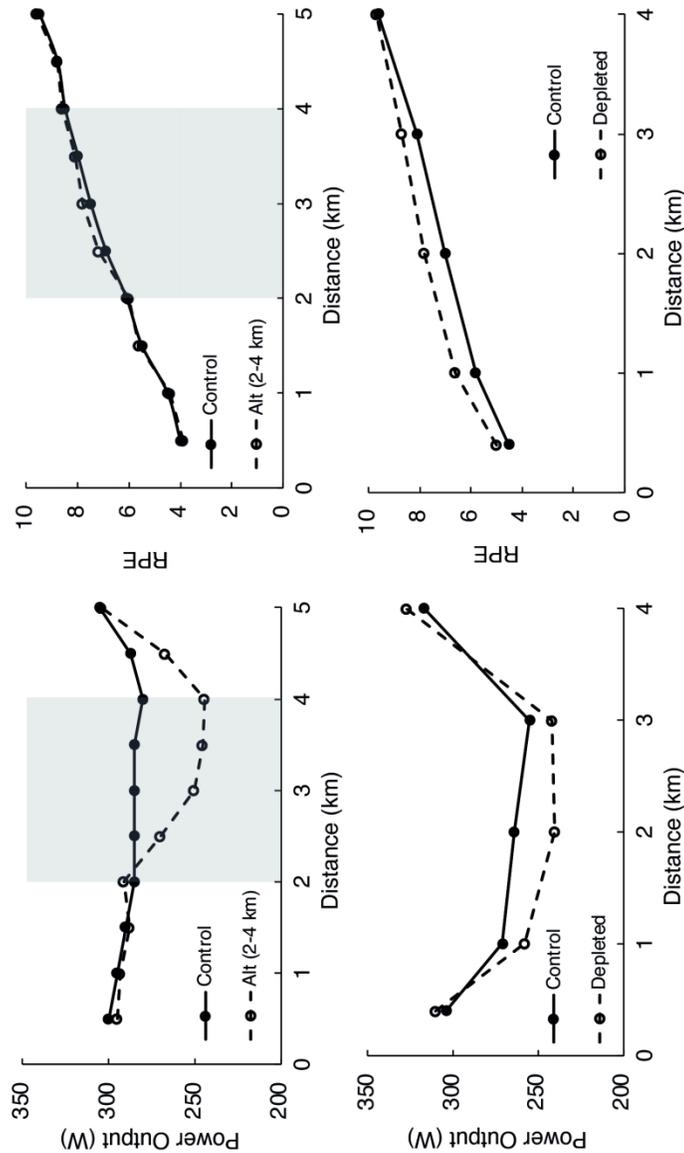


Figure 3: Schematic responses of the degree to which changes in PO are used to regulate the growth of RPE during heavy exercise. In one trial (upper panels) the subjects completed a 5-km cycle time trial, either breathing room air throughout, or breathing a hypoxic mixture between 2-4 km.28 During hypoxia, the PO is rapidly reduced and then returns to normal when normoxia is restored. However, the growth of RPE across the duration of the time trial is barely affected. In another trial (lower panels) the subjects competed a 4-km time trial in either a control condition or following an exercise/diet manipulation calculated to cause muscle glycogen depletion. In the depleted condition there were profound decreases in PO, after the opening 400-m segment, but only modest increases in RPE.92

142x224mm (300 x 300 DPI)

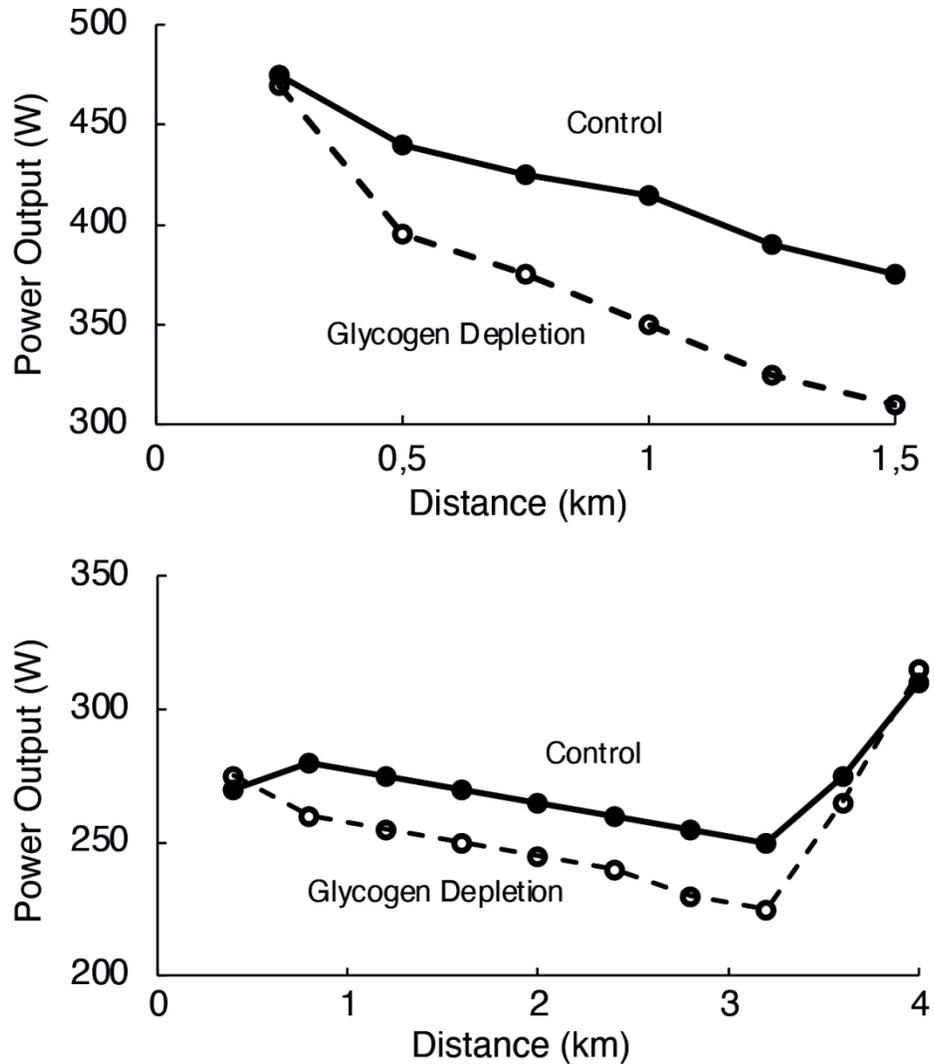


Figure 4: Schematic of the effect of glycogen depletion during time trials of 1.5 and 4.0-km. In concert with the effect of a pre-exercise template there is no effect on PO at the beginning of the time trial, but there is a rapid and progressive decrease in PO throughout the course of the glycogen depleted time trial.⁸⁷

112x141mm (300 x 300 DPI)

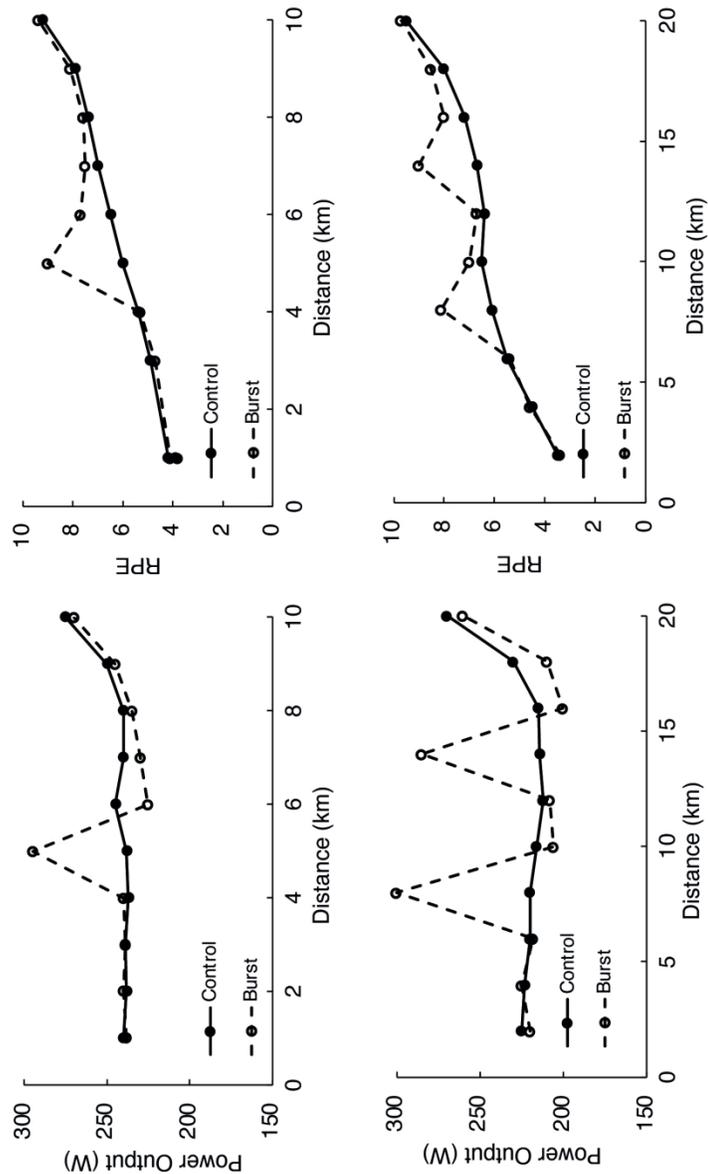


Figure 5: Schematic responses of 10-km (upper panels) 79 and 20-km (lower panels) 88 cycle time trials where one or more bursts, as if the rider were trying to “break away from the peloton” were inserted. In both cases, during the burst the RPE grew at a higher rate than in the control (self-paced) trial, and slowly recovered after the burst, consequent to a reduction in PO. The data demonstrate that the rate of growth of RPE is tightly controlled and that PO is adjusted to maintain the expected rate of growth of RPE.

145x225mm (300 x 300 DPI)

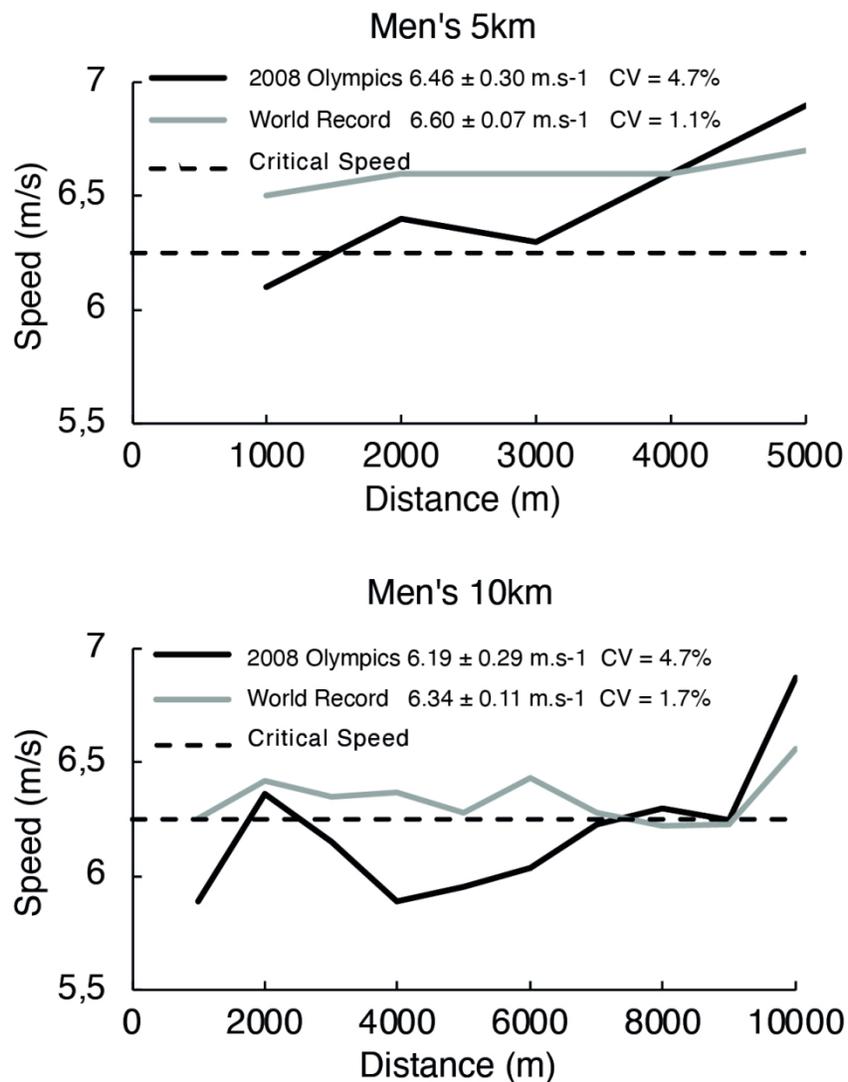


Figure 6: Speed profiles of Kenesa Bekele (ETH) during world record 5-km and 10-km races and during Olympic gold medal races in the 2007-2008 time period. Note that the variation in pace during the championship events is much larger ($CV \sim 3x$ greater). For reference, the Critical Speed (dashed line), calculated from public record performances, approximates the velocity of the 10 km world record.

109x145mm (300 x 300 DPI)

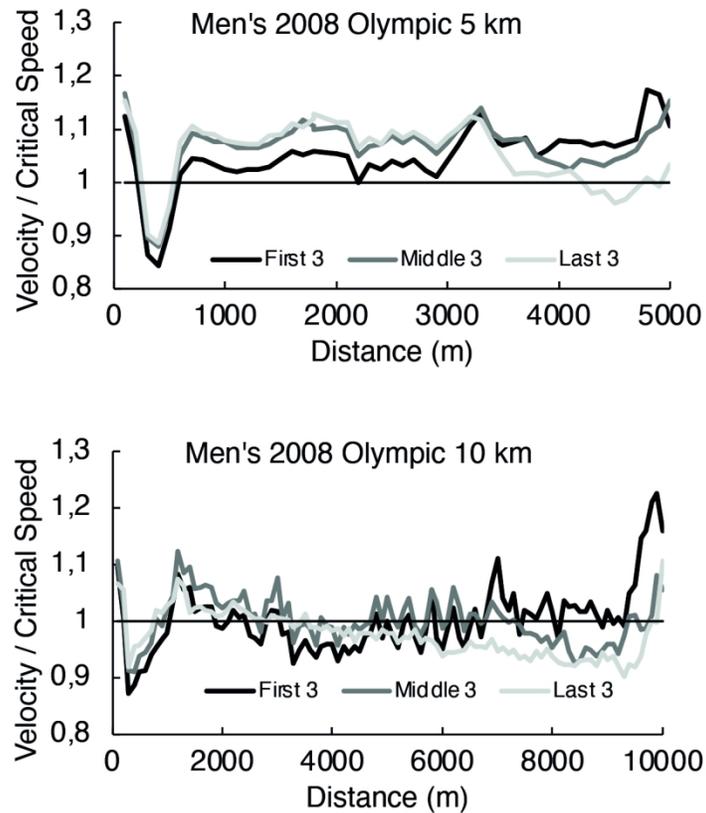


Figure 7: Speed profiles of the first 3, middle 3 and last 3 runners in the men's 5-km and 10-km Olympic finals (Beijing 2008). The data are normalized to the individual values for Critical Speed, which emphasizes that the first 3 runners are running at a physiologically easier pace during the early part of the race. This may serve to preserve D' and allow them to run at a relatively higher percentage of their already higher CS during the closing stages of the race. A better preserved D' also increase the likelihood of producing a more effective end-spurt.¹¹⁴

109x174mm (300 x 300 DPI)

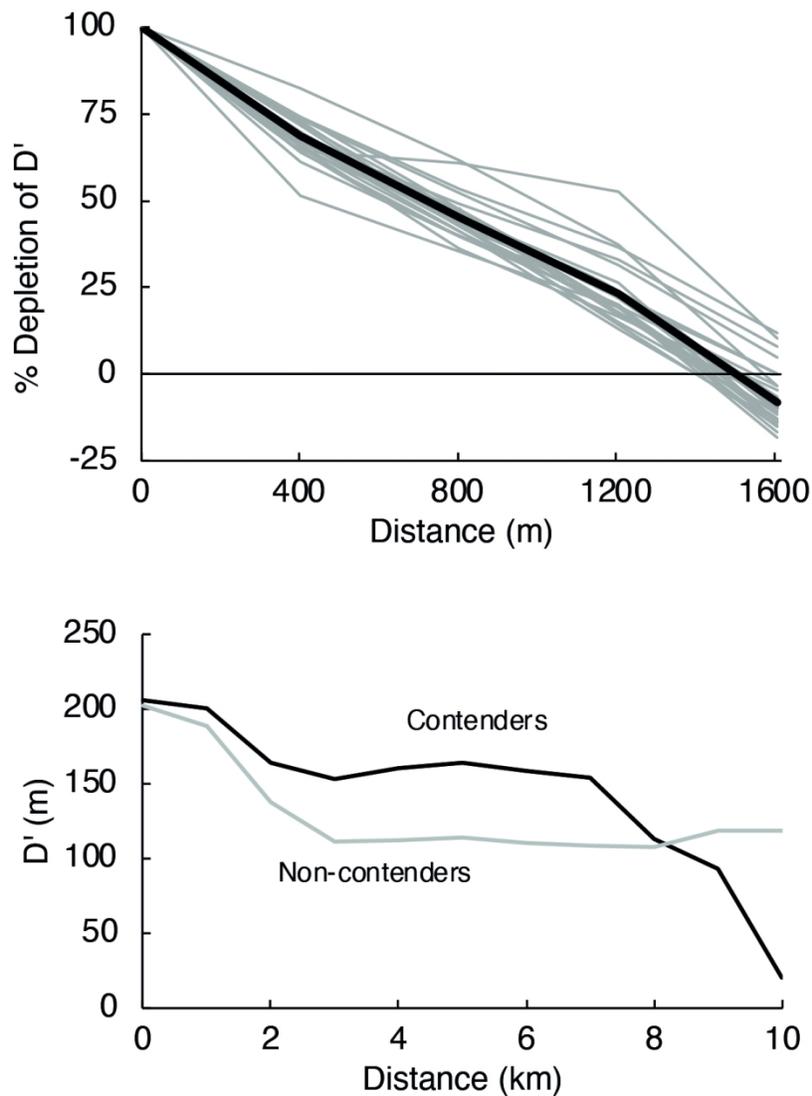


Figure 8 Top: Progressive depletion of D' , to essentially zero values, during the course of World Record performances in the 1-mile run, based on historical data since ~1920. The CS was subtracted from the observed speed during each 402-m lap, and the remaining distance was subtracted from the D' (both CS and D' were computed based on published historical races for that athlete).¹⁰⁷ Bottom: Progressive depletion of D' to near zero values in competitors in contact with the leader with 400-m remaining in the men's 10-km final at the 2008 Olympics. In athletes who dropped off the leader prior to 400-m remaining, D' decreased early, but then remained constant or even increased during the remainder of the race.¹⁰⁸

111x154mm (300 x 300 DPI)