Medical Hypotheses 150 (2021) 110575

Contents lists available at ScienceDirect

Medical Hypotheses

journal homepage: www.elsevier.com/locate/mehy

Critical oxygenation: Can muscle oxygenation inform us about critical power?

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ARTICLE INFO

Keywords:
Near-infrared spectroscopy
Critical power
Muscle oxygenation
Critical oxygenation
Power-duration

ABSTRACT

The power-duration relationship is well documented for athletic performance and is formulated out mathematically in the critical power (CP) model. The CP model, when applied properly, has great predictive power, e.g. pedaling at a specific power output on an ergometer the model precisely calculates the time over which an athlete can sustain this power. However, CP presents physiological inconsistencies and process-oriented problems. The rapid development of near-infrared spectroscopy (NIRS) to measure muscle oxygenation (SmO_2) dynamics provides a physiological exploration of the CP model on a conceptual and empirical level. Conceptually, the CP model provides two components: first CP is defined as the highest metabolic rate that can be achieved through oxidative means. And second, work capacity above CP named W'. SmO_2 presents a steady-state in oxygen supply and demand and thereby represents CP specifically at a local level of analysis. Empirically, exploratory data quickly illustrates the relationship between performance and SmO_2, as shown during 3-min all-out cycling tests to assess CP. During these tests, performance and SmO_2 essentially mirror each other, and both CP and W' generate solid correlation with what would be deemed their SmO_2 counterparts: first, the steady-state of SmO_2 correlates with CP. And second, the tissue oxygen reserve represented in SmO_2, when calculated as an integral corresponds to W'. While the empirical data presented is preliminary, the proposition of a concurring physiological model to the current CP model is a plausible inference. Here we propose that SmO_2 steady-state representing CP as critical oxygenation or CO. And the tissue oxygen reserve above CO would then be identified as O'. This new CO model could fill in the physiological gap between the highly predictive CP model and at times its inability to track human physiology consistently. For simplicity's sake, this would include acute changes in physiology as a result of changing climate or elevation with travel, which can affect performance. These types of acute fluctuations, but not limited to, would be manageable when applying a CO model in conjunction with the CP model. Further, modeling is needed to investigate the true potential of NIRS to model CP, with a focus on repeatability, recovery, and systemic vs local workloads.

Introduction

In their 2016 publication, Poole and colleagues [42] outline the relevance of the hyperbolic power-duration relationship termed the critical power (CP) model, as accredited to findings by Archibald Hill in 1925 [22] and later Monod and Scherrer [36]. The model identifies the boundary between tolerable and intolerable severe intensity exercise [7,8]. Exercise attempted above this boundary – known as CP – will result in exhaustion when attempting to maintain a constant work rate. This time to exhaustion is in direct relation to the extent to which work is being performed above CP [49,50]. When plotting constant power or speed in relation to time to exhaustion the obvious non-linearity of this relationship becomes apparent. There is a curvilinear nature in the strong decline of performance in relation to duration, with an ever-developing asymptote of tolerable performance as the time axis extends outwards [7,8].

Perhaps, the extremes of performance best serve as an example of this phenomenon. Consider, at first the top speed of current 100 m world record holder Usain Bolt, at speed exceeding 40 km/h (average greater than 37 km/h). Secondly, consider the average speed of current 1500 m world record holder Hicham El Guerrouj, at 26.2 km/h. Then, finally consider the average speed of current marathon world record holder Eliud Kipchoge, at approximately 21 km/h; Eliud Kipchoge's performance is highly predicted by a CP model [27]. All three speeds represent

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https://doi.org/10.1016/j.mehy.2021.110575
Received 17 December 2020; Received in revised form 17 February 2021; Accepted 14 March 2021
Available online 23 March 2021

the maximum of human performance, but a very different frame of reference when discussing tolerable performance. All three speeds maximize speed for the allotted distance, but the fall-off in speed between 100 m and 1500 m is greater than 10 km/h for a change in distance of 1400 m. Whereas, the decrease in average speed between 1500 m and a full marathon – a distance difference of more than 40 km – is merely 5 km/h. This simple example should make the relationship between speed or power and time to exhaustion clear, as well as its adaptability and trainability; thereby highlighting the value of the CP model. The model itself has two main components. First and foremost is the asymptote described above, designated CP. In our runner example, Eliud Kipchoge benefits from an extremely high CP or critical speed, 6.04 m/s to be exact [27]. The second component is the finite work capacity that can be achieved above CP, designated W'; in other words, the integral of the power-duration curve. In our running example, Usain Bolt benefits from an extremely large W' (or D' for distance rather than work), which is associated with this extreme speed above what must be a much lower critical speed.

CP has proven to be a formidable diagnostic tool with predictive power in various endurance disciplines as would be expected; including cycling [1], running [34], and swimming [11]. Attempts to apply the CP model to other, non-classic or non-endurance variable-pace exercise sporting disciplines are also on the rise [30,50]. For example, Giles and colleagues [19] recently showed that critical force, as a counterpart to CP can be used to understand the limits of exercise tolerance in finger flexor performance in rock climbers. Still, how well a CP model represents the excess of athletes and athletic disciplines is difficult to evaluate.

Physiological inconsistency

Numerous avenues of critique exist and perhaps the most intriguing is the question of physiological inconsistency [6,12,55]. The human system is inherently volatile as it struggles with daily adjustments to function as efficiently as possible. High-performance demands and training load increase this volatility. It is therefore difficult to assume that a CP model – even if individualized for a specific athlete – would represent performance accurately in all situations, under all conditions, at all times. For example, altitude change directly affects CP, reducing CP in trained cyclists [52]. Concretely, in the study by Townsend and colleagues, nine trained cyclists completed time trials at five different altitudes between 250 m and 4250 m to determine CP and W'. CP decreased with increasing altitude and at maximum altitude, W' was also decreased. Salam and colleagues [46] showed that mental fatigue can affect the CP model. In this case, trained cyclists completed a 30-min Stroop task to induce mental fatigue before a time to exhaustion test. The mental fatigue had no negative effects on CP, but reduced W'.

Process-oriented problems

Alongside these physiological inconsistencies, the CP model is also susceptible to process-oriented problems. For example, Bishop and colleagues demonstrated that the duration selected for the predictive test used to determine CP significantly alters the outcome [4]. In the study, ten students completed five all-out predictive tests at preselected constant power out-puts. Then three variations of the CP model were calculated, 1) using the three highest power outputs tests, 2) the three lowest power output tests, and 3) using tests 1, 3, and 5. The CP prediction was significantly different for the three calculations with the group concluding that duration and intensity selected for the test(s) significantly influence the results. The same was confirmed by Mattioni Maurana and colleagues [35] using a similar design with five trials, which also pointed out that the mathematical model chosen to calculate CP also varied the results significantly. For example, when choosing an exponential model, the CP outcome is significantly higher than when choosing either a two or three-parameter hyperbolic model. The effect of the mathematical model selection to determine CP is seconded by Gaesser and colleagues [18], who concluded that the parameter estimates of five different mathematical models differed significantly. Even when ignoring the aforementioned problems with determining CP, a considerable discrepancy in CP can be found. A study by Smith and Hill [51] showed that a minimum variation in CP parameters of 5% can be assumed – and this is under experimental conditions. Jones and colleagues [25], strong proponents of CP, argue for a minimal "gray area" of "3–5% with careful attention to protocol". While CP itself may be a powerful predictive tool in various sporting disciplines [1,19,27], the experimental data provided above questions the practicality of CP as a purely output-oriented model. Nonetheless, the relationship between CP and other physiological markers is well documented.

CP and physiological markers

CP itself is defined as the highest metabolic rate that can be achieved through oxidative means [42]. It has been proposed that CP represents a specific metabolic rate, in the case of Barker and colleagues [1] a critical oxygen consumption (VO_2). When assessing CP through the lens of pulmonary gas exchange Poole and colleagues [43] examined the physiological response of steady-state exercise over 24 min of constant load cycling at CP, resulting in a steady-state response in the undermentioned parameters. In contrast to exercise above CP, which resulted in increases in VO_2, blood lactate, lactate-pyruvate ratio, and respiratory frequency, as well as decreases in pH and bicarbonate. Furthermore, there appears to be a relationship between CP and the respiratory compensation point (RCP) providing additional physiological insight into the separation of tolerable and intolerable severe intensity exercise [3,10]. Considering the definition of CP provided, it would follow that CP and maximal lactate steady state (MLSS) would reflect one another. However, this is not the case, and the disagreement has been shown in numerous instances [10,44]. The discrepancy has recently been commented on by Jones et al. [25], who acknowledge the difference between CP and MLSS, with CP occurring at a greater power output than MLSS. The authors claim that CP, and not MLSS, represents a maximal metabolic steady state. They argue that maximal metabolic steady-state should be defined by distinct physiological responses rather than arbitrary exercise durations. Accepting this line of argument, CP has a strong foundation of support, beyond the already mentioned relationships to systemic gas exchange data. A study by Chidnok and colleagues [9] shows a clear metabolic threshold between work rates above and below CP. Muscle metabolite levels at work rates above CP result in increases in inorganic phosphate (Pi) and ADP levels accompanied by decreases in creatine phosphate (PCr) and pH, which are all important factors in fatiguing muscles. These findings are seconded by Jones et al. [29]. To further push the point that CP is the highest metabolic rate that can be achieved through oxidative means it was shown that the inspiration of hyperoxic gas resulted in a significant upward shift of CP and increased time to exhaustion, despite maintaining the same overall change in pH and PCr at point of exhaustion [60]. This strongly indicates a relationship between oxygen supply and demand and CP, while maintaining a finite work capacity above CP, or W'. In the case of W', hyperoxic gas resulted in a decrease in W'; contradicting the notion of W' being equivalent to an anaerobic reserve to be discussed later.

Rectifying the problem: can NIRS help?

The relationship between CP and other physiological threshold markers has been outlined, as have inconsistencies [6,10,44]. These discrepancies are attributable to several factors as established by Jones et al. [25], but some may also be a cause of volatility in a physiological system, as mentioned earlier. Can this dilemma be rectified? As a point of deduction, if performing tasks at CP is reflected by stabilization of varying physiological metrics, it can be assumed that measuring these physiological metrics could give us insight into the attainment of CP,

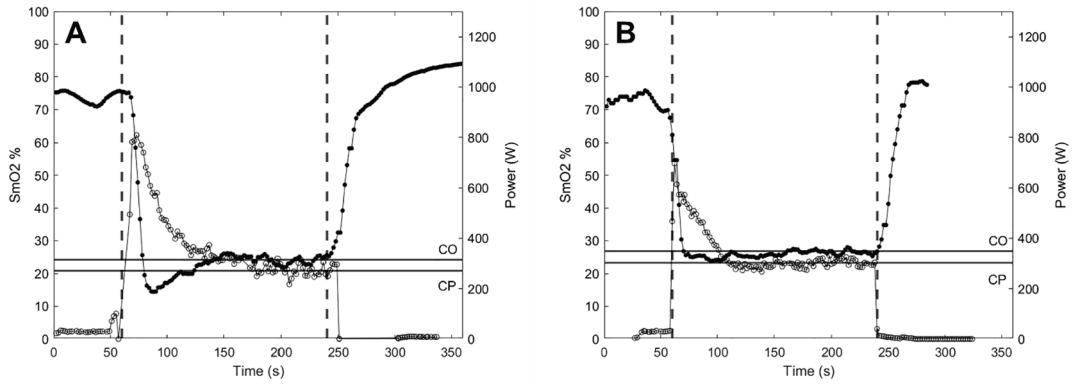

Fig. 1. Two examples are exploratory data collected to assess the relationship between CP and SmO_2. A) presents data with an O_2 extraction reserve (area below CO) that requires the application of model 2 in order to fit the CO model. B) presents data that does not exhibit this O_2 extraction reserve. Dashed vertical lines represent the start and stop of cycling protocol; 3-min all-out test. Closed circles (●) represent SmO_2. Open circles (○) represent power output. Horizontal lines represent CO and CP respectively.

and would do this in a much more dynamic fashion than the rigidity of a power meter, for example. However, unlike a power meter the various measurement tools used to assess the physiological data discussed above are either impractical or expensive; or a combination of both. For example, gas exchange data collection requires tedious laboratory equipment, mostly limits data collection to generic exercise, and tags on a hefty price tag. A tool that could potentially bridge this gap between performance and physiology in the CP model is near-infrared spectroscopy (NIRS); a tool growing in availability and popularity [41]. NIRS discerns muscle oxygenation (SmO_2) and provides a user with information about oxygen supply and demand at the local level, in real-time [2]. Of the physiological metrics described above, all can be linked to oxidative metabolism and the ability to supply and utilize oxygen. Systemically, the link between oxygen supply and demand is the very basis of perhaps the most widely accepted physiological performance measure: maximally attainable VO_2 (VO_2peak). As mentioned before the first component of CP is the highest metabolic rate that can be achieved through oxidative means [42]. Therefore, it is a modest assumption that NIRS could provide insight into the CP model from the physiological perspective. Applying phosphorus magnetic resonance spectroscopy (P-MRS) assessing muscle metabolite development [9,29], Vanhatalo and colleagues [60] showed that changes in SmO_2 track changes in PCr, Pi, ADP, and pH in relation to CP. PCr dynamics and SmO_2 have been cross-validated by Ryan and colleagues [45], identifying NIRS as a valid alternative. This is underscored physiologically by the fact that PCr availability and recovery are dependent on oxygen availability [21]; highlighting the importance of oxygen availability for even high-intensity bouts of exercise above CP. The second component of the CP model, W', is also acknowledged to be associated with oxidative metabolism [42]. While previously W' has been described as an anaerobic reserve, scrutiny by scientific study reveals that W' and CP are in fact two integrated systems that rely on oxygen availability [5,57]. Broxterman and colleagues [5] nicely show that blood flow occlusions result in a drastic change in CP and W'. In the study, CP in occluded limbs was reduced to less than 0 w, which was to be expected if CP is dependent on oxidative metabolism. However, W' increased in the occluded limb, which cannot be explained if W' is an anaerobic reserve constant. This shift in CP and W' could additionally be seen in the SmO_2 data presented directly in the study.

Hypothesis

Muscle oxygen availability as well as oxygen supply and demand mechanics, are primary factors in the ability to both maintain exercise steady-state and perform exercise intensity above CP. Therefore, it is plausible to assume that SmO_2 as measured by NIRS could help identify CP and W'. SmO_2 has been identified by two underlying components, oxygen supply and demand, and oxygen tissue reserve capacity [41]. In both the expected response and in underlying principles, these two components of SmO_2 reflect the two components of the CP model: CP and W'. One is a steady-state principle, while the other is a reserve capacity, which crystallizes the hypothesis proposed: CP can be evaluated through SmO_2 steady state, while W' can be assessed through SmO_2 reserve capacity. Thereby, a physiological approximation of the CP model can be generated, with the advantage of direct physiological feedback as opposed to a physical framework. As an homage to the performance model, the physiological model proposed will be termed critical oxygenation (CO) as the counterpart to CP, and then logically follows the term O' as the counterpart to W'.

Exploratory data

Fourteen participants (nine males and five females; weight: 67.6 ± 9.9 kg; height: 175.9 ± 6.9 cm; age: 23.9 ± 5.5 years [mean ± SD])

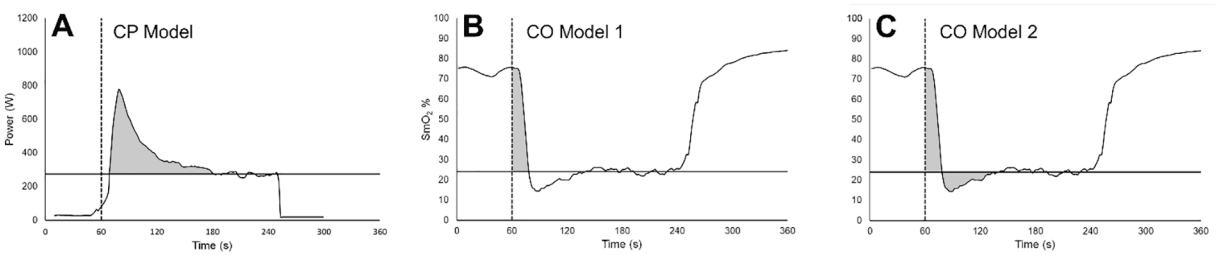

Fig. 2. A) CP model as proposed by Vanhatalo et al. (59) to calculate CP (horizontal line) and W' (shaded area). B) CO model 1 was proposed to calculate CO (horizontal line) and O' (shaded area), excluding the area below CO. C) CO model 2 proposed to calculate CO (horizontal line) and O' (shaded area), including the area below CO.

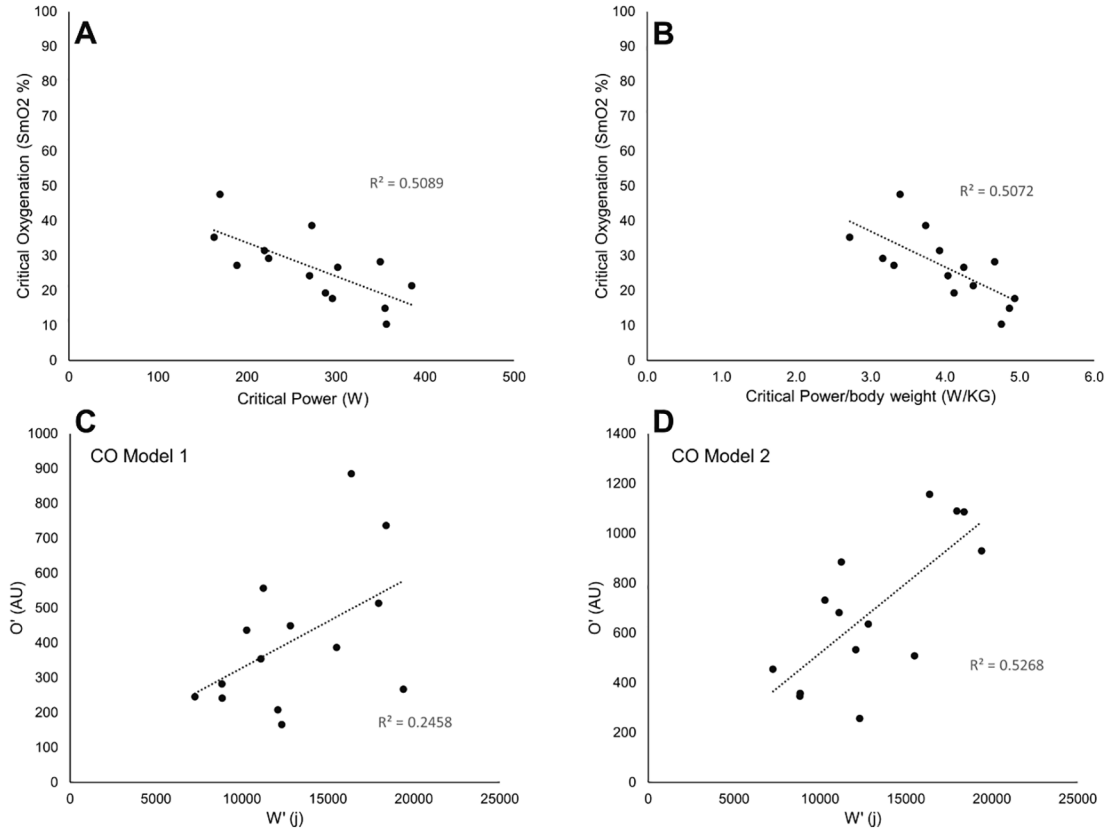

Fig. 3. A) correlation between critical oxygenation (CO) and critical power (CP); $r(13) = 0.713$, $p = .004$. B) correlation between CO and CP as a ratio of bodyweight; $r(13) = 0.712$, $p = .004$. C) correlation between O' and W' using CO model 1; $r(13) = 0.496$, $p = .071$. D) correlation between O' and W' using CO model 2; $r(13) = 0.726$, $p = .003$.

completed a 3-min all-out test [56] to determine CP and W'. Participants first performed a warm-up at 100 W, followed by 5 min of rest. Participants then started 3 min of unloaded baseline pedaling, followed by the all-out 3-min effort. The procedure followed the example of Vanhatalo and colleagues [56]. Visual analysis of the SmO_2 data quickly identified the similarity between the power profile and the SmO_2 profile (see Fig. 1). This realization yielded a simple analysis and results. CP and W' were analyzed as prescribed by Vanhatalo et al. [56] and the principle of the path of least resistance demanded that the SmO_2 data be analyzed in the same manner (see Fig. 2). This generated model 1 with the following results, assessed at a significance level set at an alpha of 0.05. For CP and CO, results show a significant negative correlation, $r(13) = 0.713$, $p = .004$ (see Fig. 3). However, for W' and O', model 1 was not significant, $r(13) = 0.496$, $p = .071$ (see Fig. 3). When taking a closer look at the power curve and the SmO_2 curve, the largest descriptive difference between the two is the fact that SmO_2, in eight of fourteen cases, dips below the CO threshold, an effect not seen in a power-duration curve (see Figs 1, 4 and 5). This phenomenon appears to be consistent and deserves an explanation. More importantly, it may be a determining factor to a successful model. If SmO_2 is a tissue reserve capacity as proposed, then this additional SmO_2 extraction should be an important characteristic to consider. Therefore, model 2 is proposed, which further integrates the area below the CO threshold (see Fig. 2). Model 2, when adding the area under CO yields a significant positive correlation between W' and O', $r(13) = 0.726$, $p = .003$ (see Fig. 3). Ensuring that the complete SmO_2 extraction is integrated into a model appears to be a vital characteristic for the correlation between O' value and W'. When rank-ordering participants by W' magnitude, the largest values of W' are generated using model 2 (inclusion of negative dip below CO). These are also the cases, that in the results of model 1 fall out of the correlation as a result of W' being to small, without the area below CO. It would thus appear that a large W' is associated with an O_2 extraction capacity beyond CO, similar to other findings identifying an O_2 extraction reserve [23,24] (see Fig. 4).

Discussion

The CP model is a consistent and intriguing model to predict athletic performance. However, the model is not without its limitations. The fact that the model is based exclusively on performance output results, without the scrutiny of the physiological system behind the performance output, can result in rather large and accumulating error sources. If the basic phenomena of the CP model were to be united with a reliable physiological measure, this could greatly increase the predictive power of the model. The hypothesis presented offers such a unification using SmO_2 as a physiological source.

The presented data set is meant to first identify an observational source for the generation of the hypothesis, and second to underscore the physiological framework proposed. SmO_2 illustrates two key components of muscle oxidative capacity: 1) oxygen supply and demand through the trending information of the NIRS signal and 2) oxygen reserve capacity through the magnitude of the possible change in the NIRS signal [41]. The ability to maintain adequate oxygen supply to match oxygen demand is the basis of exercise steady-state theory [17,28]. In the CP model, CP represents "the greatest metabolic rate that results in wholly oxidative energy provision, where wholly oxidative considers the active organism *in toto* and means that energy supply through substrate-level phosphorylation reaches a steady-state" [42]. Considering this definition, it is but a small step to assume that, if SmO_2 accurately reflects oxygen supply and demand, an assessment of changing SmO_2 slopes could represent CP. Specifically, SmO_2 at CP must remain constant to represent the steady-state; as is seen in the

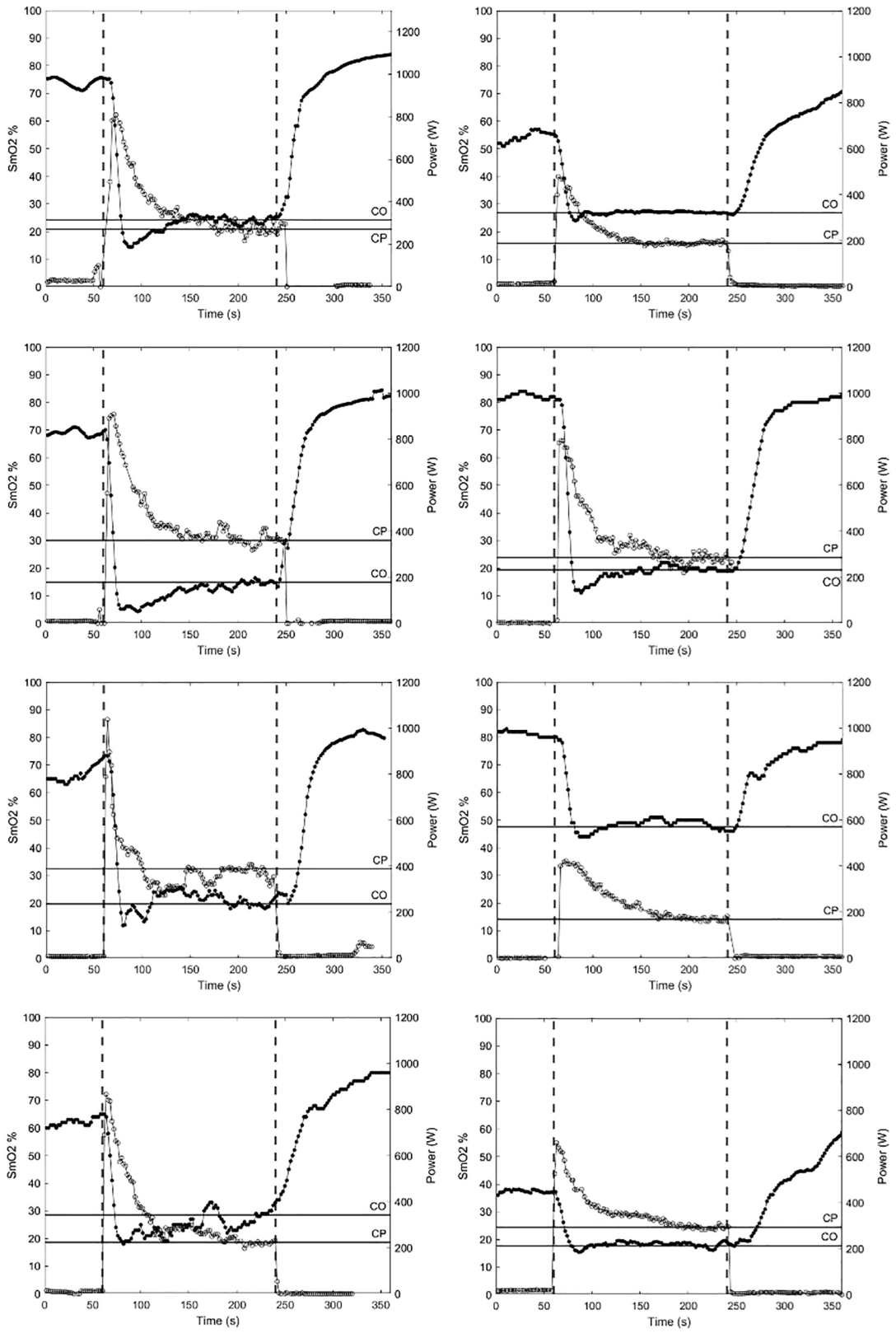

Fig. 4. Eight of fourteen examples of the exploratory data collection to assess the relationship between CP and SmO_2. These eight examples exhibit the O_2 extraction reserve (area below CO) which requires model 2 in order to fit the CO model. The specific selection criteria of this consideration were the predictable pattern of a strong SmO_2 decrease, this decrease exceeding the CO threshold, followed by a recovery to the CO threshold. In several cases this was not an exceedingly large area, nonetheless, advanced the success of model 2. Dashed vertical lines represent the start and stop of cycling protocol; 3-min all-out test. Closed circles (●) represent SmO_2. Open circles (○) represent power output. Horizontal lines represent CO and CP respectively.

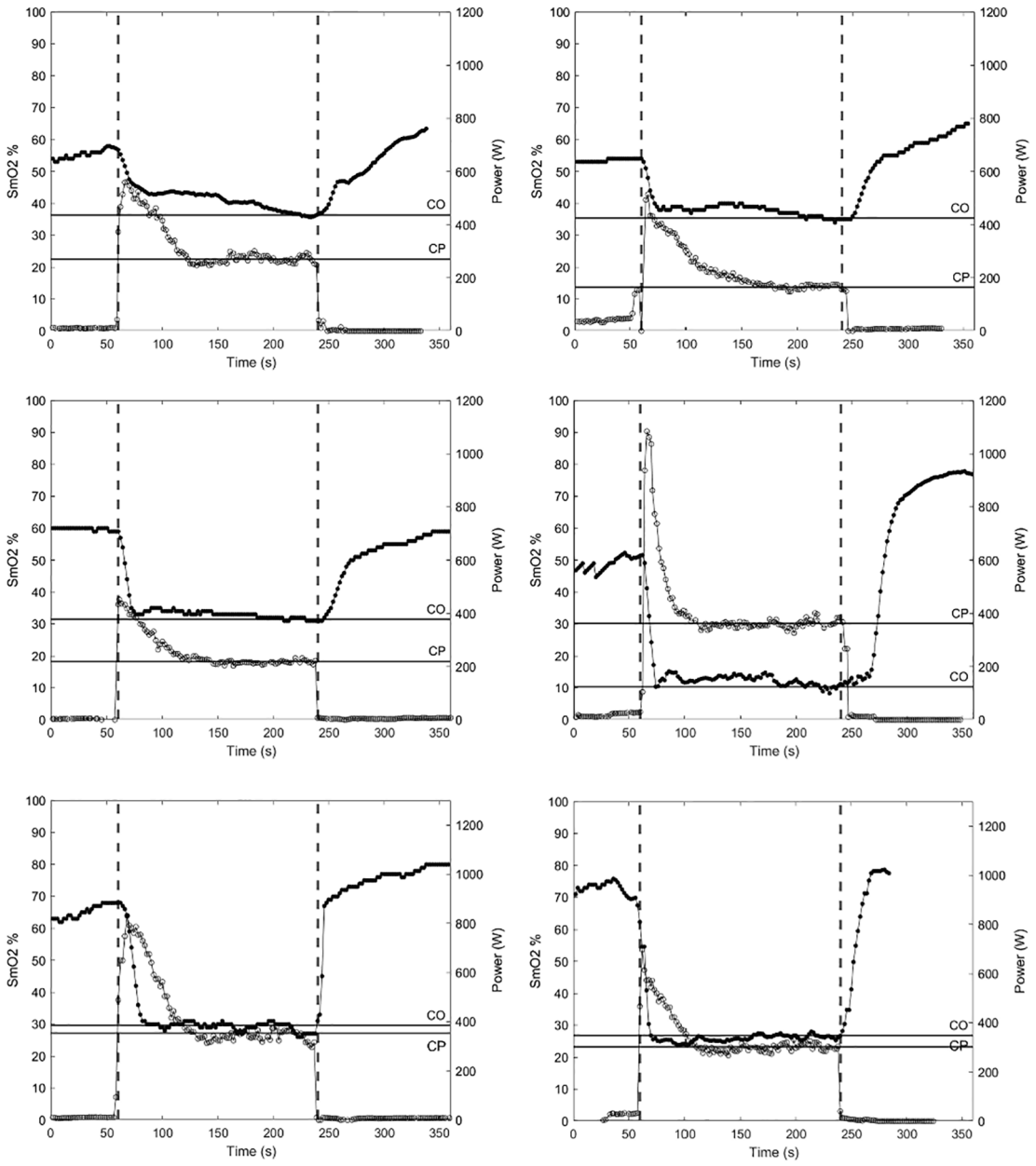

Fig. 5. Six of fourteen examples of the exploratory data collection to assess the relationship between CP and SmO_2. These six examples do not exhibit the O_2 extraction reserve (area below CO) and therefore showed considerable success applying model 1. These examples did not show a decrease in SmO_2 below the CO threshold following the initial decrease in SmO_2 with the onset of exercise. The top right and top left examples show an additional peculiar pattern, in that they both have a much longer decreasing trend in SmO_2 until the CO threshold is truly reached. When looking at the power curve, this could be a result of a non-faithful execution of the 3-min all-out test. Nonetheless, this data does not harm the CO model. Dashed vertical lines represent the start and stop of cycling protocol; 3-min all-out test. Closed circles (●) represent SmO_2. Open circles (○) represent power output. Horizontal lines represent CO and CP respectively.

exploratory data presented. While this is perhaps somewhat pedestrian, of greater interest may be the fact that, when considering in terms of CO, a greater muscle deoxygenated steady state, is correlated to a higher CP. This prediction again is seconded in other findings, such as in the relationship between CP and VO_2 an often-discussed topic [28,33]; which links CP to VO_2peak. It is then reasonable to assume that greater CP would result in greater oxygen extraction as depicted by SmO_2. This assumption is upheld by experimental data showing a correlation between greater deoxygenation and higher VO_2peak [38,54]. W' is also associated with VO_2peak, though to a smaller extent than CP [40,53]. Nonetheless, the ability to supply and extract oxygen is a component of W'. While classically W' was referred to as a form of anaerobic reserve, experiments contradict these findings. More accurately stated: "CP and W should not be considered as separate ''aerobic'' and ''anaerobic'' entities but rather as components of an integrated bioenergetic system" [42]. If W' can be manipulated through experiments by changing oxygen supply with hyperoxic gas [40] or blood flow restriction [5], the available oxygen – or lack thereof – determines W'; emphasizing its direct relationship to oxygen availability. Therefore, SmO_2 levels could be seen as helpful in determining changing W'. The fact that this could be tracked in real-time using cost-effective and portable tools greatly enhances its application in the field.

The physiological laboratory is now increasingly mobile, and a CO model derived from portable NIRS sensors would lend itself as a powerful accessory to static and often unwieldly laboratory settings. It would provide the ability simply determine the boundaries of

performance, on par with gold standard evaluations [31], on a daily basis. Additionally, it provides a wide-range of feedback to athletes and coaches, from cadence efficiency when cycling [59] to potential muscular overload following a trail running race [20]. Finally, its ability to not only track systemic changes, but also isolate single working muscles makes it an attractive tool for sporting disciplines that currently lack classical testing methods. For example, such utility would be invaluable in rock climbing, as mentioned in the introduction. When applied to assess SmO_2 during critical force testing with elite level climbers, NIRS shows substantial predictive power in determining the time to task failure during high effort bouts [13,16]. Moreover, CP has been promoted as a useful tool to understand fatigue in not only health, but also in patient populations [42]. If CO is useful in the understanding of CP, then this would advance its application into the field of Sports Medicine and general practice as well.

It should be recognized that a single NIRS device collects SmO_2 data from a very specific measurement site that is limited to a single muscle. This would imply that a single muscle measurement could reflect a whole-body activity. While the NIRS and VO_2peak comparisons made earlier would imply that this is – at least to a certain degree – plausible, caution is warranted. For example, Wang and colleagues [58] show discrepancies in SmO_2 breakpoints between the vastus lateralis and the gastrocnemius during incremental cycling exercise. Furthermore, it should be noted that even within single muscles, heterogeneity in terms of NIRS derived oxygenation measures can be seen [39]. The data presented is from a cycling exercise, which is a highly localized quadricep dominant activity, that can be easily assessed using NIRS. Increasing the complexity of movement, already to something like running raises questions about the straightforward implementation of the model presented.

Further directions

The results of this study need to be verified and the findings applied to varying conditions. Numerous questions arise in the discussion of this comparison. Clearly, there is a floor effect for SmO_2 when considering its relation to W'. The SmO_2 integral calculated cannot assume an area below 0% and therefore, perhaps, arbitrary units of deoxy-and oxyhemoglobin may be better suited for this calculation. However, considering that local muscle extraction and VO_2peak are closely related [48], the floor effect of SmO_2 may represent a physiological truism [14,15]. Furthermore, the experimental design forced a mostly negative or falling trend in SmO_2, as with performance. In other words, the model proposed does not comment on the reconstitution of W' and how SmO_2 would reflect this. W' does not recover in a linear fashion, as is the case with its depletion [50], and it would be reasonable to assume that the recovery of O' would be similar. This begs the question if O' reconstitution can simply be calculated in the reverse function of its depletion; this is unlikely. The final point of interest, for consideration in future experiments, is that SmO_2 can be altered through training interventions, both acutely and chronically [20,30,37]. This is also true for CP and W' [32,47]. If the relationship proposed is true, an intervention should show the same predetermined shift in CO and O' as it does in CP and W'.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The hypothesis proposed is the culmination of over ten years of practical in-field data collections, observations, and exchange with an innumerable number of experts private and public; many more than can be named here. For this reason, an acknowledgment should be made to the scientific community as a whole. Specifically, we would like to thank Roger Schmitz, Jürg Feldmann, and Brett Kirby for constructive dialogue to advance the topic. We would also like to thank Catherine Haber for her constructive feedback and improvement of the manuscript at large.

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