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The Effect of Graded Running Protocols On Peak Oxygen Consumption and Intramuscular Oxygen Saturation

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Abstract

Aim: The aim of this investigation was to examine the impact of two different running protocols on peak oxygen consumption (VO_2max) and regional intramuscular oxygen saturation (SmO_2) levels in one highly trained runner.

Methods: VO_2 and SmO_2 were measured simultaneously during a gradually ascending running protocol and a Bruce protocol. VO_2 was measured by breath-by-breath spiroergometer gas analysis system (ZAN®, Germany), and SmO_2 was measured from both gastrocnemius muscles using a wireless near-infrared spectroscopy device (BSXinsight®, USA). The correlation between VO_2 and SmO_2 data was determined by Pearson correlation coefficients over the test stage mean values. The change of VO_2 and SmO_2 within each stage was determined by first-degree polynomials.

Results: Peak VO_2 in the Bruce protocol (4640 ml/min) was higher than peak VO_2 in the running protocol (4390 ml/min), but no difference was observed in end-test SmO_2 decreases. There were highly significant negative correlations between VO_2 values and SmO_2 values (r=-0.960-0.990, $p<0.001$). SmO_2 values measured in the right and left gastrocnemius muscle decreased similarly in both protocols (r=0.993, r=0.987, $p<0.001$).

Conclusion: Central and peripheral physiological processes of oxygen consumption are not always congruent, and the test protocol exert an influence due to the complex interplay of physiological and biomechanical factors.

Keywords

MaxVo2,
Near İnfrared Spectroscopy,
Muscle oxygenation.

Article Info

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Kademeli Koşu Protokollerinin Tepe Oksijen Tüketimi ve Kas İçi Oksijen Doygunluğu Üzerindeki Etkisi

Özet

Amaç: Bu araştırmanın amacı, üst düzey antrenmanlı bir koşucuda, iki farklı koşu protokolünün zirve oksijen tüketimi (VO_2max) ile bölgesel kas içi oksijen satürasyonu (SmO_2) üzerindeki etkisini incelemektir.

Yöntem: Kademeli artan koşu protokolü ve Bruce protokolü esnasında VO_2 ve SmO_2 eş zamanlı olarak ölçülmüştür. VO_2, her nefeste spiroergometre gaz analiz sistemi (ZAN®, Almanya) ile ölçülürken SmO_2, kablosuz yakın kızılötesi spektroskopi cihazı (BSXinsight®, ABD) kullanılarak her iki gastroknemius kasından ölçülmüştür. VO_2 ve SmO_2 verileri arasında ilişki, test kademe ortalamaları üzerinden Pearson korelasyon kat sayıları ile belirlenmiştir. Her bir kademe süresince VO_2 ve SmO_2 değişimi 1. derece polinomlarla belirlenmiştir.

Bulgular: Bruce protokolünde zirve VO_2 (4640 ml/dk) değeri koşu protokolü zirve VO_2 (4390 ml/dk) değerine göre daha yüksek bulunmuştur, ancak test sonu SmO_2 düşüşleri arasında fark gözlenmemiştir. VO_2 değerleri ile SMO_2 değerleri arasında negatif yönde çok yüksek düzeyde anlamlı ilişki mevcuttur (r=-0,960-0,990, $p<0{,}001$). Her iki protokolde sağ ve sol gastroknemius kasında ölçülen SmO_2 değerleri benzer şekilde düşüş göstermiştir (r=0,993, r=0,987, $p<0{,}001$).

Sonuç: Oksijen tüketiminin merkezi ve periferik fizyolojik süreçleri her zaman uyumlu değildir ve test protokolü, fizyolojik ve biyomekanik faktörlerin karmaşık etkileşimi nedeniyle bir etki oluşturur.

Anahtar Kelimeler

Vo2Max,
Yakın Kızılaltı Spektroskopi,
Kas Oksijenlenmesi.

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INTRODUCTION

Oxygen Consumption

Oxygen consumption is the process of inhaling air containing oxygen, transporting the oxygen via the bloodstream to the working muscles, and using it for energy conversion in the muscle fibers (Sneel and Mitchell, 1984). The body uses the oxygen consumed during physical activity to meet its energy demands, which depend on the intensity of the exercise (Skinner and McClellan, 1980; Spriet, 2022).

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This concept is of great interest in the field of exercise physiology, specifically in relation to maximum oxygen consumption, also known as VO_2max (Sietsema and Rossiter, 2023). Hill and Lupton (1923) were the first to conduct running experiments and observe that oxygen consumption increases linearly with increasing running speed. However, they noted that there was an individual maximum limit to oxygen consumption at which the subjects reached a plateau, even if the running speed was increased. Today, determining maximum oxygen uptake has been established as the most accurate method for assessing not just aerobic fitness, but also cardiovascular health (Mohajan and Mohajan, 2023).

Test Protocols for VO_2max Measurement

A wide number of test methods and protocols have been developed and validated to measure maximal oxygen consumption. Especially endurance athletes were tested in laboratory settings, for instance on a treadmill or bicycle ergometer, as well as in simulated real-life competitions. The three main methods most commonly used in research are submaximal testing, maximal testing, and field testing (Scheer et al., 2018; Kang et al., 2001).

The submaximal testing is an estimation of the individual's maximum oxygen consumption from oxygen consumption below the point of maximal effort. Submaximal testing is generally preferred in clinical populations because these individuals are often unable to complete a protocol that requires a maximal level of exercise. Although not a direct measure of maximal oxygen consumption, extrapolating data from submaximal exercise is a fairly accurate method of estimating an individual's VO_2max (Nolan et al., 2014; Kathy et al., 2023).

Field testing measures an athlete's maximum oxygen consumption in their actual training and/or competition environment. This familiarity can benefit the athlete, but it can also make it more challenging for researchers to monitor performance (Nabi et al., 2015). When comparing field tests to lab tests using similar protocols in both environments, VO_2max values do not differ significantly. This is illustrated by a study involving eighteen well-trained runners who completed peak performance protocols on both an outdoor track and a laboratory treadmill: There was no significant difference in VO_2max between the treadmill test and the field test, mean VO_2max was 63.5 versus 63.3 ml/kg/min (Meyer et al., 2003).

Nevertheless, the most widely accepted method for measuring maximal oxygen consumption is to perform maximal exercise tests in a laboratory. These protocols use progressively higher exercise levels to elicit a maximal effort from the subject. Respiratory gases are collected and analyzed in the laboratory throughout the test. Such testing offers the advantage of being highly controllable by the examiner, thereby eliminating many possibilities of error that may exist outside the laboratory. Because the examiner is in control of the test, the subject is more likely to produce a true maximal effort, which accurately captures the maximal oxygen consumption. In this context, a number of studies in the literature have investigated the effects of different VO_2max test protocols on total oxygen consumption and performance, albeit with inconclusive results. The conflicting findings observed in these studies can be attributed to the fact that the participants were drawn from different population groups, and were largely untrained (Vanhoy, 2012).

In laboratory tests, researchers can measure a range of physiological data such as VO_2, heart rate, rating of perceived exertion (RPE), and lactate as exercise intensity increases. These variables allow researchers to examine the physiological process that occurs from the beginning of exercise to maximal effort. However, such physiological diagnostics have a general limitation in that they determine the oxygen utilization and physiological parameters of the entire body. Until recently, there were no practical methods for assessing circulatory parameters and energy metabolism in peripheral regional muscles.

The advent of near-infrared spectroscopy (NIRS), however, has offered non-invasive, cost-effective and easy-to-use solutions for monitoring regional muscle energy metabolism. It is increasingly used in athletic performance studies and in clinical situations such as cardiovascular disease (Biçer and Çotuk, 2022). Near-infrared spectroscopy is based on the fact that biological tissues are permeable to light in the near-infrared spectrum, which is considered an 'optical window' between 700-1000 nm. In this range, water absorption is low, allowing light to penetrate the tissue and reach the light receptors. The intensity of the perceived light is mainly influenced by changes in hemoglobin and oxyhemoglobin levels (Çotuk et al., 2020; Quaresima et al. 2003).

The existing literature on the subject indicates that there is currently only limited information available regarding the impact of the testing protocol on intramuscular O_2 saturation. The purpose of this study was to investigate the synchronous changes in oxygen consumption and regional intramuscular oxygen saturation levels during two different running protocols in a highly trained athlete in order to obtain a mechanistic understanding of the "protocol effect".

METHOD

Model of the research

The study was approved by the Marmara University Faculty of Medicine Clinical Research Ethics Committee. This study was conducted in accordance with the principles of the Declaration of Helsinki. All participants signed an informed consent form.

The universe and sample of the research/study group of the research

An 8-year licensed long-distance athlete with national-level achievements in track, road, and cross-country running participated in the study. Due to his participation in cross-country running, he had included incline running in his training program.

Data collection tools of the research

Two distinct test protocols were employed in the study to ascertain VO_2Max. The Bruce protocol involved a three-minute rest period, a three-minute warm-up at a speed of 3 km/h on a 0% incline, and the commencement of the test at a slow walking pace at 10% incline, with an increase in speed and incline occurring at three-minute intervals. Both the incline and the speed increased by 3% every three minutes. The Bruce protocol is analogous to ascending slowly stairs and is suitable for individuals of all fitness levels. The second test protocol, designated as the "Speed protocol," commenced with three minutes of rest and a three-minute warm-up at a speed of 3 km/h. Thereafter, the speed was increased by 1 km/h every minute until exhaustion, which was defined as the point at which the subject could no longer maintain the required pace (at a constant 1% incline). This protocol has been designed for competitive athletes. The athlete was initially evaluated using the Bruce protocol, and subsequently, the Speed protocol was employed. The interval between the two test protocols was 72 hours.

Physiological Measurements

In both test protocols, the athletes' VO_2Max values were determined according to the breath-by-breath technique using a 680 USB model gas analysis system from ZAN® (Germany). Following each measurement, the ergospirometer was calibrated. The intramuscular oxygen saturation of the athlete was quantified using a wireless and portable near-infrared spectroscopy device from BSXinsight® (USA). The widest part of the gastrocnemius (medio-lateral) muscle was identified and its distance from the calcaneus and tibia was recorded in centimeters to ensure identical placement in both tests.

Data analysis of the research

The correlation between oxygen consumption and SmO_2 data was analyzed using Pearson correlation coefficients, with the mean values of the individual steps serving as the basis for the calculation. In order to harmonize the data with the Speed protocol, the three-minute increments of the Bruce protocol were divided into one-minute increments. The statistical significance value employed for these analyses was $p < 0.001$.

To assess the dynamic reaction of muscle oxygenation to the momentary change in power output, the change in SmO_2 within each stage of the test was computed. First-degree polynomials were fitted to the SmO_2 data separately for each stage (and side), and the end-to-start values for each stage were subtracted. The mean value of the SmO_2 data obtained from the simultaneous measurement of the oxygen saturation of the right and left gastrocnemius muscles of the athlete was taken for analysis.

FINDINGS

The subject of the study was a 20-year-old male long-distance runner with a height of 175 cm, a body weight of 61.1 kg, and a BMI of 19.95.

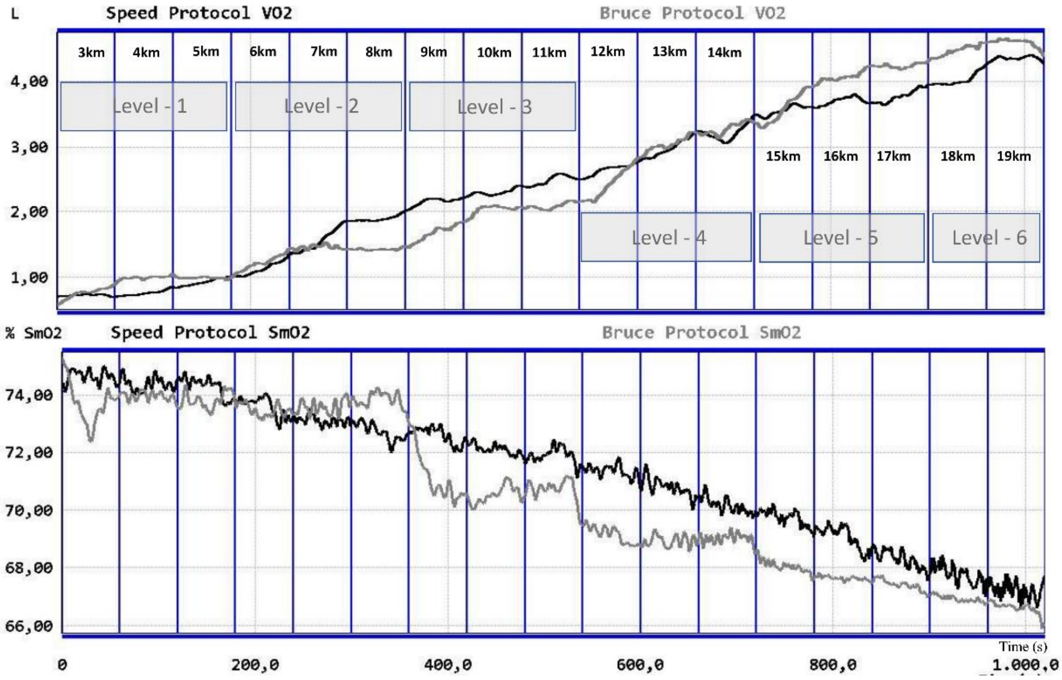

Figure 1: Oxygen consumption and intramuscular oxygen saturation during the Speed and Bruce protocol against time (s) **Speed Protocol VO_2**: Oxygen consumption during the speed protocol. **Bruce Protocol VO_2**: Oxygen consumption during the Bruce protocol. **Speed Protocol SmO_2**: Intramuscular oxygen saturation during the Speed protocol. **Bruce Protocol SmO_2**: Intramuscular oxygen saturation during the Bruce protocol.

The subject successfully completed both tests to the point of exhaustion in the same time period of 17 minutes. The oxygen consumption and intramuscular oxygen saturation are presented in Figure 1. In the Bruce protocol, the stage transitions are characterized by abrupt and steep increases in oxygen uptake, which then level out during the stage. In the Speed protocol, oxygen uptake exhibits a relatively linear increase. A divergence between the two VO_2 curves can be observed during the transition to running in the speed protocol (after 6 km/h), which corresponds to the middle of the second phase of the Bruce protocol. This divergence is evidenced by the lower oxygen consumption observed in the Bruce protocol. This phenomenon is observed in the Speed protocol up to 12 km/h, which corresponds to the beginning of the fourth stage of the Bruce protocol. At 15 km/h and in the fifth stage, the oxygen consumption of the Bruce protocol exceeds that of the Speed protocol.

The mean values of SmO_2 obtained from the right and left gastrocnemius muscles were nearly identical at the start of both test sessions. In the continuation of the test, at the attainment of the speed of 9 km/h in the Speed protocol, and the third stage in the Bruce protocol, both curves diverge, with the SmO_2 value of the Bruce protocol remaining lower (figure 1).

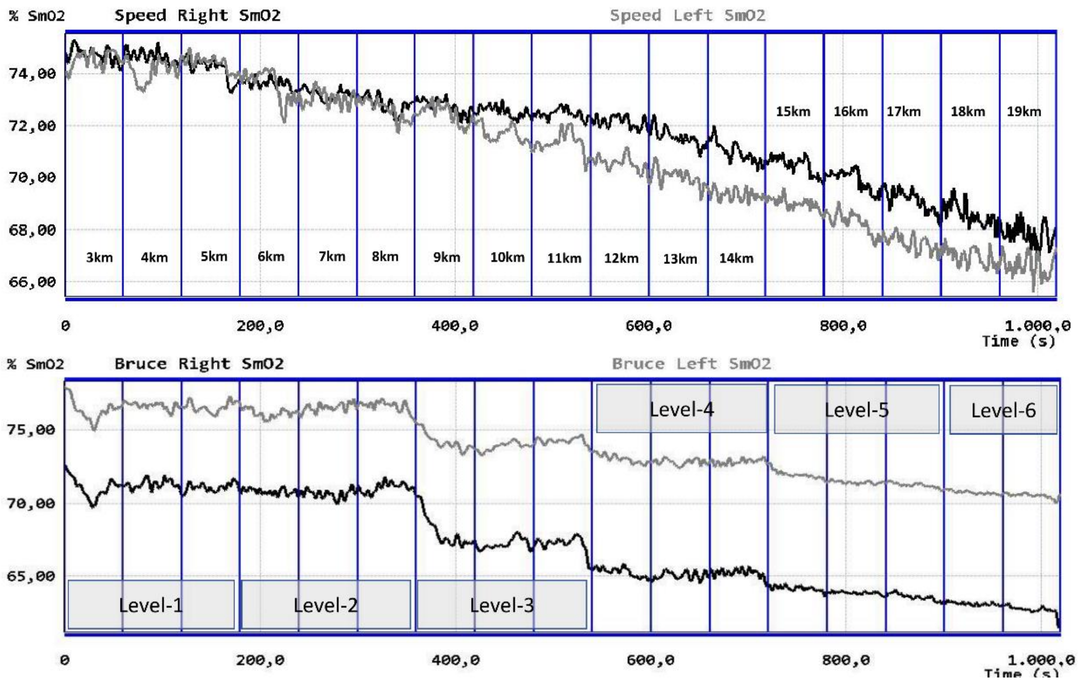

Figure 2: Synchronous evolution of left and right calf intramuscular oxygen saturation during the Speed and Bruce protocol against time (s). **Speed Protocol Right/Left SmO_2**: Intramuscular oxygen saturation during the Speed protocol obtained from the Right/Left gastrocnemius muscle. **Bruce Protocol Right/Left SmO_2**: Intramuscular oxygen saturation during the Bruce protocol obtained from the Right/Left gastrocnemius muscle.

Figure 2 depicts the SmO2 values obtained simultaneously from the athlete's right and left gastrocnemius muscles during the Speed and Bruce protocols. In the Speed protocol, the SmO_2 levels remained relatively constant up to 5 km/h. Nevertheless, a decline in the oxygen saturation levels in both legs was observed following the commencement of running at 6 km/h. At 10 km/h, there was a divergence in the SmO_2 levels between the two legs (left calf values were then lower), yet the pattern of decline persisted in a similar manner. In the Bruce protocol, the athlete walked during stages 1 and 2 and commenced running at the beginning of stage 3. This was accompanied by a marked decline in the oxygen saturation levels. Although the initial SmO_2 values exhibited considerable disparity between the two legs, there was a notable degree of similarity in the subsequent decline within the designated test range (right calf values remained consistently lower throughout the duration of the test).

Table 1: VO_2max and SmO_2 values obtained in the Speed and Bruce protocols

	VO_2max (ml/min)	**VO_2max (ml/kg/min)**		**SmO_2 max (%)**	**SmO_2 min (%)**	**SmO_2 diff (%)**
Speed Protocol	4390	71.85	Speed Right	74.7	68.1	6.6
			Speed Left	74.4	66.8	7.6
Bruce Protocol	4640	75.94	Bruce Right	71.1	63.0	8.1
			Bruce Left	76.5	70.6	5.9

The VO_2max value obtained in the inclined Bruce protocol was 5.7 % higher than in the Speed protocol. The muscular desaturation value obtained in the inclined Speed protocol was 1.4 % higher than in the Bruce protocol (table 1).

Table 2: Correlation of VO_2max and SmO_2 values obtained in the Speed and Bruce protocols

		Speed VO_2	**Speed Right SmO_2**
Speed Walk Right SmO_2	Pearson's r	-0.974***	Walk
Speed Walk Left SmO_2	Pearson's r	-0.988***	0.987***
Speed Run Right SmO_2	Pearson's r	-0.970***	Run
Speed Run Left SmO_2	Pearson's r	-0.990***	0.980***
		Bruce VO_2	Bruce Right SmO_2
Bruce Walk Right SmO_2	Pearson's r	-0.960***	Walk
Bruce Walk Left SmO_2	Pearson's r	-0.969***	0.993***
Bruce Run Right SmO_2	Pearson's r	-0.970***	Run
Bruce Run Left SmO_2	Pearson's r	-0.983***	0.977***

Speed VO_2: The amount of oxygen consumed during the Speed protocol. **Speed Walk Right SmO_2**: Intramuscular oxygen saturation from the right gastrocnemius muscle from start of walking until exhaustion during the Speed protocol. **Speed Walk Left SmO_2:** Intramuscular oxygen saturation from the left gastrocnemius muscle from start of walking until exhaustion during the Speed protocol. **Speed Run Right SmO_2:** Intramuscular oxygen saturation from the right gastrocnemius muscle from start of running until exhaustion during the Speed protocol. **Speed Run Left SmO_2:** Intramuscular oxygen saturation from the left gastrocnemius muscle from start of running until exhaustion during the Speed protocol. **Bruce VO_2:** The amount of oxygen consumed during the Bruce protocol. **Bruce Walk Right SmO_2:** Intramuscular oxygen saturation obtained from the right gastrocnemius muscle from start of walking until exhaustion during the Bruce protocol. **Bruce Walk Left SmO_2:** Intramuscular oxygen saturation from the left gastrocnemius muscle from start of walking until exhaustion during the Bruce protocol. **Bruce Run Right SmO_2:** Intramuscular oxygen saturation from the right gastrocnemius muscle from start of running until exhaustion during the Bruce protocol. **Bruce Run Left SmO_2:** Intramuscular oxygen saturation from the left gastrocnemius muscle from start of running until exhaustion during the Bruce protocol. *** $p<0.001$ level of statistical significance.

There is a very high negative correlation between oxygen consumption and SmO_2 values during the two test protocols. There is also a very high positive correlation between the SmO_2 values of the two legs (Table 2).

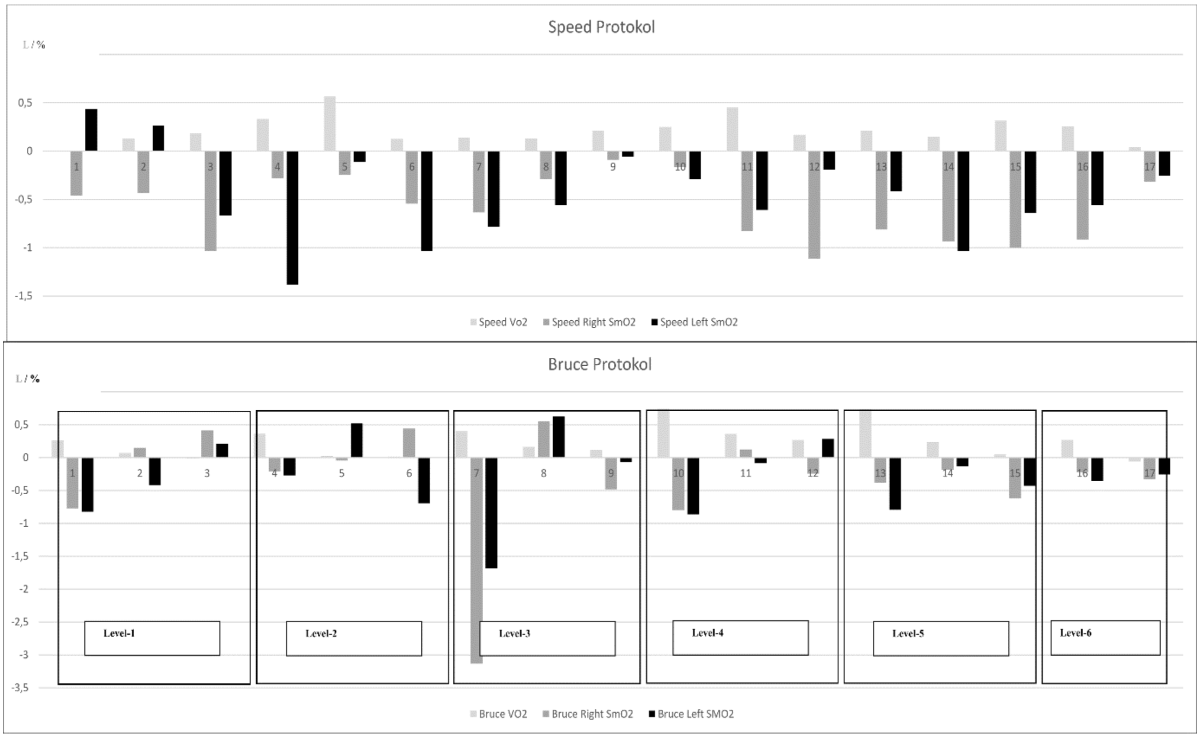

Figure 3 : Speed and Bruce protocol VO_2 and SmO_2 changes within each stage. **Speed VO_2**: VO_2 changes within each stage of the Speed protocol. **Speed Right SmO_2**: Changes of intramuscular oxygen saturation of the right gastrocnemius muscle within each stage of the Speed protocol. **Speed Left SmO_2**: Changes of intramuscular oxygen saturation of the left gastrocnemius muscle within each stage of the Speed protocol. **Bruce VO_2**: VO_2 changes within each stage of the Bruce protocol. **Bruce Right SmO_2**: Changes of intramuscular oxygen saturation of the right gastrocnemius muscle within each stage of the Bruce protocol. **Bruce Left SmO_2**: Changes of intramuscular oxygen saturation of the left gastrocnemius muscle within each stage of the Bruce protocol.

In the Speed protocol, a consistent increase in oxygen consumption was observed within the respective stages. Following a fluctuating period in the initial two minutes of the Speed test, the SmO_2 values declined in a consistent fashion throughout each subsequent stage, from the third minute onward, until the conclusion of the test.

The Bruce protocol was also subjected to further analysis by dividing each three-minute stage into one-minute sections. Due to the low intensity of the initial two stages and the fact that the athlete was walking, fluctuations were observed in oxygen consumption and SmO_2 values. The athlete's transition to the third stage of exertion is marked by the onset of running and a concomitant surge in oxygen uptake accompanied by a pronounced decline in the SmO_2 levels. However, during the second minute of this stage, there was an increase in the values of SmO_2. Subsequent stages exhibited a tendency for similar patterns to recur.

DISCUSSION

To date, there has been limited investigation into the simultaneous effects of different test protocols on oxygen uptake and muscular oxygen saturation. The VO_2max values obtained from the two tests in this case study were higher for the Bruce protocol than for the Speed protocol. In this context, studies comparing VO_2max measurements using inclined treadmill logs with those using horizontal treadmill logs have not produced conclusive results.

The research conducted has produced conflicting results due to the wide variety of subjects included in the early studies. When testing untrained subjects, higher VO_2max measurements were obtained with an inclined protocol compared to a horizontal protocol (Taylor et al., 1955; Astrand & Saltin, 1961). When trained subjects were included, the results of the studies were inconclusive, with either inclined (Freund et al., 1986; Allen et al., 1986) or horizontal protocols (Wilson et al., 1979) producing higher VO_2max or no difference (Kasch et al., 1976). Freund et al. (1986) found no significant difference in VO_2max between the inclined protocol (53.1 ± 4.0 ml/kg/min) and the horizontal protocol (53.6 ± 3.9 ml/kg/min) in 22 men who had previously exercised moderately. However, after completing a 12-week training program, which included 35-minute running sessions on inclined/undulating terrain at 65-85% of VO_2max, the VO_2max values showed a significant difference in favor of the inclined protocol (59.0 ± 5.6 ml/kg/min versus 56.6 ± 4.5 ml/kg/min). Allen et al. (1986) confirmed this result using the same study design, even though flat terrain was used in the training period. These two studies from the same research group suggest that regardless of the training modality (flat versus inclined), the inclined protocols produced higher VO_2max values after endurance training.

During inclined testing, VO_2max may be measured higher due to the activation of more muscle mass compared to flat tests. Furthermore, mechanical or neuromuscular limitations may restrict the depth of breathing during horizontal running (Pokan et al., 1995). Vanhoy (2012) supported the suggestion that muscles are more activated during inclined testing, finding that lactate levels were 2 mmol/L higher during the inclined protocol compared to the flat protocol. In this group of elite trained athletes, the Bruce protocol elicited higher VO_2max values than the flat protocol (75.3 ± 6.9 ml/kg/min versus 71.2 ± 6.7 ml/kg/min). In support of this, Costil et al. (1974) reported that auxiliary muscles, such as the vastus lateralis, which assist the body in lifting against an incline, are more active in inclined protocols. The study by Allen et al (1986) identified a further rationale for the elevated oxygen consumption observed in inclined protocols when compared to horizontal protocols. This rationale is attributed to an augmented duration and force of muscle contraction, in conjunction with lower stride frequency and a prolonged ground contact duration.

The current study's results (Table 1) are comparable to those of Vanhoy (2012) because the athlete we studied was highly accomplished at the national level in cross-country, track, and road running, and his training included inclined running. Further indicating the athlete's level of performance, the sudden jumps in oxygen consumption that occurred during the stage transitions in the Bruce protocol decreased slightly in the second and third minutes of the stage. It is assumed that the systemic response and steady rate were recorded during the relatively undemanding test phases. Consistent with this idea, the SmO_2 data exhibited both decreases and increases during the transition from walking to running (figures 1 and 2). It is noteworthy that, despite the higher VO_2max value observed in the Bruce protocol, oxygen consumption was significantly lower than in the Speed protocol at power levels below the ventilatory threshold (figure 1). This can be attributed to an increase in movement efficiency based on the different contraction patterns previously mentioned.

The decline in SmO_2 levels during the tests varied between the two legs (table 1). This is a strength of our study compared to the literature, where SmO_2 data are often collected from unilateral muscles or muscle groups. In our study, we collected data from symmetrical calf muscles simultaneously. The difference in the SmO_2 curves observed between the two legs may be attributed to the capillary structure in the dominant leg of the athlete, which may be influenced by a different blood supply. Alternatively, the differing muscle contraction durations and biomechanical running patterns may also contribute to the observed difference. Nevertheless, table 2 illustrate a strong negative correlation between oxygen consumption and SmO_2 levels for both legs, wether calculated from the start of walking or running. Note that the correlation values for the start of walking and running were obtained from a highly experienced and trained runner. Therefore, these values may vary among a larger and more diverse group of athletes.

Comprehensive analysis of the data, both overall and in detail, is critical when testing elite athletes. On occasion, the oxygen consumption observed during the Bruce protocol displays a decline while concomitantly exhibiting a reduction in SmO_2 values, which is a phenomenon that may be perceived as counterintuitive (figure 1). In a comparable manner, the decrease in SmO_2 at the end of the tests was marginally less pronounced in the Bruce protocol despite the VO_2max being measured to be higher (table 1). In order to gain a comprehensive understanding of the data, it is essential to evaluate the differences in the dynamic changes in addition to the average values. Consequently, the dynamic changes in SmO_2 values within each stage of the test were calculated (figure 3) in order to capture the reaction of the subsystems to the momentary change in power output. Additionally, it appears physiologically accurate to consider the 20-second delay in circulation between the lungs and muscles when calculating the correlation. However, it is worth noting that this delay not apply equally to everyone (Spencer et al., 2012). In this context, it is of paramount importance to consider the intricate interrelationship between these variables when developing a model of the peripheral and central circulatory system.

Overall, the literature confirms the results of our study. In their study, Spencer et al. (2012) divided their graded exercise test into 10-second increments and observed a decrease in SmO_2 levels that was similar to the findings in our study. Consistent with our findings, Austin et al. (2005) discovered a strong correlation (r=-0.88) between SmO_2 and VO_2max values during a graded exercise test. Shibuya and Tanaka (2003) reported a decrease in SmO_2 levels similar to our study during a gradually increasing cycle ergometer test with a 30W increase every 2 minutes. They found a strong correlation between this decline and VO_2max (r=-.933). Yano et al. (2005) observed a similar decrease in SmO_2 with a very high negative correlation to oxygen consumption (r =-0.89) during a cycle ergometer test with a 25-watt increase per minute until exhaustion. Crum et al. (2017) reported a strong negative correlation (r=-0.730) between SmO_2 depletion and oxygen consumption during a gradually increasing cycle ergometer test.

RESULTS

The analysis of the present case demonstrates that central and peripheral physiological processes of oxygen consumption are not always congruent, and that the respective contingencies exert an influence. While VO_2 max (central) was measured to be higher in the inclined Bruce protocol, this was not reflected in the SmO_2 (periphery), which did not demonstrate a higher total SmO_2 drop compared to the flat Speed protocol. The inclined protocol elicited side differences and fluctuations in SmO_2 during the stage, despite the consistent increase of VO_2. Nevertheless, the overall evolution of both parameters during both testing procedures exhibited a very high significant correlation.

In light of the results of this study, it is pertinent to ask whether the analysis of competitive athletes should be limited to examining averages or whether individual characteristics should be considered. It will be essential to complement the assessment based on traditional physiological parameters by also considering how physiological subsystems respond to performance. The integration of a multitude of accomplished athletes into this meticulous analysis will augment the comprehension of their individual solutions in the complex interplay of physiological and biomechanical factors.

Ethical Approval Permission Information
Ethics Committee: Marmara University Faculty of Medicine Clinical Research Ethics Committee
Division / Protocol No: 09.2016.415

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