THE EFFECTS OF DIFFERENT PRIOR EXERCISES ON OXYGEN UPTAKE KINETICS AND EXERCISE TOLERANCE IN SUPRAMAXIMAL RUNNING PERFORMANCE

Elina Moilanen

Master's Thesis
Science of Sport Coaching and Fitness Testing
Faculty of Sport and Health Sciences
University of Jyväskylä
Spring 2020
Supervisors: Juha Ahtiainen & Jussi Mikkola

ABSTRACT

Moilanen, E. 2020. The effects of different prior exercises on oxygen uptake kinetics and exercise tolerance in supramaximal running performance, Faculty of Sport and Health Sciences, University of Jyväskylä, Science of Sport Coaching and Fitness Testing, Master's thesis, 52 pp.

Introduction. Rapid response of VO_2 kinetics at the beginning of the endurance exercise has been found beneficial for the performance. In sports, prior exercises have been used to enhance the VO_2 kinetics as well as the exercise tolerance of the performance, and many earlier studies have shown beneficial effects of prior high intensity exercises on these variables. In addition to the capacities of the respiratory and circulatory systems, the importance of neuromuscular capacities in endurance performance have been noticed. The aim of this study was to investigate the effects of continuous severe intensity prior exercise and intermittent prior exercise on VO_2 kinetics and exercise tolerance in supramaximal running exercise compared to continuous moderate intensity prior exercise. The second aim was to investigate associations between neuromuscular abilities and endurance performance.

Methods. Participants (n=10) visited the laboratory five times separated by 3-7 days. During the first visit, incremental VO_2max test was completed by running on a treadmill. The next three visits included supramaximal running tests on a treadmill with three different prior exercises, in randomized order. Prior exercise protocols were continuous moderate intensity (control condition, S1), continuous severe intensity (S2) and intermittent (S3) prior exercise. The intensities were 75 % of LT for S1, 70 % Δ for S2 and 110 % vVO_2max for S3 and for the supramaximal test. The duration of the prior exercise protocols was 6 minutes. The recovery period between the prior exercise protocol and supramaximal test was 20 minutes including 15 minutes of passive and 5 minutes of active recovery. Supramaximal tests were done until volitional exhaustion. During the last visit, neuromuscular performance, including leg press 1 RM, CMJ and 30-m speed test, was measured.

Results. Statistically significant difference ($p < 0.05$) was found between S1 and S2 in total VO_2 measured in 15-120 s of the supramaximal performance (mean ± SD 5867 ± 1506 for S1 and 5963 ± 1496 for S2), but there were no significant differences between conditions concerning any other variables of VO_2 kinetics. There were no statistically significant differences between the conditions in exercise tolerance. Significant correlations were found between vVO_2max and leg press 1 RM ($r = 0.688$, $p < 0.05$) and vVO_2max and speed test 0-10 m time ($r = –0.692$, $p < 0.05$) and time to exhaustion of the supramaximal test S1 and CMJ ($r = 0.661$, $p < 0.05$), supramaximal test S2 and CMJ ($r = 0.833$, $p < 0.01$) and supramaximal test S3 and CMJ ($r = 0.809$, $p < 0.01$).

Conclusion. Continuous severe intensity prior exercise can increase energy production from aerobic sources during the first two minutes of the following supramaximal performance when compared to moderate intensity prior exercise, but this might not improve the performance in exercise with supramaximal intensity and short duration. Prior exercise intensity and recovery time should be chosen so that it improves performance but does not produce too much fatigue. Also, the individual differences should be considered. Neuromuscular performance was found to correlate with the endurance performance, which supports the importance of neuromuscular ability also in endurance sports.

Key words: oxygen uptake kinetics, prior exercise, exercise tolerance

ABBREVIATIONS

1 RM	One repetition maximum
ATP	Adenosine triphosphate
BLa	Blood lactate
BMI	Body mass index
CMJ	Countermovement jump
CP	Critical power
GET	Gas exchange threshold
HR	Heart rate
LT	Lactate threshold
NIRS	Near infrared spectroscopy
O_2	Oxygen
PCr	Phosphocreatine
pH	Potential of hydrogen
PO	Power output
PO_2	Partial pressure of Oxygen
PPO	Peak power output
SJ	Squat jump
SLJ	Standing long jump
TSJP	Two-leg standing long jump
VO_2	Volume of oxygen uptake
VO_2max	Maximal oxygen uptake
VO_2peak	Peak oxygen uptake
vVO_2max	Velocity at maximal oxygen uptake

CONTENTS

ABSTRACT

1 INTRODUCTION

Elite athletic performance in endurance sports requires efficient transfer of energy from aerobic and anaerobic sources into velocity and power, by the cooperation of muscular, cardiovascular, and neurological factors. The velocity or the power of the performance is partly determined by the oxygen uptake VO_2 (aerobic), oxygen deficit (anaerobic) and by the gross mechanical efficiency of the performance. (Joyner & Coyle 2008.) In addition to this, it has also been noted that neuromuscular factors are related to endurance performance (Paavolainen et al. 2000; Nummela et al. 2006).

At the beginning of the exercise VO_2 is increasing exponentially. The steady state is usually achieved in 2-3 minutes after the start of the exercise. The speed – or in other words – the kinetics of this VO_2 response affects how quickly the steady state is attained. Rapid response of VO_2 kinetics represents the lower requirement of anaerobic energy production and smaller accumulation of oxygen deficit. Oxygen deficit causes depletion of muscle high energy phosphates and glycogen and it also causes accumulation of metabolites, which are related to fatigue. Fast VO_2 kinetics and smaller oxygen deficit have been found to be related to better performance. (Burnley & Jones 2007.)

In sports, it is usual to use prior or “warm-up” exercises to alter the physiological responses of the exercise and to enhance performance. Prior exercise protocols can also influence VO_2 kinetics and exercise tolerance of the performance. (Burnley & Jones 2007.) Many studies have shown that high-intensity prior exercise can accelerate the VO_2 kinetics (Bailey et al. 2009; Burnley et al. 2011; Caritá et al. 2015; Fujii et al. 2018) and improve exercise tolerance (Jones et al. 2003; Bailey et al. 2009). Prior sprint exercise has also been shown to affect positively VO_2 kinetics (Tordi et al. 2003; Wilkerson et al. 2004), but its effects on exercise tolerance are not that clear. The intensity of the prior exercise and the recovery time between the prior exercise and the performance can affect the ion and metabolite concentrations in muscles and in blood, which also affect performance (Bailey et al. 2009; Christensen & Bangsbo 2015).

2 PHYSIOLOGY OF HIGH INTENSITY ENDURANCE EVENTS

Elite athletic performance in endurance sports requires efficient transfer of energy from aerobic and anaerobic sources into velocity and power, by the cooperation of muscular, cardiovascular, and neurological factors. Intensities in the Olympic endurance events are above 85 % of the maximal oxygen uptake (VO_2max). Even though energy in these events is mainly produced from aerobic sources, in most sports athletes must also be able to cope with fatigue at intensities that stimulate anaerobic metabolism. The velocity or the power of the performance is partly determined by the oxygen uptake VO_2 (aerobic), oxygen deficit (anaerobic) and by the gross mechanical efficiency of the performance (figure 1). (Joyner & Coyle 2008.) In addition to the factors presented in this model, it has been noted that neuromuscular factors contribute to the endurance running performance (Paavolainen et al. 2000; Nummela et al. 2006).

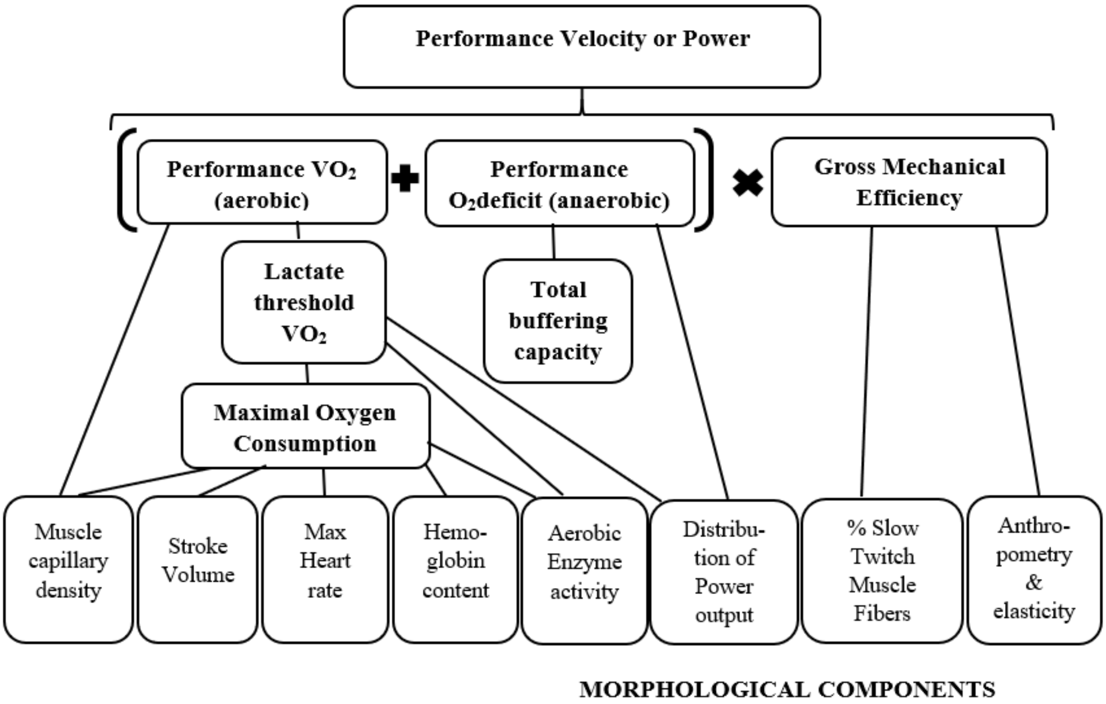


FIGURE 1. Schematic representation of the physiological factors that work as determinants of performance velocity or power output (modified from Joyner & Coyle 2008).

During the exercise, the energy requirements of the muscle increases. Three processes, two without and one with the presence of oxygen, work together to fulfil these requirements, and the distribution of each depends on the duration and intensity of the exercise. At the initial stages of exercise, energy is provided from the immediate energy sources. These sources include using the stored ATP and splitting the high-energy phosphagen, phosphocreatine (PCr). The second process – usually called the anaerobic glycolysis – includes the anaerobic breakdown of muscle glycogen to pyruvic acid and then to lactic acid. The third process is what is usually called aerobic or oxidative metabolism and it means mainly the breakdown of carbohydrates and fats in the presence of oxygen. (Gastin 2001.)

The immediate energy sources and the anaerobic glycolysis form together the anaerobic energy system because they produce energy without the presence of oxygen. They can produce energy rapidly, but their capacity is limited. At the beginning of the high-intensity exercise, depletion of the PCr stores and the reduction in muscle pH causes a reduction in the work output. Aerobic energy system is able to produce a lot of energy but is limited by the limits of oxidative phosphorylation and the oxygen delivery to the muscle. Anaerobic energy system can respond immediately to the high energy demands, but the role of aerobic energy production increases, when intense exercise must be sustained for extended periods. Energy production from aerobic sources can be measured with the measurement of pulmonary oxygen uptake, which has been found to have a direct relationship to the aerobic energy production. Measurement of anaerobic energy production has been found more challenging due to its nature as a more intracellular. (Gastin 2001.)

According to the review of Gastin (2001), the energy production from aerobic sources during high intensity exercise lasting 120 s is about 60 %. When the duration of high-intensity exercise is 3-4 minutes, the energy production from aerobic sources is about 75-80 %. (Gastin 2001.) In high intensity endurance events which last a few minutes, like rowing and cycling races, cross-country skiing sprints and middle-distance runs, the rapid activation of aerobic metabolism is critical. At the onset of the exercise, ATP produced from the aerobic metabolism cannot fulfil the ATP demand, and anaerobic energy sources must be used. Energy is provided from PCr hydrolysis and anaerobic glycolysis, which causes accumulation of inorganic phosphates and protons as well as intracellular acidosis, which are suggested to cause skeletal muscle fatigue and reduction in force production. (Temesi et al. 2017.) Also, in the study of Black et al. (2017) it was noted that severe intensity exercise (>CP) causes decrease in muscle ATP, PCr and pH, increase of lactate levels in blood and muscle and reduction in muscle excitability. The exercise intolerance in this kind of exercise is associated to changes in muscle metabolic milieu (Black et al. 2017).

In short duration high intensity endurance events, the exercise intensity can exceed the VO_2max. For example, in the simulated 800-m and 1500-m running events the exercise intensity has been reported to be 113 ± 9 and 103 ± 6 % of VO_2peak, respectively (Spencer & Gastin 2001). In the same study, it was also noted that even though the intensity of the exercise is higher than VO_2max, the contribution of aerobic energy production remains high. The duration of the simulated running events were 1:53 ± 0:02 minutes for 800-m and 3:55 ± 0:03 for 1500-m. The proportion of aerobic metabolism was 66 ± 4 % for 800-m and 84 ± 3 % for 1500-m event. (Spencer & Gastin 2001.) Carter et al. (2006) were comparing the effects of exercising at different intensities on VO_2 kinetics and also reported the metabolic responses of exercising at 100, 110 and 120 % of VO_2max (table 1). The study was completed by running on a treadmill with recreationally active participants (Carter et al. 2006).

TABLE 1. Metabolic responses to exhaustive severe and supramaximal exercises (mean ± SEM); EE = end exercise; HR = heart rate; VO_2 = volume of oxygen uptake; O_2 = oxygen; O_2 def = oxygen deficit (modified from Carter et al. 2006).

	80% Δ	**100% VO_2max**	**110% VO_2max**	**120% VO_2max**
Speed (km/h)	15.9±0.5	17.0±0.5	18.7±0.6	20.8±0.7
Time to exhaustion (s)	588±47	313±50	139±6	85±5
Δ lactate (mM)	4.8±1.1	5.2±0.7	4.7±0.6	3.6±0.7
EE HR (beats/min)	182±4	179±6	174±6	175±2
EE VO_2 (ml/min)	4175±708	4191±718	3880±719	4148±600
% VO_2 max attained	101±1	101±1	97±2	96±2
Total O_2 consumed (mL)	31177±2469	15288±1748	5948±583	2912±308
O_2 def. at TDs (mL)	2379±154	3871±667	3389±263	6311±353
O_2 def. at exhaustion (mL)	14771±896	13685±810	13548±792	14776±786

3 OXYGEN UPTAKE KINETICS

3.1 Oxygen uptake kinetics during exercise

At the beginning of the exercise VO_2 is increasing exponentially. The steady state is usually achieved in 2-3 minutes after the start of the exercise. The speed – or in other words – the kinetics of this VO_2 response affects how quickly the steady state is attained. (Burnley & Jones 2007.) According to the review of Hughson (2009), VO_2 kinetics is affected by many factors including, for example, physical fitness, prior exercise, muscle fibre composition, cardiac output, metabolic substrates, enzyme activation and some disease states. Faster VO_2 kinetics are associated with increased fitness, prior moderate or heavy exercise, increased muscle blood flow and enzyme activity, higher percentage of slow twitch fibres and higher intracellular PO_2. Opposite characteristics are related to slower VO_2 kinetics as well as some disease states. (Hughson 2009.)

According to Burnley and Jones (2007), VO_2 response to exercise shows three different phases: phase I, II and III. The phase I of VO_2 kinetics starts from the beginning of the exercise. This phase is called the cardiodynamic component. Cardiodynamic component does not yet reflect the oxygen uptake of the muscles because of the 10-20 s delay between oxygen unloading in the muscle and the arrival of this blood to lungs. The second phase of VO_2 kinetics is usually called the fundamental, primary, or fast component, and it seems that during this phase pulmonary VO_2 reflects the muscle VO_2 quite well. Phase II covers the exponential part of the response and phase III is the steady state phase in low and moderate exercise intensities. When exercising at intensities above the lactate threshold, the VO_2 keeps increasing after the primary phase and in this case the phase III is called the "slow component". The VO_2 response to heavy exercise is demonstrated in figure 2. (Burnley & Jones 2007.)

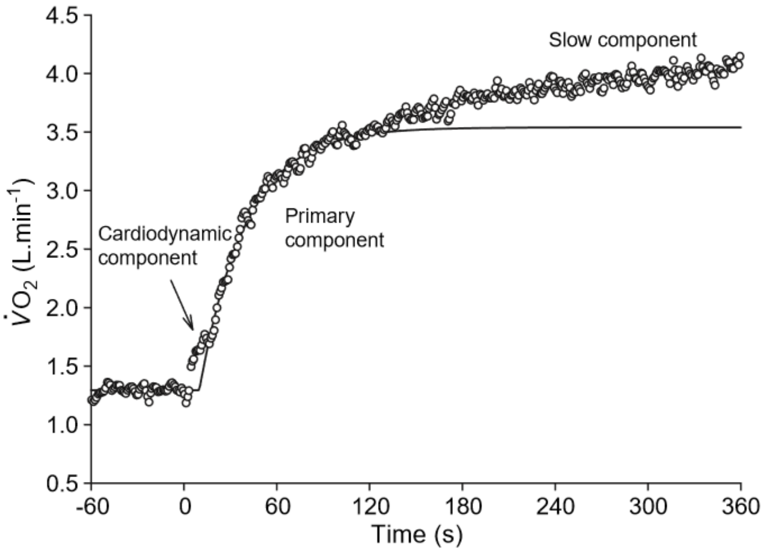


FIGURE 2. The VO_2 response to heavy-intensity exercise in a healthy individual (Burnley & Jones 2007).

Exercise intensity has also an effect on VO_2 kinetics response. Four exercise intensity domains have been defined by using the dynamic characteristics of pulmonary gas exchange and blood-acid base status during constant-load exercise (table 2). When exercising at moderate intensity, one can notice two components in VO_2 kinetics response before the steady state. When exercising at intensity which is above the lactate threshold, the third phase of response is usually called the “slow component”. During slow component, VO_2 does not achieve exact steady state but continues to rise in a slow time course, and it rises even above the anticipated VO_2 value. Usually the studies investigating the VO_2 slow component have used an intensity called “50 % delta” which represents the power output from halfway the lactate threshold and VO_2max. At extreme intensity levels one can notice only two components and there is not evident slow component. Extreme intensity is defined to be the power output at which exhaustion occurs before attainment of VO_2max. (Burnley & Jones 2007.)

VO_2 kinetics can be affected by training (Burnley & Jones 2007) and athletes with different performance levels have also found to have differences in VO_2 kinetics (Bosquet et al. 2007). Athletes with higher performance levels can have a faster VO_2 kinetics and smaller O_2 deficit at the beginning of the exercise than lower level athletes. (Bosquet et al. 2007.)

TABLE 2. Exercise intensity domains (Burnley & Jones 2007).

Domain	Boundaries	$\dot{V}O_2$ kinetic responses	Endurance time	Likely fatigue mechanisms
Moderate	Upper: LT	Two components; steady state achieved within 3 min in healthy individuals	>4 h	Hyperthermia (in the heat), reduced central drive/ motivation ("central fatigue"), muscle damage (running)
Heavy	Lower: LT Upper: CP	Three components; slow component evident after primary phase; steady state delayed by 10–20 min; elevated $\dot{V}O_2$	Up to ~3–4 h	Glycogen depletion, hyperthermia
Severe	Lower: CP Upper: highest power that elicits $\dot{V}O_{2max}$ before fatigue	Two/three components; slow component evident that develops continuously if power below $\dot{V}O_{2max}$; no steady state; $\dot{V}O_{2max}$ attained if sustained	Up to ~30–45 min	Depletion of finite energy store represented by W' or the oxygen deficit and/or accumulation of fatiguing metabolites (e.g. H^+, $H_2PO_4^-$)
Extreme	Lower: highest power eliciting $\dot{V}O_{2max}$	Two components; no slow component evident; $\dot{V}O_{2max}$ not attained	<120 s	As for severe + excitation–contraction coupling failure

Note: LT = lactate threshold; CP = critical power.

3.2 Measurement of oxygen uptake kinetics

Oxygen uptake kinetics is measured breath-by-breath from pulmonary gas exchange and the data is usually linearly interpolated to the 1-second time intervals (Keir et al. 2014). The measured variables in most studies include VO_2 amplitudes, time constants, time delays and/or mean response times (Burnley et al. 2000; Tordi et al. 2003; Wilkerson et al. 2004; Bosquet et al. 2007; Burnley et al. 2011; Christensen & Bangsbo 2015; Caritá et al 2015). VO_2 response can be characterizes by using the two- or three component or monoexponential function depending on the intensity of the exercise. Two component exponential functions are used for moderate intensity exercise and three component exponential functions for heavy intensity exercise (Burnley et al. 2000). When characterizing the primary VO_2 response from supramaximal performance, usually the monoexponential model is used and it is:

$$VO_2(t) = \text{baseline} + \text{amplitude}(1 - e^{-(\text{t - time delay})/\text{time constant}})$$

where $VO_2(t)$ is VO_2 to a given time (t). Baseline VO_2 is usually measured before the test at rest or during low intensity exercise. The amplitude means the absolute increase in VO_2 above baseline. The time constant represents the rate at which the VO_2 rises and it calculated as a time it takes to reach 63 % of the amplitude. The time delay is the time it takes to the primary component to begin. (Christensen & Bangsbo 2015.)

3.3 Effects of prior exercises on oxygen uptake kinetics

In sport, it is usual to use prior or “warm-up” exercises to alter the physiological responses of the exercise and to enhance performance. Prior exercise protocols can also influence VO_2 kinetics and exercise tolerance of the performance. (Burnley & Jones 2007.) Different level athletes have found to have differences in VO_2 kinetics (Bosquet et al. 2007) but the prior exercise effects seem to same with the non-athletes and athletes (Cárita et al. 2015). The intensity of the prior exercise and the recovery time between the prior exercise and the performance also affects the response of prior exercise on VO_2 kinetics and performance (Bailey et al. 2009).

3.3.1 Continuous prior exercises

Probably the most classic study of the effects of continuous prior exercises has been the study of Gerbino et al. (1996), in which they studied the effects of supra-LT and sub-LT prior exercise on supra-LT and sub-LT cycling performances. Supra-LT meant the intensity corresponding the 50 % of the difference between the LT and VO_2max (50 % Δ). The intensity of sub-LT was 90 % of the LT. The results of the study showed that the VO_2 kinetics of the supra-LT performance were accelerated by supra-LT prior exercise but not by the sub-LT prior exercise. Prior exercises had no effects on VO_2 kinetics of the sub-LT performance. The authors suggested that the possible mechanisms behind the speeded VO_2 kinetics of supra-LT performance could be increased metabolic acidosis of the working muscles after the supra-LT prior exercise which increases the muscle perfusion during the exercise. (Gerbino et al. 1996.)

A few years later, same kind of results were also found in the study of Burnley et al. (2000), in which the authors were studying the effects of heavy prior exercise, especially, on the phase II oxygen uptake kinetics of heavy cycling exercise. The study included four different protocols, which comprised of two six-minute exercise bouts separated by six minutes of recovery. The protocols were: 1) moderate prior exercise followed by moderate exercise, 2) moderate prior exercise followed by heavy exercise, 3) heavy prior exercise followed by moderate exercise and 4) heavy prior exercise followed by heavy exercise. The intensity of moderate exercise was 80 % of the VO_2max and the intensity of the heavy exercise was 50 % Δ. The results of the study showed that prior exercises had no effects on moderate intensity exercise and the VO_2 kinetics during heavy exercise were not affected by prior moderate exercise. Heavy prior exercise significantly lowered the mean response time of the second heavy exercise but had no effect on VO_2 amplitude. According to authors of this study, the most important effect of the heavy prior exercise was that it significantly reduced the amplitude of the VO_2 slow component and reduced the mean response time. (Burnley et al. 2000.)

Burnley et al. (2002) were comparing the effects of two different prior exercise protocols and passive warming of muscles on VO_2 kinetics of heavy cycling exercise. The first prior exercise protocol included three minutes of baseline cycling at 20 W, six minutes of heavy intensity cycling at the intensity corresponding 50 %Δ and six minutes of pedalling at 20 W. The second prior exercise protocol included one 30-s maximal all-out sprint, three minutes of rest and three minutes of pedalling at 20 W. The passive warming of muscles comprised of 40-minute period of leg warming in hot water bath (42°C), three minutes of rest and three minutes of pedalling at 20 W. The heavy exercise after prior exercise protocol was done at the same intensity as heavy prior exercise (50 % Δ). In this study, both the prior heavy exercise and prior sprint exercise increased significantly the absolute primary VO_2 amplitude and decreased the slow component amplitude of VO_2 kinetics of the heavy exercise. Passive warming had no significant effects on VO_2 kinetics, and the effects of heavy and sprint exercise were qualitatively similar. (Burnley et al. 2002.)

Draper et al. (2006) were comparing the effects of moderate intensity and high intensity prior exercise on VO_2 kinetics during two-minute severe intensity running. The moderate intensity prior exercise included six minutes of running at speed equivalent to 90 % of ventilatory threshold. The high intensity prior exercise included six minutes of running at speed corresponding 50 % of the difference between ventilatory threshold and VO_2peak (50 % Δ).

The prior exercise protocol was followed by six minutes of recovery before the two-minute severe intensity running. The study showed that the amplitude and the speed of VO_2 response were no different between two conditions. (Draper et al. 2006.)

Bailey et al. (2009) were studying the effects of prior exercises with different intensities and different recovery durations on VO_2 kinetics and exercise tolerance in severe intensity cycling exercise. The severe-intensity exercise was performed at intensity corresponding the 80 % of the difference between GET and VO_2max. The study design included six different prior exercise protocols with different combinations of exercise intensity and recovery duration. The prior exercise protocols were: 1) six minutes at intensity of 40 % of the difference between GET and VO_2max (40%Δ) followed by three minutes of recovery (40-3-80), 2) six minutes at 40%Δ followed by nine minutes of recovery (40-9-80), 3) six minutes at 40%Δ followed by 20 minutes of recovery (40-20-80), 4) six minutes at intensity of 70 % of the difference between GET and VO_2max (70%Δ) followed by three minutes of recovery (70-3-80), 5) six minutes at 70%Δ followed by nine minutes of recovery (70-9-80) and 6) six minutes at 70%Δ followed by 20 minutes of recovery (70-20-80). Severe-intensity exercise was also once performed without prior exercise, which worked as a control condition. The study showed that the overall VO_2 kinetics response was accelerated relative to control in all prior exercise conditions except the 40-9-80 and 40-20-80 conditions. The conclusion of the study was that VO_2 kinetics are not altered by prior exercise if the intensity is too low (40%Δ) and the duration of the recovery is too long (40-9-80 and 40-20-80 conditions). The effect on VO_2 kinetics is greatest if a high intensity prior exercise is coupled with a short recovery (the 70-3-80 condition.) (Bailey et al. 2009.)

The aim of the study of Burnley et al. (2011) was to investigate the effects of heavy-intensity and severe-intensity prior exercises on VO_2 kinetics and power-duration relationship of severe-intensity cycling. The heavy intensity prior exercise included six minutes of cycling at intensity of 50 % of the difference between GET and CP followed by 10 minutes of recovery. The severe intensity prior exercise included six minutes of cycling at intensity that corresponded to the power output which could be maintained for eight minutes and it was also followed by 10 minutes of recovery. The effects of prior exercises were tested on four different severe intensity work rate exercises and the intensities of these performances were

GET + 60 %, 70 %, 80 % or 100 % of peak work rate and exercises were performed until exhaustion. After the prior exercise participants had one-minute of unloaded pedalling, six minutes of passive rest and three minutes of unloaded pedalling before the severe intensity exercise. Both heavy and severe intensity prior exercises accelerated the VO_2 kinetics of the following performance. (Burnley et al. 2011.)

Christensen & Bangsbo (2015) were investigating the effects of prior exercise intensity and the duration of the recovery on performance, blood metabolites and the VO_2 response in a four-minute maximal cycling exercise. The used prior exercise protocols were 1) 20 minutes of cycling at intensity corresponding 50 % from PPO followed by six minutes of rest (MOD6), 2) an incremental exercise with intensities of 25 %, 50 %, 75 % and 100 % of PPO and two 20-second sprints followed by six minutes of recovery (HI6) and 3) equal to HI6 but followed by 20 minutes of recovery (HI20). The results of the study showed that HI6 had the highest pulmonary VO_2 at the initial phase of the performance, but reduced performance compared with MOD6. (Christensen & Bangsbo 2015.)

Maturana et al. (2018) were comparing the effects of three-minute prior exercise to traditional six-minute model at relative intensities, that would produce similar levels of fatigue, on VO_2 kinetics. The VO_2 kinetics were tested from an exercise performed an intensity corresponding PO at 90 % of GET. The three-minute prior exercise was done with the intensity corresponding 90 % of PPO and six-minute prior exercise with the intensity corresponding 80 % of PPO. The study showed that prior exercises with different duration, but same fatigue produced the same speeding of VO_2 response. (Maturana et al. 2018.)

The aim of the study of Fujii et al. (2018) was to test the effects of moderate-intensity prior exercise and a work-matched high-intensity prior exercise on final sprint power output and VO_2 response of two-minute supramaximal cycling exercise. The supramaximal exercise comprised of 90 seconds of constant workload cycling with the workload corresponding to 110 % of VO_2peak followed by 30 seconds of maximal cycling. Exercise was done after three different prior exercise protocols: 1) control condition: no prior exercise, 2) 10 minutes of cycling at workload of 40 % of VO_2peak (moderate-intensity) and 3) five minutes of cycling at workload of 80 % of VO_2peak (high-intensity). There were five minutes of recovery between the prior exercise protocol and supramaximal performance in all conditions. The results showed that VO_2 during 90 seconds of constant load cycling was higher after the high-intensity than moderate-intensity prior exercise as well as post-prior exercise blood lactate concentration. Both prior exercise protocols improved final sprint performance, but the high-intensity prior exercise might have a better effect on short duration (< 10 s) maximal sprinting performance. Figure 3 represents the VO_2 responses after the control condition and prior exercises. (Fujii et al. 2018.)

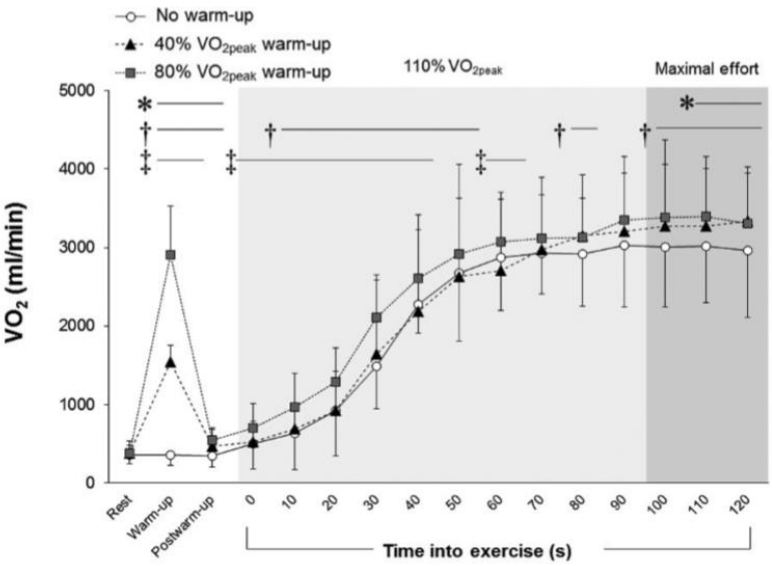


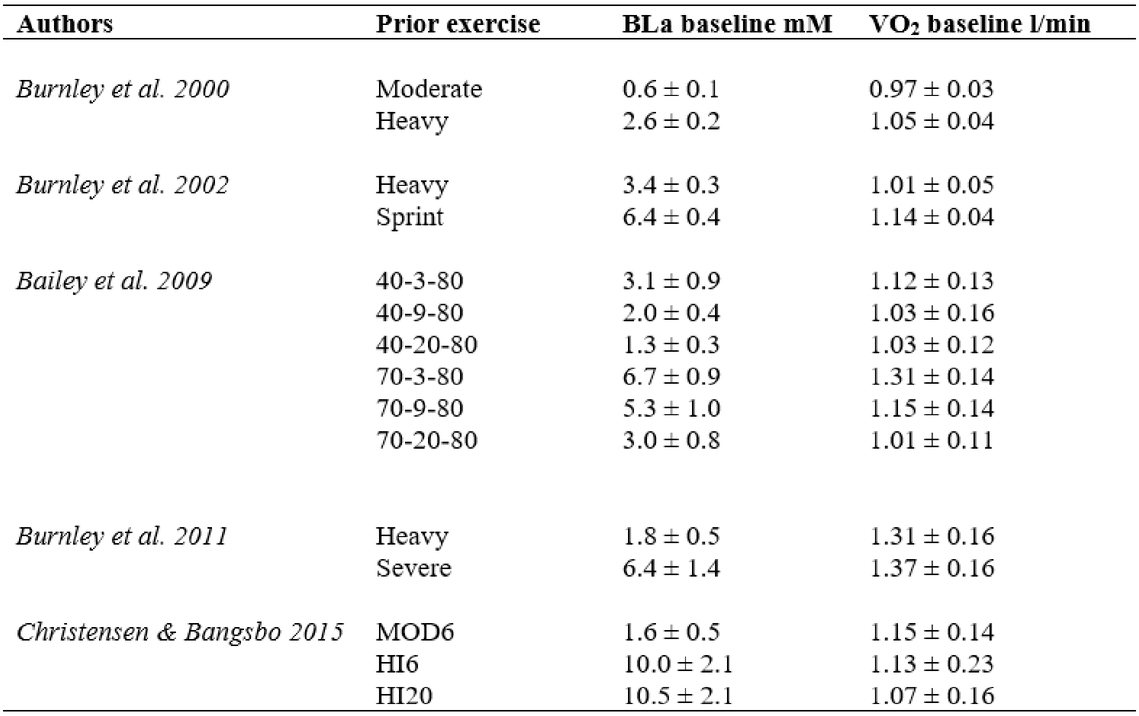
FIGURE 3. Oxygen uptake (VO_2) measured during rest (before prior exercise), prior exercise, post-prior exercise rest, and during 120 s of supramaximal cycling consisting of 90 s of cycling at a workload that corresponds to 110% VO2peak followed by 30 s of maximal cycling (Fujii et al. 2018).

Thus, according to earlier studies, it seems that to accelerate the VO_2 kinetics, the intensity of the prior exercises must be high enough. VO_2 kinetics of the high intensity exercise have been found to increase after six-minute prior exercise at intensity of 50 % Δ. Protocols of these studies have included six-minute prior exercise followed by six-minutes of recovery after which second bout of six-minutes is performed and the studies have been done by cycling. (Gerbino et al. 1996; Burnley et al. 2000; Burnley et al. 2002.) In the study of Draper et al. (2006), which was done by running, the performance from which the VO_2 kinetics were measured, was two minutes severe intensity running and, in this study, there were no differences between the moderate intensity and high intensity prior exercises effects on VO_2 kinetics. The study of Bailey et al. (2009) considered many factors affecting the performance and VO_2 kinetics of the performance after prior exercises. It was also noted in their study that VO_2 kinetics were not accelerated if the intensity of the prior exercises was too low (40 %Δ) and additionally, if the recovery time between the prior exercise and performance was too long (9 and 20 minutes). The greatest effect on VO_2 kinetics was achieved when the intensity prior exercise was higher (70% Δ) and the recovery time shorter (three minutes). (Bailey et al. 2009.) Same kind of results were also found in the study of Christensen & Bangsbo (2015), in which the best effect on VO_2 kinetics was found after the high intensity prior exercise with the short recovery (six minutes) compared to moderate prior exercise and high intensity prior exercise with longer recovery. Maturana et al. (2018) found out that the prior exercise eliciting similar levels of fatigue but having different duration had similar effects on VO_2 kinetics of moderate cycling exercise. In the study of Fujii et al. (2018), however, the work-matched, five-minute high-intensity prior exercise produced higher VO_2 during 90 seconds of constant supramaximal cycling compared to 10-minute moderate exercise.

As can be seen from the table 3, after prior exercises, the baseline blood lactate levels as well as baseline VO_2 levels are elevated. The levels are elevated more when the intensity of the prior exercise is high. (Burnley et al. 2000; Burnley et al. 2002; Bailey et al. 2009; Burnley et al. 2011; Christensen & Bangsbo 2015.) In the study of Burnley et al. (2000), the moderate prior exercise did not elevate VO_2 and blood lactate levels much from the baseline, but heavy prior exercise did. In the study of Burnley et al. (2002), both the heavy and the sprint prior exercise elevated the VO_2 and blood lactate baseline levels, but increase was much greater after the sprint prior exercise. In the study of Bailey et al. (2009), the intensity of 70%Δ elevated the baseline lactate levels more than the intensity of 40%Δ. Same kinds of results can be also found in the study of Burnley et al. (2011), in which the severe prior exercise elevated the baseline levels of lactate and VO_2 more than heavy intensity prior exercise and in the study of Christensen & Bangsbo (2015), in which the baseline lactate levels were after the moderate intensity prior exercise 1.6 ± 0.5 and after the high intensity prior exercises about 10 mM.

The recovery time between the prior exercise and the trial also affects the baseline levels as can be seen from the study of Bailey et al. (2009), in which the blood lactate and VO_2 baseline values were higher after the shorter recovery times. The study also showed that the VO_2 kinetics were accelerated the most after the 70-3-80 condition, which also elevated the blood lactate and VO_2 baseline values more than other conditions (Bailey et al 2009).

TABLE 3. Baseline values of blood lactate (BLa) and VO_2 after different prior exercises in different studies.



Authors	**Prior exercise**	**BLa baseline mM**	**VO_2 baseline l/min**
Burnley et al. 2000	Moderate	0.6 ± 0.1	0.97 ± 0.03
	Heavy	2.6 ± 0.2	1.05 ± 0.04
Burnley et al. 2002	Heavy	3.4 ± 0.3	1.01 ± 0.05
	Sprint	6.4 ± 0.4	1.14 ± 0.04
Bailey et al. 2009	40-3-80	3.1 ± 0.9	1.12 ± 0.13
	40-9-80	2.0 ± 0.4	1.03 ± 0.16
	40-20-80	1.3 ± 0.3	1.03 ± 0.12
	70-3-80	6.7 ± 0.9	1.31 ± 0.14
	70-9-80	5.3 ± 1.0	1.15 ± 0.14
	70-20-80	3.0 ± 0.8	1.01 ± 0.11
Burnley et al. 2011	Heavy	1.8 ± 0.5	1.31 ± 0.16
	Severe	6.4 ± 1.4	1.37 ± 0.16
Christensen & Bangsbo 2015	MOD6	1.6 ± 0.5	1.15 ± 0.14
	HI6	10.0 ± 2.1	1.13 ± 0.23
	HI20	10.5 ± 2.1	1.07 ± 0.16

3.3.2 Intermittent prior exercises

In addition to continuous prior exercises, also the effects of intermittent prior exercises on oxygen uptake kinetics have been studied. In their study, Tordi et al. (2003) were testing the hypothesis that VO_2 kinetics at the onset of heavy cycling exercise would be altered after 3 x 30-s all out prior exercise. The study design comprised of four minutes of baseline cycling, six-minute exercise at intensity of 85 % of VO_2peak followed by 10 minutes of rest, 3 x 30-s sprints separated by four minutes of rest, six minutes of rest followed by four minutes of baseline cycling and another six-minute exercise at intensity of 85 % of VO_2peak. The results of the study showed that the sprint exercise had a major effect on VO_2 kinetics response of the second six-minute exercise compared to the first one. The baseline VO_2 was elevated after the sprint exercise and the time constant of phase II of VO_2 kinetics was faster. (Tordi et al. 2003.)

The effects of this kind of prior exercise were also tested in the study of Wilkerson et al. (2004). In this study, the aim was to investigate the effects of multiple-sprint exercise on VO_2 kinetics of supramaximal exercise performed at intensity of 105 % of VO_2peak until exhaustion. The study protocol included three minutes of baseline pedalling, exhaustive exercise at the intensity of 105 % of VO_2peak, 60 minutes of rest, 3 x 30-s all-out cycling separated by five minutes of recovery, 15 minutes of recovery and another exhaustive exercise at the intensity of 105 % of VO_2peak. The results of the study showed that the amplitude of primary VO_2 response of the supramaximal performance was significantly greater after the multiple-sprint exercise compared with the control condition. There were no significant differences between the time constants of VO_2 responses of the two exercises. Baseline VO_2 was significantly higher before the onset of supramaximal performance after the multiple-sprint exercise compared to control condition. In this study, also the blood lactate, HR and NIRS data was collected and results suggested that the multiple-sprint exercise might increase vasodilation and enhance muscle blood flow before and at onset of supramaximal exercise. The conclusion of the study was that prior exercise seems to increase muscle O_2 availability, does not influence to the time constant of VO_2 primary component and increases the amplitude of VO_2 response of following supramaximal exercise. (Wilkerson et al. 2004.)

Ingham et al. (2013) were comparing the effects of two different prior exercise protocols on VO_2 kinetics and 800-m running performance. The subjects performed two 800-m time trials separated by at least seven days with two different prior exercise protocols in randomized order. The first protocol worked as a control and it included 6 x 50 strides with the recovery of 45-60 seconds, which corresponded to the standard prior exercise protocol the athletes were using. The second trial was the intervention trial and it included 2 x 50 strides and one continuous 200-m high intensity run. All the strides were done at estimated 800 m pace. Prior exercise protocols were followed by 20 minutes of seated rest, after which the athletes did an assessment of perceived readiness and did another 2 x 50 strides before the 800-m trial. The results of the study showed that the 800-m running performance and overall VO_2 response were significantly improved after the intervention trial compared to control condition. (Ingham et al. 2013.)

In the study of McIntyre & Kilding (2015), the aim was to test the effects of three high-intensity intermittent prior exercise protocols with different intensities on 3 km cycling time trial. The effects of these prior exercise protocols were compared to the effects of self-selected prior exercise. All the high intensity intermittent prior exercise protocols included 10 minutes of cycling at intensity that corresponded to the 50 % between lactate threshold and lactate turnpoint, 5 x 10 s sprints and five minutes of passive recovery before the trial. The 5 x 10 s sprints were done with different intensities in different protocols, and the intensities were 100 % W_{peak}, 150 % W_{peak} and all-out. The results showed that the time constant and mean response time of VO_2 kinetics were faster after the high intensity intermittent protocols compared to self-selected protocol, but they did not improve the performance compared to self-selected protocol. The all-out prior exercise led to the fastest time constant, but to the lowest performance in 3 km time trials, which suggests that VO_2 kinetics did not align with the performance measures and that too intensive prior exercise might be harmful for the performance. (McIntyre & Kilding 2015.)

Only few studies have compared the effects of continuous and intermittent prior exercises in the same study. In the study of Christensen & Bangsbo (2015) the incremental, high intensity prior exercise including two 20-second sprints produced higher pulmonary VO_2 in the beginning of the exercise compared to the continuous, 20-minute moderate intensity prior exercise (Christensen & Bangsbo 2015). The studies of Tordi et al. (2003), Wilkerson et al. (2004), Ingham et al. (2013) and McIntyre & Kilding (2015) show beneficial effects of intermittent prior exercises on VO_2 kinetics of the following performance. However, concerning the studies available, it is not clear how significant the effects are compared to continuous high intensity prior exercises.

It is also unclear, what the effects of intermittent prior exercises are on exercise tolerance and how the speeding of VO_2 kinetics associates with performance. For example, in the studies of Tordi et al. (2003) and Wilkerson (2004), the control condition was tested during the same session preceding the prior exercise and following performance, which might have affected the following performance. All in all, there are a lot of differences in study designs including the intensity and duration of prior exercise as well as differences in recovery time between the prior exercise and performance which makes it hard to compare the different studies and find the consensus.

4 EXERCISE TOLERANCE

Endurance performance can be defined as a duration of time which an individual can maintain a certain level of performance. Time to fatigue at certain exercise intensity reflects the performance ability of the subject. (Coyle et al. 1988.) Time to fatigue or time to exhaustion forms the concept of exercise tolerance. According to Burnley and Jones (2007), lactate threshold has been thought to be the intensity at which athletes are able to perform for long time periods (30-60 minutes). As considering the VO_2 kinetics, steady state can be attained at the intensities below lactate threshold but above lactate threshold there is the existence of the slow component. During heavy intensity exercise the slow component of VO_2 kinetics represents the additional oxygen and energy cost. Slow component is larger at higher intensities and the larger it is, the shorter is the tolerable time of the work. (Burnley & Jones 2007.)

Exercise tolerance is highly related to the topic of the development of fatigue. There have been many theories about the main causes of fatigue and cessation of exercise. Earlier the accumulation of lactate and development of metabolic acidosis have been thought to be significant factors in development of fatigue (Bangsbo et al. 1996) and a bit later the role of inorganic phosphate has been considered more important (Westerblad et al. 2002). It has been found that not only the muscle fatigue, but the perception of effort has also a major role in limitation of exercise tolerance (Marcora & Staiano 2010). The study of Black et al. (2017) showed that tolerable time of work in severe intensity exercise is linked to decrease in muscle PCr and ATP as well as to increase in lactate levels in muscle and blood. It was also noted that exercise cessation in severe intensity exercise occurs mainly due to peripheral and not due to central fatigue (Black et al. 2017). However, the study of Midgley et al. (2017) investigating the factors behind the termination of exercise showed that one has usually multiple reasons for the termination of the exercise including factors of physical fatigue as well as factors not related to sensations of physical fatigue.

4.1 Measurement of exercise tolerance

Many studies investigating the effects of prior exercises on VO_2 kinetics have also examined the effects of prior exercises on exercise tolerance, which means in other words, the effects on time to exhaustion (Wilkerson et al. 2004; Draper et al. 2006; Bailey et al. 2009). Thus, the exercise tolerance can be measured as a duration subject is able to maintain a certain level of performance. There has been found to have correlations between the VO_2 kinetics and exercise tolerance, and VO_2 kinetics has been suggested to determine the highest work rate at which subject is able to tolerate the exercise (Murgatroyd et al. 2011). It has also been shown that there is a correlation between the O_2 deficit of the performance and time to exhaustion (Demarle et al. 2001; Carter et al. 2006).

4.2 Effects of prior exercises on exercise tolerance

As mentioned earlier, prior exercises have effects on VO_2 kinetics, but they also affect exercise tolerance (Burnley & Jones 2007). Jones et al. (2003) were testing the hypothesis that prior heavy exercise would extend the time to exhaustion in supramaximal exercise. In the study participants exercised to exhaustion either at intensity of 100 %, 110 % or 120 % of the work rate at VO_2peak after the control condition with no prior exercise or after heavy intensity prior exercise. The duration of the prior exercise was six minutes and the intensity 50 % of the difference between GET and VO_2peak. The study showed that the time to exhaustion was significantly longer in all supramaximal tests after heavy-intensity prior exercise compared to control condition, so the prior exercise seems to improve exercise tolerance. (Jones et al. 2003.)

Wilkerson et al. (2004) were investigating the effects of multiple-sprint exercise on VO_2 kinetics and time to exhaustion in supramaximal exercise, which was performed at intensity of 105 % of VO_2peak until exhaustion. The study protocol included three minutes of baseline pedalling, exhaustive exercise at the intensity of 105 % of VO_2peak, 60 minutes of rest, 3 x 30-s all-out cycling separated by five minutes of recovery, 15 minutes of recovery and another exhaustive exercise at the intensity of 105 % of VO_2peak. The study showed that the time to exhaustion was significantly longer in the control condition compared to the one following the sprint exercise (151 ± 20 s vs. 123 ± 8 s). (Wilkerson et al. 2004.)

Draper et al. (2006) were comparing the effects of moderate intensity and high intensity prior exercise on VO_2 kinetics and time to exhaustion in two-minute severe intensity running. The moderate intensity prior exercise included six minutes of running at speed equivalent to 90 % of ventilatory threshold. The high intensity prior exercise included six minutes of running at speed corresponding 50 % of the difference between ventilatory threshold and VO_2peak. The prior exercise protocol was followed by six minutes of recovery before the two-minute severe intensity running. In the study, there were no differences between the conditions in time to exhaustion. (Draper et al. 2006.)

Bailey et al. (2009) were studying the effects of prior exercises with different intensities and different recovery durations on VO_2 kinetics and exercise tolerance in severe intensity cycling exercise. The severe intensity exercise was performed at intensity corresponding the 80 % of the difference between GET and VO_2max. The study design included six different prior exercises protocols with different combinations of exercise intensity and recovery duration. The intensity was either 40%Δ or 70%Δ and the recovery durations either 3, 9 or 20 minutes. The exercise tolerance was improved by 15 % and 30 % above control in the 70-9-80 and 70-20-80 conditions respectively but was impaired by 16 % in the 70-3-80 condition. The conclusion of the study was that prior high intensity exercise (70%Δ) can enhance exercise tolerance in high-intensity exercise if the recovery duration in between is adequate (≥9 minutes). (Bailey et al. 2009.)

In the study of Burnley et al. (2011), where the aim was to investigate the effects of heavy intensity and severe intensity prior exercises on VO_2 kinetics and power-duration relationship of severe intensity cycling, the results showed that exercise tolerance was significantly increased after the heavy prior exercise but not after severe prior exercise. The duration of prior exercises was six minutes, intensity of heavy prior exercise was 50 % of the difference between GET and CP and the intensity of severe intensity prior exercise was the intensity that corresponded to the power output which could be maintained for 8 minutes. Both prior exercises were followed by 10 minutes of recovery before the six-minute severe intensity exercise. (Burnley et al. 2011.)

In the studies studying effects on prior exercises on both, the VO_2 kinetics and exercise tolerance, it has been noticed that prior exercises might improve both (Burnley et al. 2011; Ingham et al. 2013). Murgatroyd et al. (2011) also stated, that VO_2 might even be a key determinant of exercise tolerance. Some studies have shown, however, that the prior exercise producing the best VO_2 response does not always have the best effect on exercise tolerance, so it might be that the fast VO_2 kinetics do not always enhance performance during high intensity exercise (Wilkerson et al. 2004; Bailey et al. 2009; McIntyre & Kilding 2015; Christensen & Bangsbo 2015). The study of Bailey et al. (2009) showed that to improve exercise tolerance the intensity of the prior exercise must be high enough but there must also be enough time to recover between the prior exercise and performance.

5 NEUROMUSCULAR ABILITY AND ENDURANCE PERFORMANCE

Even though the importance of capacities of respiratory and circulatory systems for endurance performance have been emphasized, during the last decades also the role of neuromuscular characteristics in endurance sports has been noted. The neuromuscular and anaerobic characteristics of muscle contractile properties have been found to be significant especially in horizontal running performance. (Paavolainen et al. 2000.)

Bachero-Mena et al. (2017) were testing the hypothesis that lower limb strength, jumping performance and sprinting ability would significantly correlate with 800-m running times. Significant correlations were found between the 20-m sprint test and 800-m performance and 800-m performance correlated also significantly with strength variables (CMJ, jump squat and full squat). The conclusion of the study was that 800-m performance is significantly related to sprinting, jumping and strength abilities. (Bachero-Mena et al. 2017.) Correlations between sprinting ability and endurance performance were also observed in the study of Paavolainen et al. (2000) where the horizontal treadmill running speed was found to be significantly correlated with the result of 30 m speed test. Yamanaka et al. (2020) tested the correlations between sprinting ability measured as 100-m and 400-m times and performance in 5000m and 10 000m running races and found that sprinting ability correlates significantly with endurance performance.

Hébert-Losier et al. (2014) were studying the jumping and hopping skills in elite and amateur orienteering athletes and the correlations of jumping and hopping skills to sprinting and running. In the study jumping and hopping skills were analysed by using the SJ, CMJ and SLJ. The study showed that the elite athletes had better stretch-shortening-cycle utilization and rapid generation of relative maximal forces. These neuromuscular measures were related to sprinting and running abilities and aerobic performance. (Hébert-Losier et al. 2014.) Hudgins et al. (2013) were studying the correlations between the jumping ability and running performance in different running distances. Subjects of the study were 33 competitive runners participating to the distances ranging from 60 to 5000 m. All the subjects did three two-leg standing long jumps (TSJP) and the correlations between the result and running performance time were studied. The significant correlations were found between TSJP and running performance for all the distances. (Hudgins et al. 2013.) The significant correlations were also found between endurance performance and CMJs as well as between endurance performance and squat jump performance in the study of Sýkora et al. (2018).

In addition to the studies investigating the correlations of neuromuscular characteristics and endurance performance with a cross-sectional study design, there have been a major number of studies examining the effects of strength training on endurance performance. The results of the study of Paavolainen et al. (1999) showed that concurrent training of explosive strength and endurance improved 5-km running performance, and the improvement was proposed to be caused by improvement in neuromuscular characteristics leading to improved muscle power and running economy. The meta-analysis of Berryman et al. (2018) showed that strength training as a part of training in endurance sports is associated with improvement in performance and these results are related to improvements in the energy cost of locomotion, maximal force and maximal power. The systematic review of Trowell et al. (2020) showed that adding strength training to endurance training regimens improves the force-generating capacity of the muscles important in running, but more research is needed concerning how these adaptations transfer to running.

Besides studies investigating neuromuscular characteristics' correlation to running, there has been same kind of results also among the other endurance sports. The study of Kao et al. (2018) showed that there were correlations between strength and power measures and swimming performance. The study of Majumdar et al. (2017) with rowers revealed significant correlations between strength variables and 2000-m rowing ergometer performance.

Thus, there are many cross-sectional studies showing the correlations between different hopping performances and endurance performance (Bachero-Mena et al 2017; Hébert-Losier et al. 2014; Hudgins et al. 2013; Sýkora et al. 2018) and some studies showing the correlations between strength and endurance abilities (Bachero-Mena et al 2017; Kao et al. 2018; Majumdar et al. 2017). Also, the interventional studies have shown that increased force and power measures might be related to better endurance performance (Paavolainen et al.

1999; Berryman et al. 2018; Trowell et al. 2020). There are also some studies that have found correlations between sprinting ability and endurance performance like the study of Paavolainen et al. (1999) showing correlation between 30-m sprint time and horizontal treadmill running speed and the study of Bachero-Mena et al. (2017) which showed correlation between 20-m speed test and 800-m performance.

6 RESEARCH QUESTIONS AND HYPOTHESES

Effects of continuous and intermittent prior exercises have rarely been studied in the same study. Studies have been mostly done concerning the effects of prior exercises on VO_2 kinetics of exercises done with moderate and heavy intensities while the supramaximal intensities are evident in most short duration, Olympic endurance events. Also, there are not many studies concerning the effects of different prior exercises on exercise tolerance, and the relation between VO_2 kinetics and exercise tolerance seems controversial.

The aim of this study was to investigate the effects of continuous severe intensity prior exercise and intermittent prior exercise on VO_2 kinetics and exercise tolerance in supramaximal running exercise compared to continuous moderate intensity prior exercise, which worked as a control condition. The second aim was to investigate the possible relationships between the sprinting, jumping and strength abilities and endurance performance.

1. **Is there difference in VO_2 response of supramaximal performance after different prior exercise protocols?**

   Hypothesis: Yes.
   Continuous severe intensity prior exercise accelerates VO_2 kinetics compared to control condition (Bailey et al. 2009; Burnley et al. 2011; Caritá et al. 2015; Fujii et al. 2018).
   Intermittent prior exercise accelerates VO_2 kinetics compared to control condition (Tordi et al. 2003; Wilkerson et al. 2004; Ingham et al. 2013; McIntyre & Kilding 2015).

2. **Is there difference in exercise tolerance after different prior exercise protocols?**

   Hypothesis: Yes.

Exercise tolerance is higher after continuous severe intensity prior exercise compared to control condition (Jones et al. 2003; Bailey et al. 2009).

3. **Are there associations between neuromuscular ability and endurance performance?**

Hypothesis: Yes.

Jumping ability correlates with endurance performance (Bachero-Mena et al. 2017; Hébert-Losier et al. 2014; Hudgins et al. 2013; Sýkora et al. 2018).

There is a correlation between strength and endurance performance (Bachero-Mena et al. 2017; Kao et al. 2018; Majumdar et al. 2017).

Sprinting ability correlates with endurance performance (Paavolainen et al. 1999; Bachero-Mena et al. 2017).

7 METHODS

7.1 Participants

Ten participants volunteered to participate to the study. The participants were competitive and recreational athletes from endurance sports (n=9) and soccer (n=1). Participants were 20-31 years old healthy individuals. They were instructed to arrive at the laboratory in rested state, avoid strenuous exercise the day before, avoid eating and caffeine at least three hours before the tests and avoid alcohol at least one day before the study and during the whole study. The tests were done at the same time of the day (±2 h) for each participant. The characteristics of participants are presented in table 4. Participants signed a written consent form before the study, and they were informed about the possibility to quit the study at any point of the study if they wanted. The study was approved by the ethics committee of the University of Jyväskylä.

TABLE 4. Characteristics of the participants of the study (mean ± SD). BMI = body mass index; VO_2max = maximal oxygen uptake.

	n	**Age**	**Height (cm)**	**Body mass (kg)**	**BMI (m^2/kg)**	**VO_2max(ml/kg/min)**
All	10	23.8 ± 4.3	171.3 ± 7.0	68.3 ± 8.8	23.2 ± 1.7	50.8 ± 8.8
Women	6	21.7 ± 2.3	166.8 ± 4.6	62.6 ± 2.6	22.5 ± 1.5	46.3 ± 4.7
Men	4	27.0 ± 4.8	178.0 ± 3.5	76.8 ± 7.7	24.3 ± 1.6	57.6 ± 9.8

7.2 Study design

The experimental design was a cross-sectional design. Participants visited the laboratory five times separated by 3-7 days. During the first visit, maximal oxygen uptake (VO_2max), running speed at VO_2max (vVO_2max) and lactate threshold 1 (LT1) were determined from incremental test. The results were used to fix the running speed for the prior exercise protocols and for the supramaximal tests. During the next three visits participants accomplished supramaximal running tests at speed of 110 % of the vVO$_2$max until exhaustion, each time with different prior exercise protocol. The order of the prior exercise protocols was randomized. Last visit was for the measurement of neuromuscular characteristics including leg press, countermovement jump (CMJ) and 30-m speed test. Experimental design is characterized in figure 4.

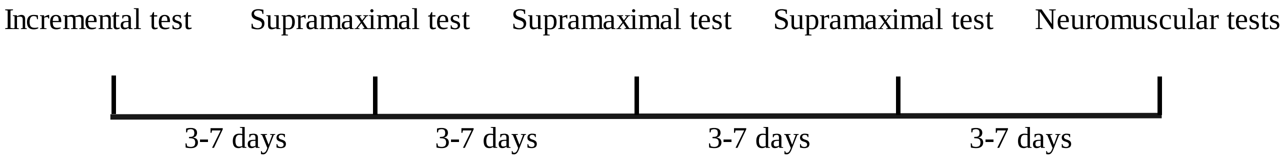


FIGURE 4. Experimental design.

7.3 Data Collection

Incremental test. When participants arrived for the first visit to the laboratory, their body mass and height were measured, and they filled in a health questionnaire. Incremental test was completed by running on a treadmill with the angle of 0.6°. The speed increased 1 km/h in every three minutes until exhaustion. The test included 8-12 three-minute stages. Before the test, participants completed a five-minute warm-up at the initial speed of the test, which responded to 7-8 km/h for women and 7-10km/h for men After the warm-up, baseline levels of blood lactate were measured from a fingertip sample (Biosen S_line Lab+ lactate analyzer, EKF Diagnostic, Magdeburg, Germany). During the test heart rate (Polar V800, Polar Electro Oy, Kempele, Finland), blood lactate and gas exchange (MasterScreen CPX, Jaeger, CareFusion Germany 234 GmbH, Hoechberg, Germany) were measured at every stage. The treadmill was stopped after every three minutes, and the lactate sample was taken. Heart rate was determined as a mean value of the last 15 seconds of every three-minute stage. The VO$_2$max was determined as a mean of two highest VO$_2$ values of consecutive 30 second periods. From the results of the lactate measurement, the lactate threshold 1 (LT1) was fixed to the point where lactate levels increased 0.3 mmol/L from the lowest value. During the first visit, after the incremental test was completed, participants were also familiarized with the technique of CMJ.

Supramaximal running tests. All the participants performed three supramaximal running tests separated by 3-7 days. Tests were preceded every time by different prior exercise and the order of them was randomized. Supramaximal test protocol is characterized in figure 5. All the prior exercise protocols started with 10 minutes of running at speed corresponding 75 % of the speed at LT1. In continuous moderate intensity exercise protocol (later referred as S1), participants continued to run at this speed for six more minutes. The idea of the moderate intensity prior exercise was to work as a control to other prior exercise conditions. Continuous severe intensity prior exercise (later referred as S2) included six minutes of running at speed corresponding 70 % of the difference between LT1 and vVO_2max. Intermittent prior exercise (later referred as S3) consisted of four 30-second sprints at the speed equal to 110 % of vVO_2max separated by 75 seconds of running at 75 % of LT1 speed. The 30-second sprints were preceded by five-second acceleration. The 20-minute recovery period between the prior exercise and supramaximal performance was comprised of 10 minutes of passive rest, five minutes of running at the speed of 75 % of LT1 speed and the last five minutes sitting on a chair/standing on a treadmill while baseline measurements of lactate and gas exchange were measured.

Baseline gas exchange measurement started two minutes before the start of the supramaximal test. Participants sat on a chair for the first 100 seconds and were asked to stand 20 seconds before the start of the supramaximal test. In supramaximal exercise participants ran on a treadmill at speed of 110% of vVO_2max until exhaustion (figure 6). Time to exhaustion was measured but not told to the participants until after the last test, in order that it would not affect to participant's next test. Blood lactate from a fingertip sample was measured after the first 10-minute run (PRE1), after the prior exercise protocol (PRE2), three minutes before the start of the supramaximal exercise (PRE3) and as well one, two and three minutes after the supramaximal exercise (POST1, POST2 and POST3). The highest value from the three post lactate measurements was taken to the analysis. Gas exchange was measured breath-by-breath during the two-minute baseline measurement as well as during the whole supramaximal exercise. Baseline measurement and first two minutes of the supramaximal performance was taken to the analysis to determine baseline VO_2 (mL/min), time delay (s), time constant (s), VO_2 amplitude (mL/min) and total VO_2 15-120 s (mL).

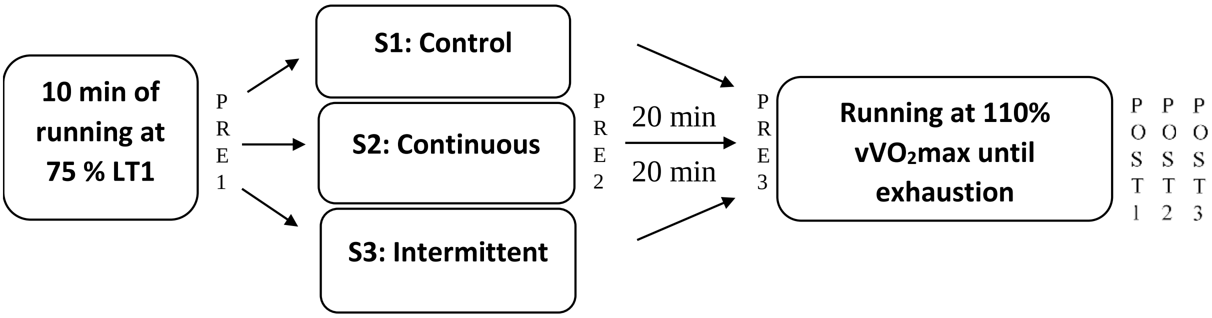


FIGURE 5. Supramaximal running tests. PRE1, PRE2, PRE3, POST1, POST2 and POST3 = points of lactate measurements; S1 control = 6 minutes of running at 75 % of lactate threshold 1 (LT1) speed; S2 Continuous = 6 minutes of running at 70% from the difference between LT1 and VO_2max speeds; S3 Intermittent = 4 x 30 s at 110 % of VO_2max speed separated by 75 seconds of running at 75 % of LT1; vVO_2max = velocity at maximal oxygen uptake.

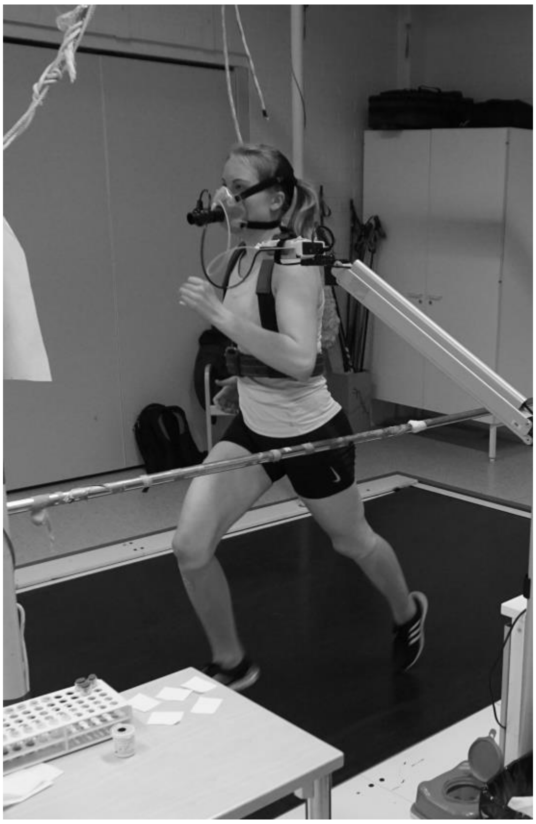


FIGURE 6. Supramaximal running test.

Neuromuscular measurements. Neuromuscular measurements were executed during the participants' last visit to laboratory. Before the test, a warm-up was done by running 10 minutes on a treadmill with speed corresponding 75 % of the LT1 speed. First, the one repetition maximum (1 RM) was tested on a DAVID F210 leg press device (figure 7). The test was performed with one (dominant) leg and with the knee angle of 60°. Participants started the test with warm up sets including 5-10 and 3-5 repetitions with 2-minutes of recovery between the sets. When warm up sets were completed, the 1 RM was tested by doing sets of one repetition and adding weights as long as the participant was able to perform the movement correctly. There was three minutes of recovery between the sets. The result was the maximum weight a participant was able to lift once. Thereafter, CMJ was tested by using the contact mat. The test started from a shoulder width standing position on a mat with hands on the hips and the participant was asked to quickly bend the knees to 90 degrees angle and jump as high as possible. The test was performed three times with one-minute of recovery between. The highest jump of the three was reported as a result. Lastly, the 30-m running test was performed on an inside track by using three photocell gates (figure 8). There was a 10-minute warm-up on an indoor track before the test including jogging, drills and 3 x 40-m runs. Test was performed three times and the times of 10-m acceleration and the time of last 20-m were recorded. The fastest times of the three tries was reported as a result.

FIGURE 7. Leg press test.

FIGURE 8. 30-m running test.

7.4 Data Analysis

Oxygen uptake kinetics. The primary component (phase II) of the VO_2 response was modelled as a mono-exponential function

$$VO2_{pII}(t) = a_0 + a \cdot \left(1 - e^{-(t-d)/\tau}\right) \qquad (1)$$

where t is time (seconds) elapsed from the beginning of the phase II, a_0 is a baseline value for VO_2, a is the amplitude of VO_2 above the baseline during the phase II, d is the time-delay of the phase II, and τ is the time constant that corresponds to the time required for VO_2 to increase by 63% of the difference between the onset and steady-state of the phase II. Example of the modelling of the phase II is represented in figure 9.

The baseline value a_0 for VO_2 was determined as the sample mean of the values measured 60 - 90 s after the onset of the baseline measurement. Thereafter, only the values measured of 135 to 240 s from the onset of the measurement were used in the model fitting. First 15 seconds of the performance were excluded from the analysis, because it represents the cardiodynamic phase, which does not yet reflect the oxygen uptake in the exercising muscles. Coefficients $a, d,$ and τ were then estimated on the data in a nonlinear least-squares sense using Levenberg–Marquardt (L-M) algorithm. The initial coefficients values were: $a = 2250, d = -0.5,$ and $\tau = 10.$ The following settings were used as the convergence criteria for the L-M algorithm:

- Maximum number of function evaluations: 500
- Maximum number of iterations: 500
- Termination tolerance used on stopping conditions involving the function value: 10^6
- Termination tolerance used on stopping conditions involving the coefficients: 10^6

The L-M algorithm converged within a preset tolerance for all the models. The total VO_2 was computed by numerical integration of the function from 135 to 240s. All the computational operations were performed using standard functions of the MATLAB® (R2019b) desktop environment and MATLAB Curve Fitting Toolbox™ (Version 3.5.10).

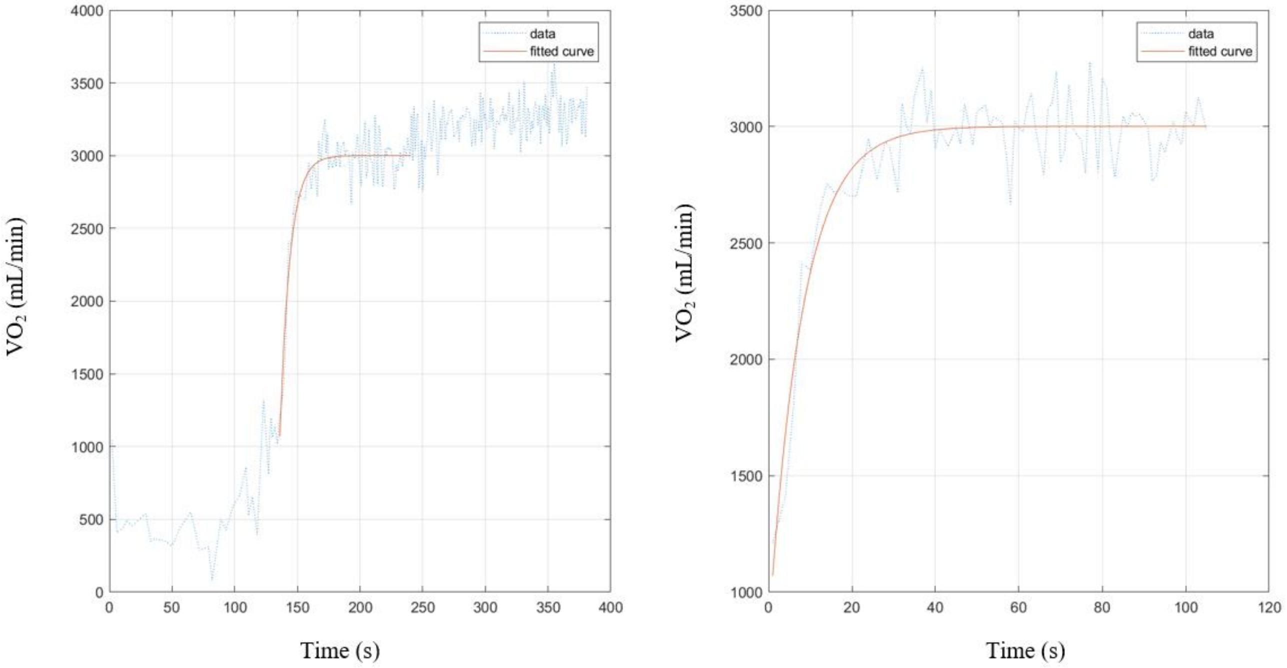


FIGURE 9. Example of the modelling of the primary phase (phase II) oxygen uptake kinetics from the present study. Left figure represents the whole data and figure on the right represents only the primary phase.

Statistical Analysis. Statistical analysis was carried out by using IBM SPSS Statistics 24. Data is presented as mean ± standard deviation (SD). Related-Samples Friedman's Two-Way Analysis of Variance by Ranks -test was used to analyse differences between different prior exercises. If significant differences were found, pairwise comparisons with Bonferroni correction were done. Correlations between endurance performance and neuromuscular characteristics were done with Spearman’s correlation coefficient. Nonparametric tests were used due to small sample size. Statistical significance was accepted when $p < 0.05$.

8 RESULTS

8.1 Supramaximal running tests

Results from the supramaximal tests are presented in the table 5. Significant differences ($p < 0.05$) were found between S1 and S2 in total oxygen consumed during the 15-120 s of the supramaximal test (VO_2 15-120 s) with the mean values ± SD of 5867 ± 1506 for S1 and 5963 ± 1496 for S2. Significant differences were also found between S1 and S2 in maximum heart rate (HRmax), lactate measured after the prior exercise (lactate PRE2) and lactate measured three minutes before the supramaximal test (lactate PRE3). Significant differences ($p < 0.05$) were found between S1 and S3 in HRmax and maximal lactate value measured 1-3 minutes after the test (lactate POST). In addition to significant difference between S1 and S2 in total VO_2 (15-120 s), there were no significant differences between different prior exercise conditions in other variables of oxygen uptake kinetics.

There were no significant differences between the different prior exercise protocols in time to exhaustion. Time to exhaustion was also analysed concerning the test order and regardless of the prior exercise used. The mean time to exhaustion was 179 ± 43 s in the first test, 195 ± 55 s in the second test and 195 ± 59 s in the third test, but the differences were not statistically significant. Time to exhaustion after different prior exercise protocols for each participant is presented in figure 10, total oxygen consumed in figure 11, VO_2 amplitudes in figure 12 and time constants in figure 13.

TABLE 5. Results from supramaximal running tests (mean ± SD) after different prior exercise protocols: S1 = control, S2 = continuous severe intensity, S3 = intermittent; VO_2 15-120 s = total oxygen consumed from 15 to 120 s; VO_2 Amplitude = rise in VO_2 from the baseline; time constant = time it takes to reach 63 % of the amplitude; time delay = time to beginning of the phase 2; HRmax = maximum heart rate; Lactate PRE2 = lactate measured after the prior exercise protocol; Lactate PRE3 = lactate measured 3 min before the supramaximal test; Lactate POST = maximum lactate value measured 1-3 min after the test.

	n	**S1**	**S2**	**S3**
Time to exhaustion (s)	10	194 ± 57	179 ± 46	196 ± 55
VO_2 kinetics:				
VO_2 15-120 s (mL)	8	5867 ± 1506	5963 ± 1496*	5910 ± 1597
VO_2 Baseline (mL/min)	8	423 ± 124	423 ± 85	403 ± 85
VO_2 Amplitude (mL/min)	8	2944 ± 792	2995 ± 818	3006 ± 898
Time constant (s)	8	13.1 ± 2.5	13.7 ± 2.5	14.0 ± 2.2
Time delay (s)	8	-1.81 ± 0.68	-2.63 ± 1.91	-2.17 ± 0.87
HRmax (bpm)	9	186 ± 8	189 ± 8*	190 ± 9*
Lactate PRE2 (mmol/L)	10	1.0 ± 0.2	6.9 ± 1.5*	3.9 ± 1.0
Lactate PRE3 (mmol/L)	10	0.9 ± 0.2	1.9 ± 0.5*	1.5 ± 0.6
Lactate POST (mmol/L)	10	12.1 ± 2.6	12.6 ± 2.7	13.0 ± 2.5*

*Significant difference ($p < 0.05$) compared to control condition S1.

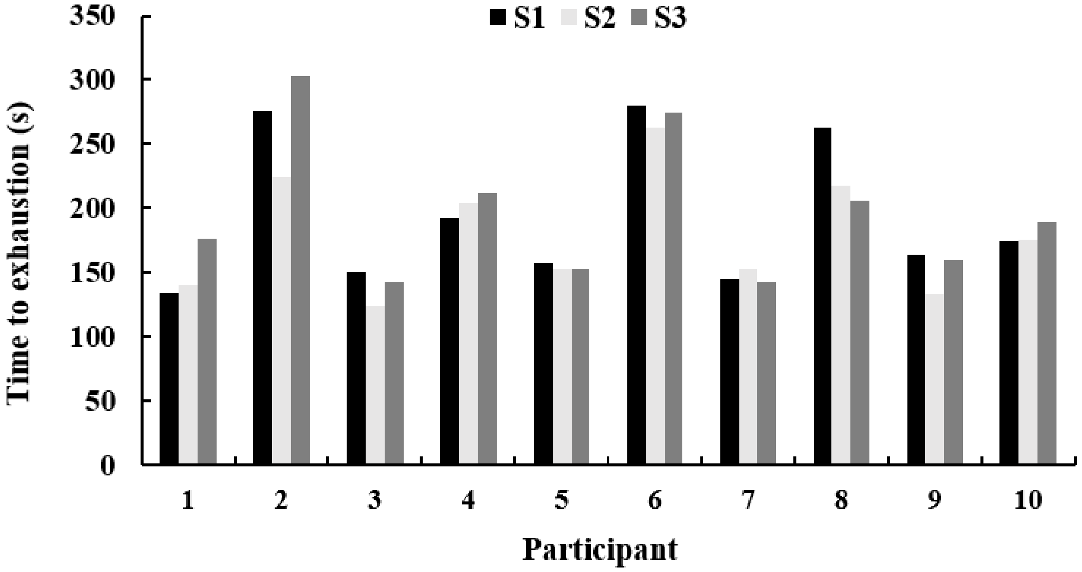


FIGURE 10. Time to exhaustion after different prior exercises (S1 = control, S2 = continuous severe intensity, S3 = intermittent) for each participant.

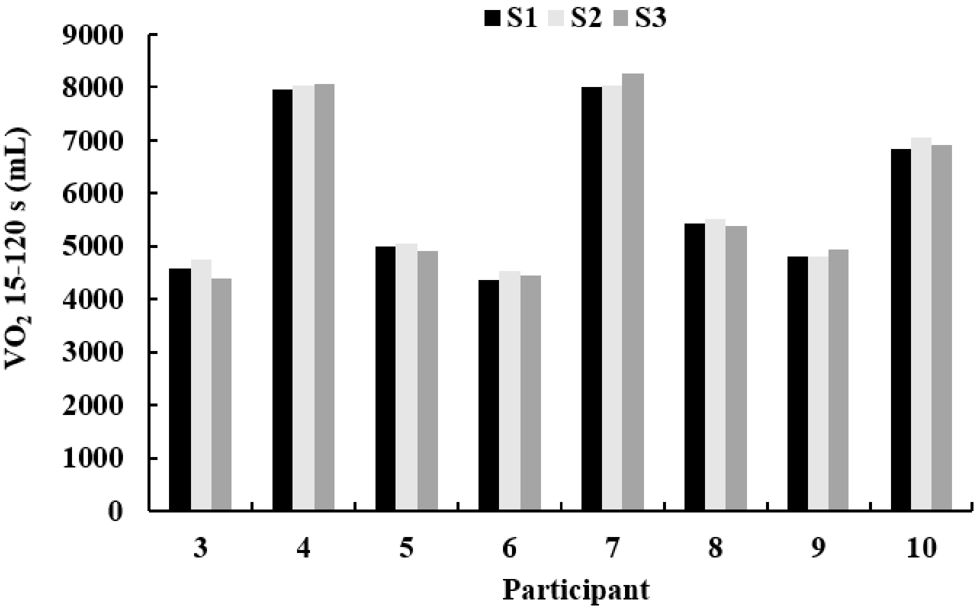


FIGURE 11. Total VO_2 (15-120 s) of the supramaximal running performance after different prior exercises (S1 = control, S2 = continuous severe intensity, S3 = intermittent) for each participant

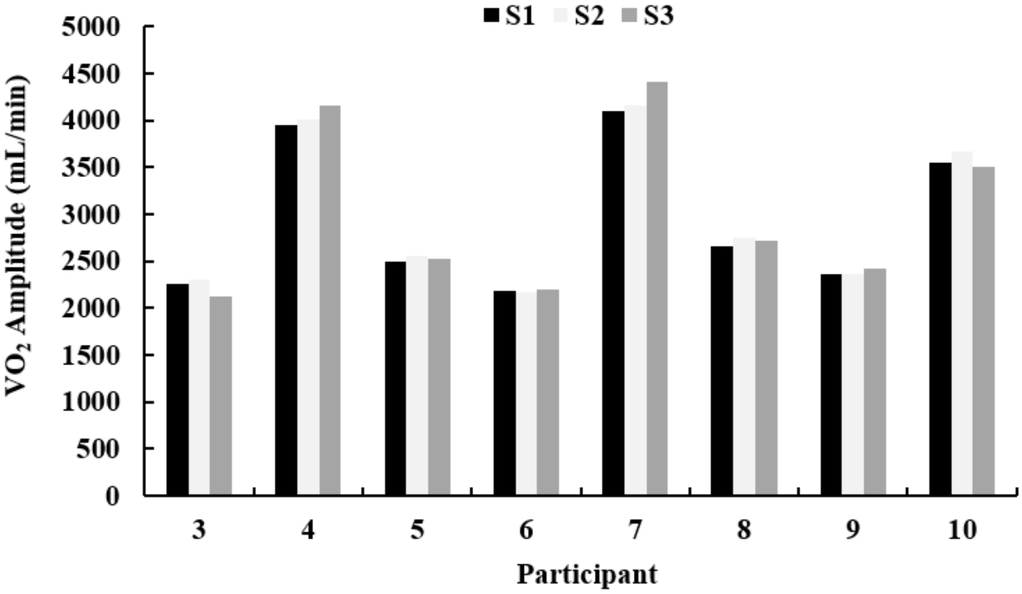


FIGURE 12. VO_2 amplitude (mL) in supramaximal running test after different prior exercises (S1 = control, S2 = continuous severe intensity, S3 = intermittent) for each participant.

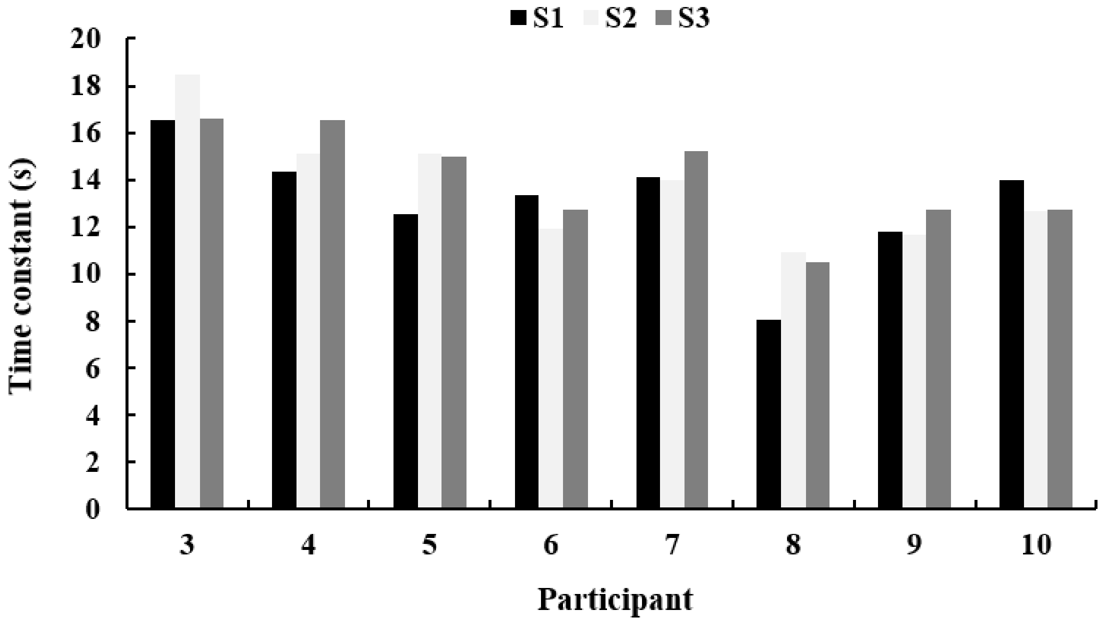


FIGURE 13. Time constant after different prior exercises (S1 = control, S2 = continuous severe intensity, S3 = intermittent) for each participant.

8.2 Neuromuscular measurements

Mean values (±SD) of the neuromuscular characteristics of the participants are presented in the table 6. Spearman's correlation coefficients between neuromuscular performance and performance in incremental test (vVO_2max) and between neuromuscular performance and time to exhaustion after different prior exercises are presented in the table 7. There were significant correlations between vVO_2max and 1 RM result, between vVO_2max 0-10 m acceleration time and between time to exhaustion in supramaximal tests and CMJ. Spearman's correlation coefficients were analysed also between neuromuscular and endurance performances in women separately and correlations were found between CMJ and time to exhaustion S2 ($r = 0.943$, $p < 0.01$) and between CMJ and time to exhaustion S3 ($r = 0.943$, $p < 0.01$). Correlations between the CMJ results and average time to exhaustion from all the three tests is presented in figure 14 concerning all the participants and in figure 15 concerning only the female participants.

TABLE 6. Results from neuromuscular tests (mean ±SD). 1 RM = one repetition maximum, CMJ = countermovement jump.

	All (n=10)	**Women (n=6)**	**Men (n=4)**
Leg press 1 RM (kg)	97 ± 30	77 ± 15	128 ± 17
CMJ (cm)	34.8 ± 4.6	32.2 ± 2.5	38.8 ± 4.3
Speed test			
0-10 m (s)	1.91 ± 0.12	1.99 ± 0.05	1.80 ± 0.04
10-30 m (s)	2.71 ± 0.22	2.87 ± 0.09	2.47 ± 0.07
0-30 m (s)	4.62 ± 0.32	4.86 ± 0.12	4.27 ± 0.09

TABLE 7. Spearman’s correlation coefficients between the neuromuscular characteristics and endurance performance. vVO$_2$max = velocity at VO$_2$max measured in incremental test; S1 = control prior exercise, S2 = continuous severe intensity prior exercise, S3 = intermittent prior exercise; 1 RM = one repetition maximum in leg press test; CMJ = countermovement jump; 0-10 m = time of the first 10 m in 30 m speed test; 10-30 m = last 20 m time in 30 m speed test; 0-30 m = total time of the 30 m speed test.

	1 RM	**CMJ**	**0-10 m**	**10-30 m**	**0-30 m**
vVO$_2$max					
Correlation Coefficient	.688*	.505	-.692*	-.578	-.598
Sig. (2-tailed)	.028	.137	.027	.080	.068
n	10	10	10	10	10
Time to exhaustion S1					
Correlation Coefficient	.326	.661*	.006	-.370	-.182
Sig. (2-tailed)	.358	.038	.987	.293	.614
n	10	10	10	10	10
Time to exhaustion S2					
Correlation Coefficient	.605	.833**	-.024	-.371	-.165
Sig. (2-tailed)	.064	.003	.947	.291	.649
n	10	10	10	10	10
Time to exhaustion S3					
Correlation Coefficient	.466	.809**	-.131	-.383	-.250
Sig. (2-tailed)	.175	.005	.718	.275	.486
n	10	10	10	10	10

*. Correlation is significant at the 0.05 level (2-tailed)

**. Correlation is significant at the 0.01 level (2-tailed)

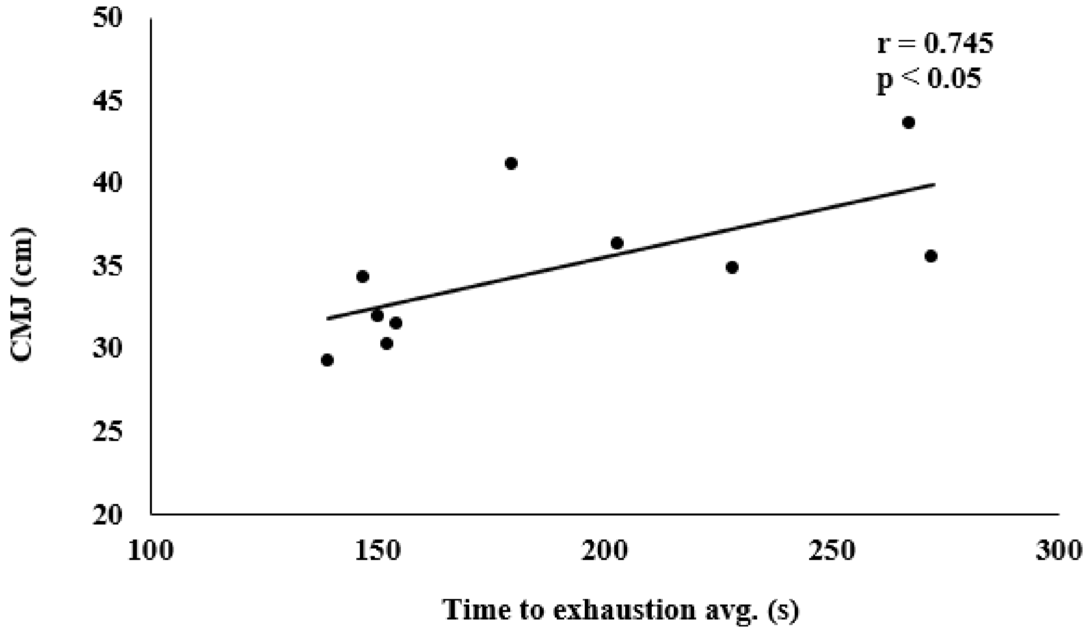


FIGURE 14. Correlation between jump height (cm) in countermovement jump (CMJ) and average of time to exhaustion (s) of the three tests including all the participants (n = 10).

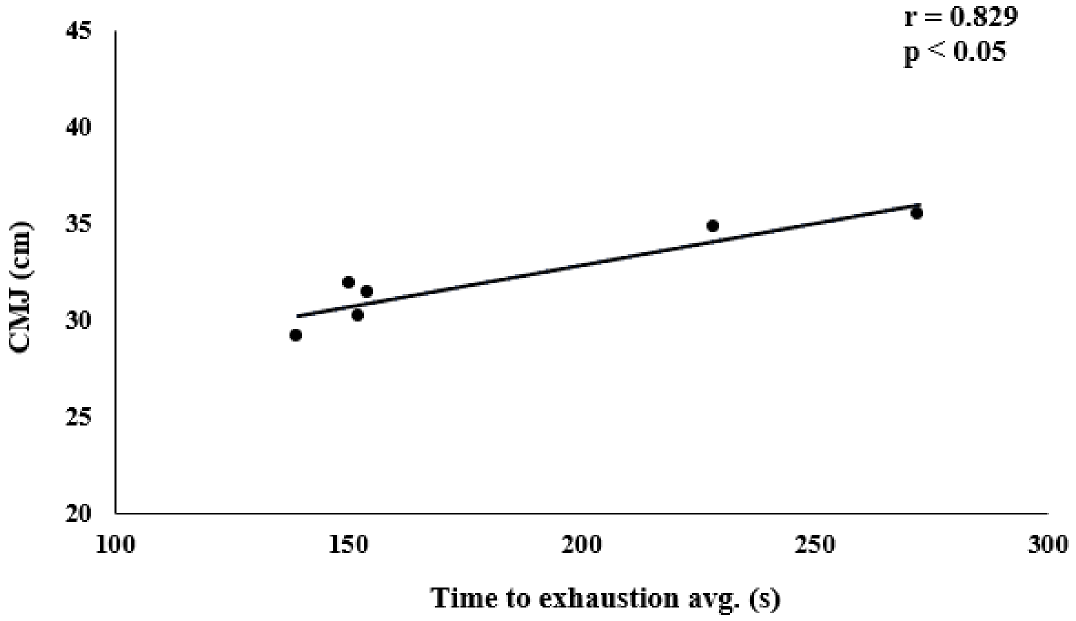


FIGURE 15. Correlation between jump height (cm) in countermovement jump (CMJ) and average of time to exhaustion (s) of the three tests including only women (n = 6).

9 DISCUSSION

Main findings. The aim of the study was to investigate the effects of continuous severe intensity prior exercise and intermittent prior exercise on VO_2 kinetics and exercise tolerance in supramaximal running performance. Regarding the oxygen uptake kinetics, statistically significant differences were only found between control prior exercise (S1) and continuous severe intensity prior exercise (S2) in total oxygen uptake measured in 15-120 s of the supramaximal performance (VO_2 15-120 s). There were no statistically significant differences between the conditions in time to exhaustion.

The second aim was to investigate the possible relationships between the sprinting, jumping and strength abilities and endurance performance. Significant correlations were found between the running speed at VO_2max (vVO_2max) and leg press 1 RM and between vVO_2max and time of the 0-10 m of the speed test. Time to exhaustion in supramaximal tests correlated significantly with the countermovement jump (CMJ) result in all the participants as well as when observing women separately. The original purpose of this study was also to examine, if the athletes with different neuromuscular abilities would have differences in which prior exercise would produce the best performance but examining this was not possible due to small sample size.

Oxygen uptake kinetics. Differences in oxygen uptake kinetics of supramaximal performance after different prior exercise protocols were examined by using five different variables. Significant differences were only found between control prior exercise (S1) and continuous severe intensity prior exercise (S2) in total VO_2 measured in 15-120 s of the supramaximal performance. According to the review of Gastin (2001), pulmonary VO_2 has a direct relationship to the body’s aerobic energy production, so it can be suggested that the energy production from aerobic sources in supramaximal performance was higher after the S2 condition compared to S1. Comparison of this result to earlier studies is challenging due to differences in study designs and the fact that many studies have not reported the total oxygen consumed during the test. Yet, in the study of Fujii et al. (2018), the five-minute high-intensity prior exercise lead to higher oxygen consumption during the following 90-second cycling at 110 % of VO_2peak when compared to effects of moderate prior exercise. In the study of Ingham et al. (2013), it was observed that prior exercise including 2 x 50 m strides and a continuous 200-m run at race pace produced higher total oxygen consumed during 800-m run compared to control. The protocol which produced higher total VO_2 in the study of Ingham et al. (2013) corresponds most to the S3 condition in the present study, but the same kind of effects were not observed in this study.

VO_2 baseline measured before the supramaximal test did not show statistically significant differences between the three different prior exercise conditions. Results are consistent with the study of Bailey et al. (2009) in which it was observed that the baseline levels of VO_2 were elevated significantly after the severe intensity prior exercise compared to control when the recovery time was lower (three or nine minutes) but not in the conditions were recovery time was 20 minutes. In the present study, the recovery time was also 20 minutes, which has probably caused that VO_2 levels were able to decline to the same level after all prior exercise protocols. Same kind of results were also observed in the study of Ingham et al. (2013), where the recovery time was 20 minutes and there were no differences in baseline VO_2 between different conditions.

VO_2 amplitude, which was measured as a rise from the baseline during the first two minutes of the supramaximal performance, did not show statistically significant differences between the three prior exercise conditions. Time constant, which was calculated as a time it takes to reach the 63 % of the amplitude and represents the speed of oxygen uptake kinetics, neither showed statistically significant differences between different conditions. These results are in contrast to some earlier studies which have found increase in VO_2 primary amplitude after the six-minute heavy (Burnley et al. 2002) and after 3 x 30 s all-out prior exercise (Wilkerson et al. 2004) and faster primary phase time constant after 3 x 30 s prior exercise (Tordi et al. 2003). However, there are also some studies showing similar results to the present study. In the study of Draper et al. (2006), there were no differences between the effects of moderate or high intensity prior exercise on VO_2 amplitude and time constant in two-minute severe intensity running. Also, the studies of Burnley et al. (2000) and Bailey et al. (2009) showed no effect of heavy and severe intensity prior exercises on the primary phase VO_2 kinetics. One must notice, however, that VO_2 amplitude is usually determined as a rise from the baseline, which can be affected for example by recovery time between prior exercise and baseline measurement as well as if the baseline measurement has been done in rest or in low intensity exercise. These factors can also cause differences between the results of different studies.

Exercise tolerance. Time to exhaustion, which represents the exercise tolerance, showed no statistically significant differences between the three conditions. The results are consistent with the study of Draper et al. (2006), which showed no difference in time to exhaustion after moderate or high intensity prior exercise in severe intense running performance. Result are also in contrast to some studies, which have presented that prior heavy and severe intensity exercises can increase the time to exhaustion (Jones et al. 2003; Bailey et al. 2009). Ingham et al. (2013) also found improved performance in 800-m running after high-intensity prior exercise compared to control.

One reason behind the varying results in different studies concerning the exercise tolerance might be, that there are multiple factors affecting to the decision when participant decides to stop the exercise (Midgley et al. 2017), and these factors are not usually controlled in the studies, which can overpower the possible effects of prior exercise. In the present study, the "learning effect" and getting more used to running supramaximal performances on a treadmill might have affected the results. The order of prior exercises was randomized, but when results were observed by the order of the exercises regardless of prior exercise protocol used, the time to exhaustion in the first tests seems slightly lower compared to next two tests, but the difference was not statistically significant.

Earlier studies have had controversial results about the relationship of oxygen uptake kinetics and performance. Some studies have shown coincidental positive effects of prior exercise on oxygen uptake kinetics and performance (Burnley et al. 2011; Ingham et al. 2013), while others have shown that faster oxygen uptake kinetics do not always enhance performance (Wilkerson et al. 2004; Bailey et al. 2009; McIntyre & Kilding 2015; Christensen & Bangsbo 2015). In the present study, continuous severe intensity prior exercise had the highest and significantly different result from control condition in total oxygen consumed in 15-120 seconds of the performance, but this condition had the lowest time to exhaustion, which confirms the observations that higher oxygen uptake does not always enhance exercise tolerance.

Differences in the results of oxygen uptake kinetics and exercise tolerance between the present and earlier studies can be partly explained by differences in study design. There are many variables that one can modify, when studying the effects of different prior exercises, which can make it difficult to compare different studies. Study designs have differences for example in the exercise mode, prior exercise intensity and duration, recovery time between the prior exercise and performance and the intensity and the duration of the performance from which the oxygen uptake kinetics are measured. In addition, there are differences between the analysis and reporting of the VO_2 kinetics in different studies, which makes it challenging to compare the results.

Blood lactate. Continuous severe intensity prior exercise (S2) produced the highest blood lactate levels measured after the prior exercise protocol and before the onset of supramaximal test. These results were significantly different compared to control condition (S1). These results suggest that the S2 condition was more strenuous compared to other conditions. Condition S2 also produced the lowest time to exhaustion, which suggests that this prior exercise might have been too strenuous for the participants of this study. There were same kind of findings also in the study of Burnley et al. (2011) in which the baseline lactate levels were found to increase significantly after the severe intensity prior exercise but time to exhaustion was longer after heavy intensity prior exercise, which did not elevate the lactate levels as much as severe intensity prior exercise. In the study of Bailey et al. (2009) it was stated that 20-minute recovery period after the severe intensity prior exercise should enable the blood lactate to decline and performance to be restored. Even though the recovery period was 20 minutes also in the present study, and blood lactate levels declined considerably during this period, the performance was slightly lower after this severe intensity condition compared to others.

Neuromuscular characteristics. In the present study, many associations were found between endurance performance and neuromuscular abilities. When examining the relationships between performance in the incremental test and neuromuscular performance, statistically significant correlations were found between vVO_2max and leg press 1 RM result and between vVO_2max and 0-10 m speed test time. However, vVO_2max did not correlate significantly with the 0-30 m time which is in contrast with the results of the study of Paavolainen et al. (2000).

Performance in supramaximal running tests were found to correlate significantly with the CMJ results but not with other neuromuscular variables. The result is in accordance with the results of the studies of Hébert-Losier et al. (2014) and Bachero-Mena et al. (2017) where running performance was found to correlate with the jumping ability. In the study of Bachero-Mena et al. (2017), 800-m running performance correlated also with strength and sprinting abilities, but the present study did not show correlations between time to exhaustion in supramaximal tests and leg press 1 RM and sprinting abilities. Deviant results of our study can be explained by the lack of familiarization of participants to leg press test and speed test, which might have caused that the participants did not reach their maximal potential in these tests. Participants of this study were recreational athletes, and they might not be used to these kinds of tests. Maximal strength was also tested with leg press device, which might not have the best correlation to actual running performance. Because the sample was quite heterogenous including both men and women, correlations were checked also among women separately. Also, in women significant correlations were found between time to exhaustion and CMJ, which supports the observation of their relation.

Strengths of the study. Study design of the present study included both, continuous and intermittent prior exercises which have not often been included in the same study. Performance, from which the oxygen uptake kinetics and exercise tolerance were measured, was supramaximal, and this intensity is more relevant to athletic performance compared to lower intensities. Also, the 20-minute recovery time was chosen to mimic the situation in the competitions of many sports and to provide enough time to restoration of performance after the prior exercise. There were no dropouts during the study and all the participants completed all the measurements. Study design was formed with care concerning every detail and its execution was successful. Methodology of oxygen uptake kinetics was planned, completed, and reported accurately.

Limitations of the study. One of the main limitations of study was the small number of participants. The sample was also quite heterogenous including both men and women and athletes from different sports and levels, which might have produced some confounding factors to the study. The analysis of oxygen uptake kinetics was done with the data from only eight participants due to problems with VO_2 measurements with two participants. There is also a possibility that we were not able to get the full potential in supramaximal tests because participants were not used to do these kinds of tests on a treadmill. Participants got their best time to exhaustion mostly during second or third supramaximal test even though the order of prior exercises was randomized. In future studies, it might be useful to have familiarization period before the actual study to diminish the effects of learning. Familiarization was done with CMJ, but it might have been useful also concerning the other neuromuscular tests too.

Scientific conclusion. The results of the study showed that continuous severe intensity prior exercise produced the highest total oxygen consumed during the 15-120 s of supramaximal running performance when compared to control and intermittent prior exercise, and the result was also significantly different from the control condition. Continuous severe intensity and intermittent prior exercises did not have significant differences in VO_2 amplitude or time constant of the primary phase VO_2 kinetics in supramaximal performance compared to control condition. There were no statistically significant differences between the conditions in time to exhaustion, but time to exhaustion was slightly lower after continuous severe intensity prior exercise compared to other conditions. Even though the continuous severe intensity prior exercise protocol produced the highest total oxygen consumed, it also produced the lowest time to exhaustion which supports the observations that VO_2 kinetics and exercise tolerance are not always linked. It can be suggested that continuous severe intensity prior exercise increases energy production from aerobic sources during the first two minutes of the following supramaximal performance compared to control, but this might not improve the performance in exercise with supramaximal intensity and short duration. This study also showed relationships between endurance performance and neuromuscular characteristic, which confirms the importance of neuromuscular ability also in endurance performance.

Practical conclusion. When choosing prior exercise protocol for athletes, the goal is to find the best combination for improving performance and not producing too much fatigue. Thus, the intensity of the prior exercise and the recovery time should be considered with care. The intensity should be high enough to produce positive effects but not too high because it might deteriorate performance. Recovery time should be long enough to restore the performance but not too long to diminish the effects of prior exercise. In this study, there was a major variability between participants in which condition produced the best performance, so individual differences should always be considered. Like many earlier studies, also the results of this study suggest that neuromuscular abilities might be associated with the endurance performance, which highlights the importance of developing athletes' maximal strength as well as rapid force production.

REFERENCES

Bachero-Mena, B., Pareja-Blanco, F., Rodríguez-Rosell, D., Yáñez-García, J. M., Mora Custodio, R. & González-Badillo, J. J. 2017. Relationships Between Sprint, Jumping and Strength Abilities, and 800 M Performance in Male Athletes of National and International Levels. Journal of Human Kinetics 58, 187-195.

Bailey, S. J., Vanhatalo, A., Wilkerson, D. P., DiMenna, F. J. & Jones, A. M. 2009. Optimizing the ”priming” effect: influence of prior exercise intensity and recovery duration on O_2 uptake kinetics and severe-intensity exercise tolerance. Journal of Applied Physiology 107, 1743-1756.

Bangsbo, J., Madsen, K., Kiens, B. & Richter, E. A. 1996. Effect of Muscle acidity on muscle metabolism and fatigue during intense exercise in man. Journal of Physiology 495 (2), 587-596.

Berryman, N., Mujika, I., Arvisais, D., Roubeix, M., Binet, C. & Bosquet, L. 2018. Strength Training for Middle- and Long-Distance Performance: A Meta-Analysis. International Journal of Sports Physiology and Performance 13, 57-63.

Black, M. I., Jones, A. M., Blackwell, J. R., Bailey, S. J., Wylie, L. J., McDonagh, S. T. J., Thompson, C., Kelly, J., Sumners, P., Mileva, K. N., Bowtell, J. L. & Vanhatalo, A. 2017. Muscle metabolic and neuromuscular determinants of fatigue during cycling in different exercise intensity domain. Journal of Applied Physiology 122, 446-459.

Bosquet, L., Duchene, A., Dupont, G., Leger, L. & Carter H. 2007. VO2 Kinetics during Supramaximal Exercise: Relationship with Oxygen Deficit and 800-m Running Performance. International Journal of Sports Medicine 28, 518-524.

Burnley, M., Jones, A. M., Carter, H. & Doust, J. H. 2000. Effects of Prior Heavy Exercise on Phase II Pulmonary Oxygen Uptake Kinetics During Heavy Exercise. Journal of Applied Physiology 89, 1387-1396.

Burnley, M., Doust, J. H. & Jones, A. M. 2002. Effects of Prior Heavy Exercise, Prior Sprint Exercise and Passive Warming on Oxygen Uptake Kinetics During Heavy Exercise in Humans. European Journal of Applied Physiology 87, 424-432.

Burnley M. & Jones A. M. 2007. Oxygen kinetics as a determinant of sports performance. European Journal of Sport Science 7 (2), 63-79.

Burnley, M., Davison, G. & Baker, J. R. 2011. Effects of Priming Exercise on VO_2 kinetics and the Power-Duration Relationship. Medicine & Science in Sports & Exercise, 2171-2179.

Caritá, R. A. C., Greco, C. C. & Denadai, S. 2015. Prior Heavy-Intensity Exercise's Enhancement of Oxygen-Uptake Kinetics and Short-Term High-Intensity Exercise Performance Independent of Aerobic-Training Status. International Journal of Sports Physiology and Performance 10, 339-345.

Carter H., Pringle, J. S. M., Barstow, T. J. & Doust J. H. 2006. Oxygen Uptake Kinetics During Supra VO_{2max} Treadmill Running in Humans. International Journal of Sports Medicine 27, 149-157.

Christensen, P. M. & Bangsbo, J. 2015. Warm-up Strategy and High-Intensity Endurance Performance in Trained Cyclists. International Journal of Sports Physiology and Performance 10, 353-360.

Coyle, E. F., Coggan, A. R., Hopper, M. K. & Walters, T. J. 1988. Determinants of endurance in well-trained cyclists. Journal of Applied Physiology 64 (6), 2622-2630.

Demarle A. P., Slawinski, J. J., Laffite, L. P., Bocquet, V. G., Koralsztein, J. P. & Billat, V. L. 2001. Decrease of O_2 deficit is a potential factor in increased time to exhaustion after specific endurance training. Journal of Applied Physiology 90, 947-953.

Draper, S. B., Wood, D. M., Corbett, J., James, D.V.B. & Potter, C. R. 2006. The effect of prior moderate- and heavy-intensity running on the VO_2 response to exhaustive severe-intensity running. International Journal of Sports Physiology and Performance 1, 361-374.

Gastin, P. B. 2001. Energy system interaction and relative contribution during maximal exercise. Sports Medicine 31 (10), 725-741.

Gerbino, A., Ward, S. A. & Whipp, B. J. 1996. Effects of prior exercise on pulmonary gas exchange kinetics during high-intensity exercise in humans. Journal of Applied Physiology 80 (1), 99-107.

Fujii, N., Nishida, Y., Ogawa, T., Tanigawa, S. & Nishiyasu, T. 2018. Effects of work matched moderate- and high-intensity warm-up on power output during 2 min supramaximal cycling. Biology of Sport 35 (3), 223-228.

Hébert-Losier, K., Jensen, K. & Holmberg, H-C. 2014. Jumping and Hopping in Elite and Amateur Orienteering Athletes and Correlations to Sprinting and Running. International Journal of Sports Physiology and Performance 9, 993-999.

Hudgins, B., Scharfenberg, J., Travis Triplett, N. & McBride, J. M. 2013. Relationship between jumping ability and running performance in events of varying distance. Journal of Strength and Conditioning Research 27 (3), 563-567.

Hughson, R. L. 2009. Oxygen uptake kinetics: historical perspective and future directions. Applied Physiology, Nutrition, and Metabolism 34, 840-850.

Ingham, S., Fudge, B. W., Pringle, J. S. & Jones, A. M. 2013. Improvement of 800-m Running Performance with Prior High-Intensity Exercise. International Journal of Sports Physiology and Performance 8, 77-83.

Jones, A. M., Wilkerson, D. P., Burnley, M. & Koppo, K. 2003. Prior Heavy Exercise Enhances Performance during Subsequent Perimaximal Exercise. Medicine & Science in Sports & Exercise 35 (12), 2085-2092.

Joyner, M. J. & Coyle, E. F. 2008. Endurance exercise performance: the physiology of champions. The Journal of Physiology 586, 35-44.

Kao, S. H., Ishida, A. & Ainsworth B. E. 2018. The Correlation Between Strength and Power Measures with Sprint Freestyle Performance in Division 1 Collegiate Swimmers. The Journal of Swimming Research 26 (1), 22-31.

Keir, D. A., Murias, J. M. Paterson, D. H. & Kowalchuk, J. M. 2014. Breath-by-breath pulmonary O_2 uptake kinetics': effect of data processing on confidence in estimating model parameters. Experimental Physiology 99 (11), 1511-1522.

Majumdar, P., Das, A. & Mandal M. 2017. Physical and strength variables as a predictor of 2000m rowing ergometer performance in elite rowers. Journal of Physical Education and Sport 17 (4), 2502-2507.

Marcora S. M. & Staiano W. 2010. The limit to exercise tolerance in humans: mind over muscle? European Journal of Applied Physiology 109, 763-770.

Maturana, F. M., Peyrard, A., Temesi, J., Millet, G. Y. & Murias, J. M. (2018) Faster $\dot{V}O_2$ kinetics after priming exercises of different duration but same fatigue. Journal of Sports Sciences 36 (10), 1095-1102.

McIntyre, J. P. R. & Kilding, A. E. 2015. Effects of high-intensity intermittent priming on physiology and cycling performance. Journal of Sports Sciences 33 (6), 561-567.

Midgley A. W., Earle, K., McNaughton, L. R., Siegler, J. C., Clough, P. & Earle, F. 2017. Exercise tolerance during VO2max testing is a multifactorial psychobiological phenomenon. Research in Sports Medicine 25 (4), 480-494.

Murgatroyd, S. R., Ferguson, C., Ward, S. A. Whipp, B. J. & Rossiter, H. B. 2011. Pulmonary O_2 uptake kinetics as a determinant of high-intensity exercise tolerance in humans. Journal of Applied Physiology 110, 1598-1606.

Nummela, A. T., Paavolainen, L. M., Sharwood, K. A., Lambert, M. I., Noakes, T. D. & Rusko, H. K. 2006. Neuromuscular factors determining 5 km running performance and running economy in well-trained athletes. European Journal of Applied Physiology 97, 1–8.

Paavolainen, L., Häkkinen, K., Hämäläinen, I., Nummela, A. & Rusko, H. 1999. Explosive strength training improves 5-km running time by improving running economy and muscle power. Journal of Applied Physiology 86 (5), 1527-1533.

Paavolainen, L., Nummela A. & Rusko H. 2000. Muscle power factors and VO_{2max} as determinants of horizontal and uphill running performance. Scandinavian Journal of Sports Medicine 10, 286-291.

Spencer, M. R. & Gastin, P. B. 2001. Energy system contribution during 200- to 1500-m running in highly trained athletes. Medicine & Science in Sports & Exercise 33 (1), 157-162.

Sýkora, J., Brünn, D., Martin, P. & Ratko, P. 2018. is there any connection between endurance, explosive strength and speed performance? Journal of Physical Education and Sport 1 (18), 363-365.

Temesi J., Maturana, M. F., Peyrard, A., Piucco, T., Murias, J. M. & Millet, G. Y. 2017. The relationship between oxygen uptake kinetics and neuromuscular fatigue in high intensity cycling exercise. European Journal of Applied Physiology 117, 969-978.

Tordi, N., Perrey, S., Harvey, A. & Hughson, L. 2003. Oxygen Uptake Kinetics During Two Bouts of Heavy Cycling Separated by Fatiguing Sprint Exercise in Humans. Journal of Applied Physiology 94, 533-541.

Trowell, D., Vicenzino, B., Saunders, N., Fox, A. & Bonacci, J. 2020. Effect of Strength Training on Biomechanical and Neuromuscular Variables in Distance Runners: A Systematic Review and Meta-Analysis. Sports Medicine 50, 133-150.

Westerblad, H., Allen, D. G. & Lännergren, J. 2002. Muscle Fatigue: Lactic Acid or Inorganic Phosphate the Major Cause? News in Physiological Sciences 17, 17-21.

Wilkerson, D. P., Koppo, K., Barstow, T. J. & Jones, A. M. 2004. Effect of Prior Multiple Sprint Exercise on Pulmonary O2 Uptake Kinetics Following the Onset of Perimaximal Exercise. Journal of Applied Physiology 97, 1227-1236.

Yamanaka, R., Ohnuma, H., Ando, R., Tanji, F., Ohya, T., Hagiwara, M. & Suzuki, Y. 2020. Sprinting Ability as an Important Indicator of Performance in Elite Long-Distance Runners. International Journal of Sports Physiology and Performance 15, 141-145.