

**FIELD TEST FOR MEASURING VO<sub>2</sub>PEAK IN PARKOUR: A  
PILOT STUDY**

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## ABSTRACT

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**Introduction.** Parkour has become a widely followed physical activity and there are plans by Federation Internationale de Gymnastique for it to become an Olympic event. However, the physical demands of the activity have not been thoroughly examined. The purpose of this study was to examine the physical demands of parkour from the perspective of oxygen consumption in an obstacle course and to develop a field test to estimate oxygen consumption of parkour movement at different velocities. Movement on the obstacle course consisted of vaulting and running. Vaulting is a parkour specific way to move over obstacles.

**Methods.** A total of 10 male parkour athletes (mean age  $26.3 \pm 4.2$  years) volunteered for the study. The subjects completed a test to voluntary exhaustion on a specifically designed obstacle course and testing protocol, while their oxygen consumption was measured with a portable measuring device. The obstacle course was designed, so that it can be used as a field test and the design was adapted from 20m shuttle-run test. Validity of the designed testing protocol for cardiovascular fitness testing was assessed by achievement of  $VO_{2max}$  criteria (plateau in oxygen consumption,  $RER > 1.1$ , maximal heart rate and lactate values  $> 8$ ). Data, from individual subjects, was pooled to create a regression line for the estimation of oxygen consumption in vaulting.

**Results.** Designed testing protocol met  $VO_{2max}$  testing criteria. All subjects achieved  $RER > 1.1$ , lactate  $> 8$  and maximal heart rate. In addition, in 89% of measurements a  $VO_2$  plateau was observed. The mean test duration was 12 minutes and 12 seconds. Mean  $RER$ -values increased to a level above 1.0 at speed 7.0 km/h. Mean  $VO_{2peak}$  was  $44.0 \pm 1.65$  ml/kg/min and a regression line followed formula  $y = 4.15 + 3.73x$ .

**Conclusion.** The achievement of  $VO_{2max}$  criteria and suitable test duration indicates that the field test protocol is valid for assessing cardiovascular fitness. The linear increase in oxygen consumption with increasing velocity, suggests that the achieved final speed could be used to estimate oxygen consumption in parkour field test. The observation that oxygen consumption was high for any given speed, indicates that vaulting requires more oxygen than what is usually observed in running at similar speeds. The results also indicate a large demand for anaerobic energy production in vaulting, even at low speeds.

**Key words:**  $VO_{2max}$ , parkour, vaulting, field test, cardiovascular fitness,  $VO_{2peak}$

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# 1 INTRODUCTION

In the advent of new aspiring sports, it is evident that old methods of field testing are not suitable for measuring athletes' capabilities. A new standardized field test is required for measuring cardiorespiratory fitness in parkour and similar movement disciplines. Sports (locomotion) in 2019 is more varied than running, cycling or swimming, and testing methods should better be able to assess individuals' fitness in a more varied movement setting. Many new laboratory tests have been made to accommodate this. Scientists have developed a treadmill for climbing (vertically rotating mat with climbing holds on it) and wide enough treadmills for cross-country skiing tests. However, there is a demand for field tests to assess cardiorespiratory fitness in the absence of laboratory equipment. Estimation of cardiorespiratory fitness can help coaches and athletes to modify training accordingly. Currently, there is no cardiovascular field test suitable for parkour. Parkour athletes can choose from existing field tests to measure strength or power required in their discipline. For example, a standing jump test is adequate enough for assessing jumping power in parkour. However, a field measurement for  $VO_{2peak}$  is needed. A typical shuttle run or walking assessments for  $VO_{2peak}$  are not descriptive of oxygen consumption in parkour activities.

The aim of this thesis is to pilot a field test for assessing cardiorespiratory fitness in parkour activities. The results of the pilot test are used to validate the testing protocol and to get preliminary information on energy demands of parkour. In this thesis, the existing knowledge of cardiorespiratory field tests on other movement modalities is adapted for creation of the pilot protocol. Furthermore, the data obtained in this study is used to create preliminary norms for estimating  $VO_{2peak}$  in parkour based on field test performance. To ensure encompassing and representative data, top-level parkour athletes are recruited from all over Europe. Therefore, the results are not skewed by local training culture, but instead can be generalized to broad spectrum of parkour athletes.

## 2 PARKOUR

Parkour is defined as "The activity or sport of moving rapidly through an area, typically in an urban environment, negotiating obstacles by running, jumping, and climbing" (Oxford Dictionaries 2019) or "the sport of traversing environmental obstacles by running, climbing, or leaping rapidly and efficiently" (Merriam-Webster 2019). However, it started as a game for teenagers in Paris suburbs. Game that soon developed philosophical aspects to it. Mainly to train parkour was to train to be strong both physically and mentally. This philosophy culminates in the phrase "be strong to be useful". Other ideals for how one should move while doing parkour include being as efficient and as controlled as humanly possible. (Angel 2011, 9 – 42.)

Angel (2011, 9) carries on to define parkour as "physical training methodology and a particular approach and way of thinking about movement and creative spatial mapping. It is physical and emotional activity that involves only the body to overcome obstacles within a route. This may involve running; climbing; vaulting; jumping; traversing; balancing, or any other physical means to get from one point to another. Some simplify this stating it as finding a way of getting from 'point A' to 'point B'."

Currently parkour is an emerging sport, and the The Fédération Internationale de Gymnastique (FIG) has planned world championships for parkour in 2020 (FIG council 2018) and parkour to be added to the Olympic program for 2024 (Butler 2017). It is next to impossible to estimate the number of practitioners parkour currently has, because it can be practiced informally without equipment and it does not require individuals to be part of any organizations. The interest in parkour can be represented by popularity on internet platforms like Youtube. For example, parkour practitioner group "Storror" has 3.92 million subscribers on Youtube (Storror Youtube channel 2019) and their three most watched videos have 87 million views, 73 million views and 32 million views respectively. In contrast on official Olympic games Youtube-channel there are 3.32 million subscribers and their top three sports related videos have 27 million, 23 million and 17 million views (Olympic Youtube channel 2019). The most popular video on Olympic games channel is Usain Bolt's 100m world record run, which is viewed 27 million times on Youtube, whereas many Parkour related videos have multitudes of more views.

Locomotion in parkour is hard to define with strict attributes attached to it, this is because of the playful characteristics of the parkour game. Individuals set goals for themselves for each training session and there is great variance in what a single session might involve. Parkour training is an individual journey, where one challenges his physical and mental abilities and gets to know himself better (Henry 2017). Common characteristics to parkour locomotion include leaping, swinging, vaulting, climbing and running. These modalities of movement are used to go over, through and around obstacles in an urban environment (Angel 2011, 273-287; Atkinson 2009; DeFreitas 2011; Pihlaja & Junttila 2012). The movements have been influenced by variety of sports including for example gymnastics, track & field, army obstacle courses, martial arts, climbing and acrobatics (Pihlaja & Junttila 2012).

This thesis approaches parkour training from the view point of the Yamakasi (founding members of parkour and Art du déplacement). The author of this thesis has trained with the originators of the sport and have acquired knowledge on how it was originally trained. Typical training session with the Yamakasi include long strenuous repetitive actions i.e. running the stairs, crawling or hanging. Usually, these activities are done to collective exhaustion to a point where continuing would be next to impossible. The nature in which parkour was originally trained can be characterized as an endurance exercise. Therefore, in this thesis the focus is on the endurance aspect of Parkour.

One of the most typical movement types in parkour is going over obstacles by vaulting e.g. jumping or stepping over. Vaulting involves placing a body part on the obstacle, typically one or both hands, whilst going over it (for illustration see, Figure 1). There are various ways of vaulting that have become more or less standard ways to move over obstacles (Murray 2010; Pihlaja & Junttila 2012). These include for example step vault, monkey vault, turn vault and speed vault (Angel 2011, 273-287; Pihlaja & Junttila 2012). Efficiency is often the goal of parkour techniques and when it comes to vaulting, most common techniques adhere to this ideal. In practise, vaulting should not reduce your forward momentum (similar to hurdling) and it should aim to minimize the energy cost of going over the obstacle (economy).



FIGURE 1: Example of vaulting (speed vault) on the obstacle course.

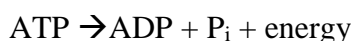
While in training sessions, vaults are often trained as individual movements, they can be applied as parts of parkour courses. Efficient completion of a parkour course sets other demands on individual movements. For example, one must control the landing from a vault to be able to face desired direction. Similarly, as with many track and field events the fluidity and speed comes from how many steps are taken between the obstacles. Currently there are no premade or set courses for parkour. It is all up to the practitioner where he/she wants to take his/her movement in a creative endeavour (Angel 2011).

In this thesis, a pilot of a simple standardisable obstacle course is designed and tested. The designed course is not aimed as a model to be used in a competition. Instead it is designed to be used as a tool for assessing energy demands of vaulting and assessing parkour practitioners' cardiovascular fitness. Golden standard for cardiovascular fitness is  $VO_{2max}$  measurements (Beltz et al. 2016).  $VO_2$  is oxygen consumption [litres/minute] and indicates how much energy can be synthesised from oxygen to produce mechanical work for movement. Currently there is no reliable means to assess maximal oxygen consumption in parkour.



### 3 ENERGETICS OF MECHANICAL WORK

Mammalian locomotion is generated by contracting muscle cells. Contracting muscle cells produce force, and the amount of force being produced per unit of time is known as mechanical work (McArdle et al. 2010, 123). Contraction of muscle cells require energy. This energy is generated by hydrolysis of adenosine triphosphate (ATP)



in which ADP is adenosine diphosphate and  $\text{P}_i$  is inorganic phosphate. This process is reversible, which allows for quick resynthesis of ATP when abundance of energy is present. Human muscle cells store limited amount of ATP, which is depleted in 1-2 seconds of maximal contracting work. For prolonged work the muscle cells need to resynthesize ATP via various metabolic processes. (Glaister 2005; McArdle et al. 2010, 135 – 138.)

*Phosphocreatine* (PCr) can be used to resynthesize ATP. This process is catalysed by creatine kinase and results in a reversible reaction in which phosphate from PCr is attached to ADP.



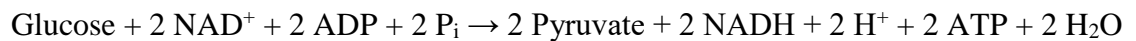
Muscle cells store approximately 80 mmol/kg of PCr in dry muscle tissue. During maximal work these stores are depleted rapidly, in an exponential pattern of decay, lasting around 10 seconds. (Glaister 2005; McArdle et al. 2010, 163.)

More than 90% of ATP synthesis happen in a coupled reaction called oxidative phosphorylation in which electrons are transferred from NADH (NAD = nicotinamide adenine dinucleotide) and  $\text{FADH}_2$  (FAD = flavin adenine dinucleotide) to oxygen molecules (McArdle et al. 2010, 139 - 141).

In endurance events lasting 5 - 20 minutes, such as the pilot field test employed in this thesis, the main source of energy (ATP) comes from breakdown of carbohydrates (McArdle et al. 2010, 170). Humans store carbohydrates in the form of glycogen in their muscle cells. These glycogen storages can be depleted as fast as 15 minutes during very high intensity exercise, but on the other hand can last for over 180 minutes in low intensity exercise (McArdle et al. 2010, 232-233). The process of breaking down carbohydrates starts with glycolysis.

### 3.1 ATP synthesis from glucose

In glycolysis carbohydrates (glucose) are degraded to pyruvate, water, free protons and NADH.

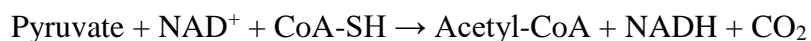


The end products pyruvate and NADH are in anaerobic conditions fermented (lactic acid fermentation) to lactate and  $\text{NAD}^+$ .



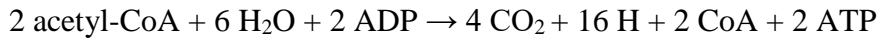
In anaerobic conditions, the energy production stops here. Lactate is not further processed for energy, while pyruvate can still be used in energy metabolism. Only 2 molecules of ATP is produced from 1 molecule of glucose in anaerobic conditions.

While in aerobic conditions pyruvate is converted into acetyl-CoA (Acetyl coenzyme A),  $\text{CO}_2$  and  $\text{NADH} + \text{H}^+$ .



These molecules are required for oxidative phosphorylation and citric acid cycle (Krebs cycle). (Guyton & Hall 2016, 856; McArdle et al. 2010, 145-147.) The degradation of glucose

continues in citric acid cycle, in which the acetyl portion of acetyl-CoA is degraded into carbon dioxide and hydrogen atoms.



As can be seen, only 4 ATP molecules per 1 molecule of glucose is formed in glycolysis and citric acid cycle. However, the reactions in glycolysis and citric acid cycle are necessary to make the hydrogen of the glucose molecule available for oxidation. The available hydrogen is oxidized in a process called oxidative phosphorylation. Oxidative phosphorylation produces a large quantity of ATP, to be precise 34 molecules of ATP per 1 molecule of glucose. Oxidative phosphorylation functions by transferring electrons from electron donors to electron acceptors such as oxygen, in redox reactions. These redox reactions release energy, which is used to synthesize ATP. (Guyton & Hall 2016, 856 – 858.)

Finally, for 1 molecule of glucose 38 molecules of ATP are synthesized, which can be used to fuel muscle contractions to do mechanical work (Guyton & Hall 2016, 859). In addition to glycolysis, oxidative phosphorylation can be fuelled by beta-oxidation (breaking down fatty acids) or proteolysis (protein degradation). However, these metabolic pathways have much lower ATP turnover rate than aerobic glycolysis, and thus are not sufficient for maintaining high intensity muscle work for short durations (McArdle et al., 2010, 159-161). In conclusion, during exercise the amount of work that can be done is limited by the amount of ATP that the cells can synthesize. This in turn is limited by the availability of oxygen for oxidative phosphorylation.

### **3.2 Oxygen transportation**

The amount of oxygen the cells have available for energy production depends on oxygen transportation capacity of the circulatory system (Docherty & Sporer 2000). Oxygen is absorbed from the air through lungs into circulating blood. Oxygen concentration of systemic blood depends on multiple factors: the partial pressure of inspired oxygen, the concentration of haemoglobin in the blood, the binding potential of oxygen molecules for haemoglobin and

sufficiency of gas exchange in the lungs. Only a miniscule portion of oxygen dissolves into the blood plasma, while large majority of oxygen molecules in the circulation are bound to the haemoglobin molecules. (Barrett et al. 2009, 523-527; Collins et al. 2015; McArdle et al. 2010, 275-280).

Collins et al. (2015) have reviewed the relationship between partial pressure, haemoglobin oxygen saturation and oxygen content of the blood. Oxygen binds to haemoglobin following a simple dissociation curve, in which as partial pressure of O<sub>2</sub> increases so does haemoglobin oxygen saturation (Figure 2). Each haemoglobin molecule has four binding sites for oxygen. In these sites, the oxygen binds into the heme of haemoglobin. Oxygen molecules are competing with carbon dioxide molecules for the same binding sites. The affinity of the binding sites is even higher for carbon dioxide molecules in comparison to oxygen molecules. This results in carbon dioxide molecules replacing oxygen molecules that are bound to haemoglobin. In addition, the affinity for oxygen increases as more binding sites become bound by oxygen molecules up to the maximum of all four binding sites being occupied. At low levels of oxygenation, this increase in affinity accounts for the increasing of slope as seen in dissociation curve. Dissociation curve is characteristically S-shaped or sigmoid, and the flattening of the curve in higher levels of oxygenation is due to haemoglobin molecules reaching full saturation.

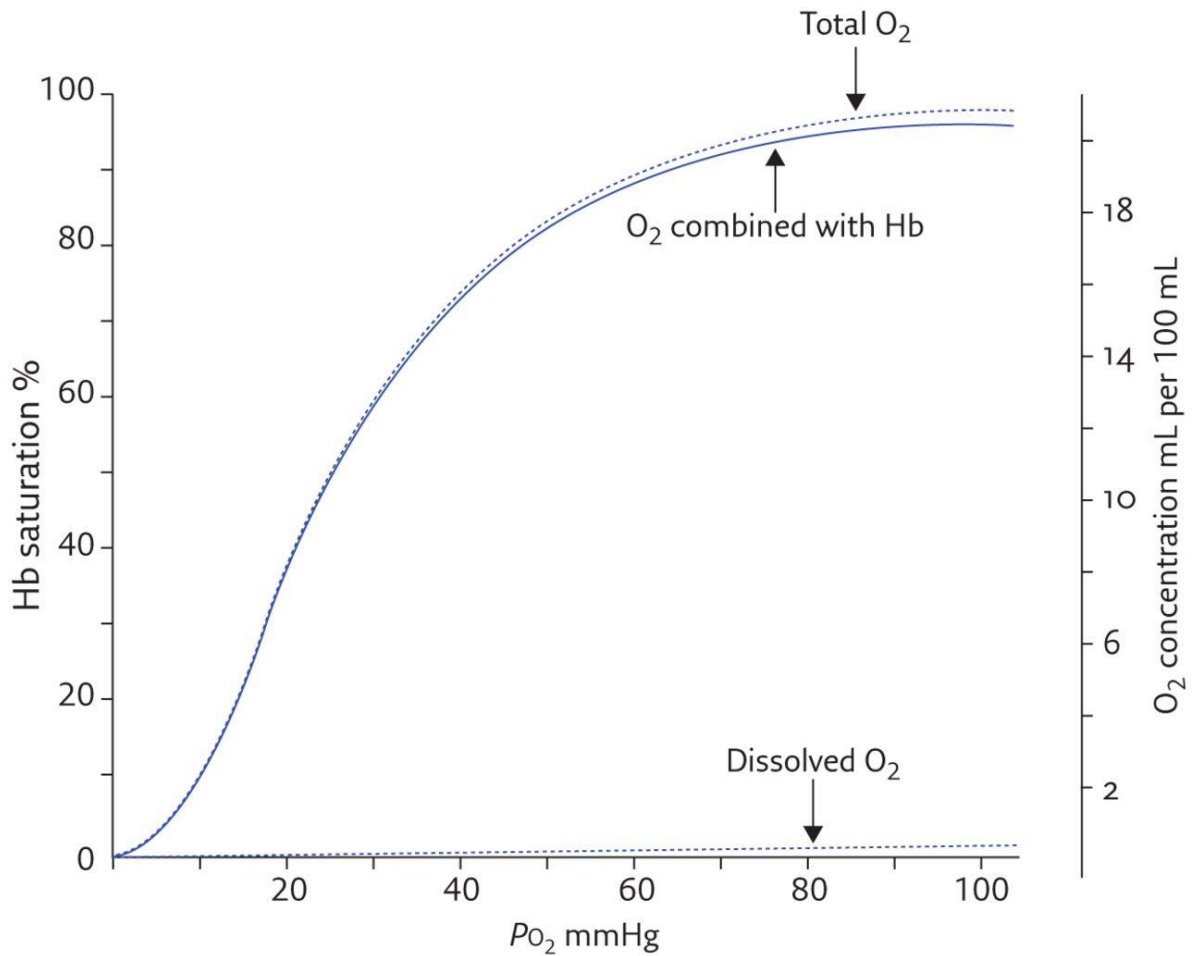


FIGURE 2. Theoretical Oxygen-haemoglobin dissociation curve. The Y-axis can be plotted as either % saturation of haemoglobin (Hb saturation) or oxygen concentration (O<sub>2</sub> concentration). The X-axis represents partial oxygen pressure (PO<sub>2</sub> mmHg). (Collins et al. 2015).

Dissociation curve is vulnerable to changes in environment. Increase in carbon dioxide partial pressure (P<sub>CO<sub>2</sub></sub>), increase in acidity (decrease of pH) and increase in temperature shift the curve, so that higher partial pressure of oxygen is required for the same amount of Hb-saturation. (Collins et al. 2015.)

### 3.3 pH and fatigue

The ability for cells to produce energy is inhibited by acidosis. Suleymanlar et al. (1992) showed a 35% decrease in oxygen consumption following a pH drop from 7.4 to 6.8 in working

muscle. During exercise, the main source of acidity is the accumulation of  $H^+$  (Robergs, 2001b). Robergs (2017) showed that glycolytic pathway, especially Glyceraldehyde-3 phosphate dehydrogenase reaction, produces the majority of  $H^+$  in breaking down of glucose. This is in contrast to commonly thought idea, that production of lactate causes acidity. Robergs also showed that Lactate dehydrogenase is actually an alkaline reaction, since it removes  $H^+$ .

pH balance is maintained by buffering accumulating  $H^+$ , transmembrane and transepithelial ion transfer processes and the adjustment of  $P_{CO_2}$  (Heisler 2004). Buffering happens on the intracellular level, where  $H^+$  is bound to buffering molecules like bicarbonate or protein complexes. Buffered ions are transferred through cell membrane by diffusion, however the transmembrane transfer process suffers from equilibrium limitations and rate of perfusion for fluids. Rate of perfusion can be affected by capillary transit capacity and adjustment of  $P_{CO_2}$ . (Heisler 2004.)

*Fatigue* was thought to be caused by acidosis (Fabiato & Fabiato 1978), by reduction of  $Ca^{2+}$  sensitivity. However, Pate et al. (1995) showed that changes in pH did not affect isometric force of rabbit's psoas muscles, suggesting that acidosis might not be the only contributor to fatigue. Allen et al. (2008) suggests that ATP, ADP, PCr, Mg and reactive oxygen and nitrogen species play a role in skeletal muscle fatigue. In addition,  $P_i$  has been shown to inhibit muscle contractions by reducing  $Ca^{2+}$  sensitivity and  $Ca^{2+}$ -activated force (Allen & Trajanovska 2012).  $P_i$  accumulates from hydrolysis of ATP, which happens in all energy production. Fatigue and acidosis seem to be the result of high energy demand, which cannot be met without cells producing inhibiting metabolites and acidity ( $H^+$ ) (Robergs 2001).

## 4 ENDURANCE PERFORMANCE

Endurance is the ability to resist fatigue (Zatsiorsky & Kraemer 2006, 162). The ability to resist fatigue is dependent on the locomotion performed and the duration of the locomotion. For events lasting under 5 minutes, endurance performance is limited by anaerobic capacity (Keskinen et al. 2010, 51). As the duration of the events increase, endurance performance becomes more dependent on aerobic capacity. The role of aerobic capacity becomes increasingly important after 2 minutes of work. (McArdle et al. 2010, 452.) In addition, intensity of work being done affects how much energy is required. High intensity work requires fast turnover rate of ATP, which can only be produced anaerobically. (McArdle et al. 2010, 163-165.)

Cardiorespiratory fitness testing aims to assess aerobic capacity which is determined by maximal oxygen uptake ( $\text{VO}_{2\text{max}}$ ), aerobic endurance, economy of the movement and the ability of neuromuscular system to produce force (Mero et al. 2007, 333).  $\text{VO}_{2\text{max}}$  testing is one of the most widely used ways of assessing aerobic fitness (Beltz et al. 2016).

### 4.1 Determinants of maximal oxygen transport and utilization

The idea of maximal oxygen uptake originated in the work of Hill and Lupton in the early 1900s. Bassett and Howley (2000) have described the  $\text{VO}_{2\text{max}}$  paradigm formulated by Hill and Lupton. The paradigm suggests that 1) there is an upper limit to oxygen intake, 2) there are differences between individuals in  $\text{VO}_{2\text{max}}$ , 3) High  $\text{VO}_{2\text{max}}$  is necessary for succeeding in endurance competitions (distance running) and 4)  $\text{VO}_{2\text{max}}$  is limited by the respiratory and circulatory systems. (Bassett & Howley 2000.)

Maximal oxygen uptake indicates how much oxygen the body can use for energy metabolism. Energy production is limited by blood's capacity to transport oxygen to the cells and muscle cells' ability to utilize oxygen (Docherty & Sporer 2000.) Maximal oxygen uptake is commonly interpreted as an index of cardiorespiratory fitness (Rowell 1974.) When observing over a period of time, oxygen uptake can be seen as cardiac output [Q] (per minute) multiplied by the difference of oxygen concentration of arterial blood compared to venous blood ( $a-v\text{O}_{2\text{diff}}$ ). This

dependency is more commonly known as Fick's equation and it was first published by Adolf Eugen Fick in 1870 (McArdle et al. 2010, 341).

$$\text{VO}_2 = Q \times a\text{-vO}_{2\text{diff}}$$

According to Beltz et al. (2016) the cardiac output is determined in this equation by heart rate (HR) and left ventricular (LV) stroke volume (SV). The stroke volume is presented as the difference of left ventricle end-diastolic volume (EDV) and end-systolic volume (ESV). Expanded formula can be described as:

$$\text{VO}_2 = \text{HR} \times (\text{EDV} - \text{ESV}) \times a\text{-vO}_{2\text{diff}}$$

Fick's equation represents central (Q) and peripheral ( $a\text{vO}_{2\text{diff}}$ ) factors of oxygen consumption. Central components are understood as factors impacting oxygen diffusion from external environment into arterial blood and the transportation of oxygenated blood to exercising muscle cells. While peripheral components refer to intracellular and molecular mechanisms that diffuse oxygen from blood into the cell and transport it to mitochondria for the use of energy metabolism. (Beltz et al. 2016.)

#### **4.1.1 Central factors of oxygen consumption**

It has been established that when oxygen consumption ( $\text{VO}_2$ ) raises the cardiac output (Q) also raises in linear fashion (Crisafulli et al. 2005). Cardiac output seems to be the limiting factor for oxygen consumption. Andersen and Saltin (1985) suggested that blood flow to exercising muscles is limited by finite cardiac output rather than muscles' capability to use oxygen. This was demonstrated in their study, in which they had subjects exercising the quadriceps muscle group, while restricting blood flow to the working muscles. They measured consumed oxygen after unrestricting blood flow. The quadriceps muscle group consumed 0.8 L/min of oxygen for 2.3 kg of muscle mass. This amount of consumed oxygen far exceeds the muscles' rate of oxygen uptake during whole body exercise.



*Heart rate* is a limiting factor for cardiac output. Maximal heart rate is age- and genetics related attribute and training has little effect on it (McArdle et al. 2010, 343). Heart rate increases linearly along with the increase of workload (Karvonen & Vuorimaa, 1988). Changes in heart rate are controlled by autonomous nervous system. As sympathetic nervous activity increases and parasympathetic decreases heart rate goes up. While opposite changes in autonomous nervous system activity result in decrease of heart rate. (Robinson et al. 1966). Exercise affects the autonomous nervous system by decreasing parasympathetic nervous system activity while simultaneously increasing sympathetic nervous system activity. This change is mediated through baroreceptors, chemoreceptors and vascular tone. (Beltz et al 2016; Robinson et al. 1966).

*Stroke volume* is affected by the volume of the left ventricle, and also acutely affected by diastole filling of the heart (Blomqvist & Saltin 1983). Blomqvist and Saltin (1983) reviewed previous research and found no association between heart size and  $VO_{2max}$ , but instead the volume of the left ventricle and  $VO_{2max}$  were correlated. Diastole filling stretches the heart muscle resulting in more force being produced when heart pumps blood into the aorta, this is also known as Frank-Starling mechanism (Guyton & Hall 2016, 119). Blood volume in circulation increases diastole filling, resulting in higher stroke volume (Levine 2008). Repeated stretching of the heart muscle by maximal diastole filling increases the volume of blood that fits into its ventricles (Guyton & Hall 2016, 119; Levine 2008.)

Force that the heart can exert is dependent on the number of contractile proteins (actin and myosin) it has. Actin and myosin form cross-bridges between each other which pull the muscle into contraction. The more cross-bridges are formed the more force is produced. More force allows the heart to pump more blood with a single stroke. (Guyton & Hall 2016, 119; Levine 2008.)

During incremental to maximal exercise autonomous neural activity becomes more sympathetic nervous dominant, which increases chronotropic activity and inotropic response. This shift in neural activity enhances myocardial contractibility, which reduces end-systolic volume and increases the volume of venous return to the heart (Beltz et al. 2016). This also allows left

ventricle to stretch more and according to Frank-Starling mechanism to contract with additional force (Allen & Kentish 1985). All this results in increased stroke volume and thus increased cardiac output (Beltz et al. 2016).

#### **4.1.2 Peripheral factors of oxygen consumption**

Arteriovenous oxygen difference ( $a-vO_{2\text{diff}}$ ) simply means the difference of oxygen concentration in arterial and venous blood. However, this difference is caused by oxygen diffusing from arterial blood into the muscle cells, therefore resulting in lesser oxygen concentration in venous blood. The amount of oxygen that diffuses to cells is dependent on the rate of diffusion and utilization of oxygen. (Honig et al. 1992.)

Circulating oxygen is transported through muscle cell membrane by diffusion, in which small particles move across the cell membrane from higher concentration (higher partial pressure of  $O_2$ ) to lower concentration. This effect is also known as Fick's law of diffusion. (McArdle et al. 2010, 256-257.) Oxygen in the muscle cells is bound to myoglobin, much like oxygen binds into haemoglobin in the bloodstream. Myoglobin serves as a storage for oxygen particles. As oxygen binds into myoglobin, the concentration gradient is altered. Altered concentration gradient facilitates diffusion of oxygen into the cells. (Jürgens et al. 2000.) Honig et al. (1992) confirmed that the  $PO_2$  in bloodstream was not the only determining factor for oxygen diffusion into the muscle cells, but there also needed to be a demand for the oxygen (low  $PO_2$  inside the cell). As the muscle cells use oxygen for energy,  $PO_2$  inside the cell decreases, this results in more diffusion of oxygen into the cell.

Cells ability to utilize oxygen is in turn limited by its capacities for oxidative phosphorylation. In oxidative phosphorylation cells use enzymes to oxidize nutrients, thereby releasing energy which is used to resynthesize ATP (adenosine triphosphate). Oxidative phosphorylation takes place in cell's mitochondria and is, therefore, limited by the number of mitochondria in the cells. Mitochondria serve as the site where the final step of electron transport chain takes place and in which  $O_2$  is consumed to make ATP. So in theory doubling the number of mitochondrial enzymes should double the capacity of oxygen consumption (Mitchell & Moyle 1967.)

However, Saltin et al. (1977) found that 120% increase in mitochondrial enzymes resulted only in 20-40% increase in  $\text{VO}_{2\text{max}}$ . This supports the view that oxygen uptake is limited by the ability to transport it and not by the ability to utilize it in the cells (Bassett & Howley 2000).

## 4.2 During exercise

Exercise increases oxygen demand on working muscles. Blood circulation meets this demand, by re-directing 80-90% of arterial blood to working muscles during maximal exercise. (Andersen & Saltin 1985; Lewis et al. 1983; Åstrand & Saltin 1961.) Blood pressure is maintained by increasing stroke volume and heart rate, which otherwise would drop due to vasodilation in working muscle cells (Lewis et al. 1983).

Heart rate increases linearly as the intensity of exercises increases. However, as exercise intensity approaches maximal intensity, a heart rate threshold is usually found after which the slope of heart rate increase is subject to large variability between individuals. After reaching the heart rate threshold, the slope of heart rate increase relative to increase in exercise intensity becomes steeper for some people, whereas for some the slope becomes less steep. (Bunc et al. 1995; Hoffman et al. 1997; Knight-Maloney et al. 2002.)

Originally it was thought that increase in stroke volume plateaued at approximately 40-50% from  $\text{VO}_{2\text{max}}$  (Bevegard et al. 1963; Grimby et al. 1966; Åstrand et al. 1964). Later research suggests that 1) stroke volume has high variability between subjects in incremental to maximal exercise 2) a plateau in stroke volume may not exist. (Gledhill et al. 1994, Krip et al. 1997, Rivera et al. 1989). Gledhill et al. (1994) observed increases in stroke volume up to  $\text{VO}_{2\text{max}}$  in healthy endurance trained young male adults, but did not observe the same in untrained young male adults. In addition, they found that ventricular filling took less time for trained subjects when compared to untrained subjects. Ferguson et al. (2001) showed same results for young female adults. Vella & Robergs (2005) did a review article which shows that, while the size of heart muscle is limited by myocardial fascia, stroke volume can still increase. This increase is contributed to enhancement of diastolic filling rate and left ventricular emptying rate. Enhancement of diastolic filling rate is contributed mainly to better pre-load, which seems to

be the result of larger blood volume. They showed that adaptations to endurance training enhance stroke volume via increase in blood volume, increase in the size of left ventricle, improvement of left ventricle compliance, increase of myocardial contractility and reduced diastolic filling time during loading. However, the researchers also showed large inter-individual variability (see Figure 3). Age, sex and fitness level affect stroke volume function during exercise. Stroke volume can either reach a classical plateau, plateau with a subsequent drop, plateau with a subsequent rise or gradual increase.

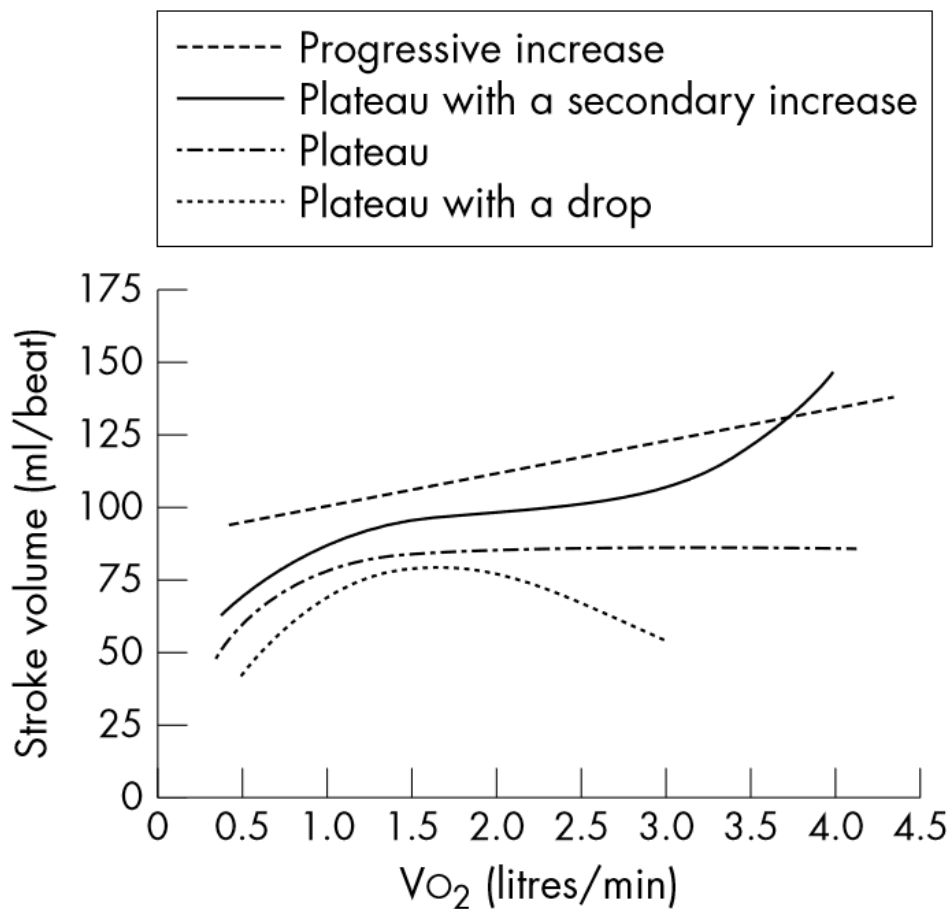


FIGURE 3: Four different types of stroke volume responses with increasing exercise intensity (Vella & Robergs 2005).

Peripheral mechanisms for maintaining  $\text{VO}_2$  during exercise are thought to be complementary to cardiac output (Beltz et al. 2016). Montero et al. (2015) did a meta-analysis on  $a\text{-vO}_{2\text{diff}}$  and its attribution to  $\text{VO}_{2\text{max}}$ . They found out that after endurance training intervention increase of

$Q_{\max}$  was linearly correlated with increase of  $VO_{2\max}$ , however changes in  $a-vO_{2\text{diff}}$  did not correlate with changes in  $VO_{2\max}$ . In case of longer interventions (12-13 weeks), the results showed significant increase in  $a-vO_{2\text{diff}}$  whereas shorter interventions (5-8 weeks) did not seem to affect  $a-vO_{2\text{diff}}$ . The researchers carried on to conclude that peripheral factors are adapting to increase in cardiac output, but are not responsible for increases in  $VO_{2\max}$ .

### **4.3 Adaptations to training**

Large physiological differences can be observed between untrained and endurance trained men. On the level of muscle cells, McArdle et al. (2010, 457) have described the differences: in comparison to untrained men the endurance trained men have larger glycogen storages (41%) and more mitochondria (103%), ATP (100%), phosphocreatine (64%), glycolytic enzymes (60%) and aerobic enzymes (133%). In addition, endurance trained men have larger stroke volume (50%), larger cardiac output (75%), lower resting heart rate (-43%), lower maximal heart rate (-5%), increased heart volume (27%) and blood volume (28%) compared to untrained men. These all result to higher  $VO_{2\max}$  (107%) in trained men.

Adaptations in peripheral factors do not seem to be the bottle neck in endurance performance (Bassett & Howley 2000). However, adaptations in cardiac output, especially stroke volume, seem to be of utmost importance in regards to endurance performance (Blomqvist & Saltin 1983). To increase stroke volume, not only size of the left ventricle has to grow, but there also needs to be larger supply of blood to accompany the increased pumping capability. Sawka et al. (2000) concluded in their review article that endurance training increases blood volume, blood plasma volume and erythrocyte volume by 10% within 30 days of endurance training. They pointed out a significant correlation between total blood volume and  $VO_{2\max}$ .

Another adaptation to training happens in capillaries. Capillary density increases in peripheral muscles as a result of endurance training (Andersen & Henriksson 1977; Brodal et al. 1977). Capillary density is thought to affect  $VO_{2\max}$  by elongating mean transit time and decreasing peripheral resistance (Bassett & Howley 2000).

## 5 MEASURING MAXIMAL OXYGEN UPTAKE

Oxygen uptake linearly follows the intensity of work being performed. Increase in workload requires more energy for muscle contractions. Larger energy demand causes more oxygen utilization for energy metabolism which is seen as an increase in oxygen uptake. This is mainly achieved by increasing cardiac output by increasing heart rate and stroke volume. (Boone & Bourgois 2012.)

Maximal oxygen uptake can be measured directly using oxygen detecting equipment that measure the amount of inhaled oxygen and compare it to the amount of exhaled oxygen. The difference between the amounts indicates how much oxygen is taken into the body and used as a fuel to the cells. (Taylor et al. 1955.)

Maximal oxygen uptake is obtained in experimental settings when oxygen uptake reaches a plateau. This is observed by continuously increasing workloads and after reaching the plateau oxygen uptake no longer increases even if the workload does. (Taylor et al. 1955.) However, it is not uncommon that a plateau does not appear in experimental settings. To combat this a variety of secondary criteria has been used to characterize the oxygen uptake measured in the last minutes of experimental settings. These criteria include high levels of lactic acid in the blood following the exercise test, elevated respiratory exchange ratio (RER) and achievement of an estimate of maximal heart rate. (Howley et al. 1995.) Astorino et al. (2000) define the criteria as: (1) a plateau ( $\Delta \text{VO}_2 < 50 \text{ mL/min}$  at  $\text{VO}_{2\text{peak}}$  and between consequent values) in  $\text{VO}_2$  with increases in workload, (2) maximal respiratory exchange ratio (RER)  $> 1.1$ , and (3) maximal heart rate within 10 beats per minute of the age-predicted maximum ( $220 - \text{age}$ ). The validity of  $\text{VO}_{2\text{max}}$  experiment is assessed by how well primary (plateau in oxygen consumption) and secondary criteria are met. Day et al. (2003) showed that even if primary criteria for  $\text{VO}_{2\text{max}}$  was not met, it did not invalidate the measurement. In their study, subjects who did not reach  $\text{VO}_2$  plateau in maximal incremental ramp test still had reached  $\text{VO}_{2\text{max}}$  when confirmed by supramaximal test.

The validity of these secondary criteria have been questioned. It has been suggested that these criteria do not guarantee that a true  $\text{VO}_{2\text{max}}$  has been reached (Howley et al. 1995; Midgley et al. 2007; Midgley et al. 2009). According to Beltz et al. (2016) review article, the critique boils down to high inter-individual variability in meeting these criteria. This variability in attaining  $\text{VO}_{2\text{max}}$  criteria allows submaximal efforts to be perceived as maximal efforts, thus not guaranteeing that true  $\text{VO}_{2\text{max}}$  has been reached. (Beltz et al. 2016.)

Testing protocols vary between the intensity of workloads, progression of the workloads, duration of the workloads and total test duration. Common characteristic of direct testing protocols is that they all end in exhaustion (inability to continue testing). However, it needs to be noted that different protocols produce different  $\text{VO}_{2\text{max}}$  values. (Beltz et al. 2016.) Muscat et al. (2015) measured  $\text{VO}_{2\text{max}}$  by treadmill and cycle ergometer and the treadmill results were up to 20% higher in comparison to cycle ergometer. Previous studies imply that the differences occur due to running requiring higher cardiac output (Q), running involving more muscle mass and requiring higher vascular conductance and  $a\text{-vO}_{2\text{diff}}$  (Buchfuhrer et al. 1983; Hermansen et al. 1970; Holmer et al. 1974; Tanner et al. 2014). These studies also suggest that in cycling, there appears to be lower rate of carbohydrate oxidation, which leads to less acidosis. Same phenomenon was observed in swimming by Holmer et al. (1974) in their study in which elite swimmers performed  $\text{VO}_{2\text{max}}$  test by both methods; swimming and running on a treadmill.  $\text{VO}_{2\text{max}}$  appears to be task specific and thus it is important that the testing protocol is suited to the demands of the activity being performed.

Even the treadmill protocols vary. Pollock et al. (1976) compared four commonly used treadmill testing protocols: Balke protocol, Bruce protocol, Ellestad protocol and modified Åstrand protocol. These protocols differed in increases of workload. Åstrand protocol does not alter running speed but increases the incline of the treadmill by 2.5% every 2 minutes. Balke also maintains constant speed but increases the incline of the treadmill by 1% every minute. Bruce protocol increases speed and grade of incline every 3 minutes. Finally Ellestad protocol increases speed until 10 minutes' mark is met, after which the grade of incline is increased by 5% followed by subsequent increases in speed. Pollock et al. (1976) found, that the individual characteristics of above mentioned testing protocols, did not affect measured  $\text{VO}_{2\text{max}}$ . However,

differences in obtaining  $\text{VO}_2$  plateau were shown. Plateau obtainment varied between the protocols from 59% (Ellestad) to 80% (Åstrand) of subjects reaching  $\text{VO}_2$  plateau.

The above mentioned treadmill protocols follow stepwise increase in workload, however with assistance of technology, it is possible to increase the workload continuously. For example, Whipp et al. (1981) used electronically braking cycle ergometers to increase the workload continuously as expressed by watts/min. This method of continuous increase in workload seems to reduce error in predicting metabolic cost at individual workloads and gives higher correlation between  $\text{VO}_2$  and the workload (Myers et al. 1991). This does not mean that incremental ramp test is better at assessing  $\text{VO}_{2\text{max}}$ . Zhang et al. (1991) compared incremental ramp test to more traditional stepwise tests and found no difference between obtained  $\text{VO}_{2\text{max}}$ .

Test protocols also vary in their duration. Buchfuhrer et al. (1983) examined protocol duration on the achievement of  $\text{VO}_{2\text{max}}$ . This study originated the recommendation for test duration of 8-12 minutes, based on obtaining highest  $\text{VO}_{2\text{max}}$  values around this range. Yoon et al. (2007) re-examined this premise and found out that protocols lasting 8-minutes were best suited for assessing  $\text{VO}_{2\text{max}}$  in men.



## 6 DESIGNING CARDIORESPIRATORY FIELD TEST FOR PARKOUR

In field tests, it is impractical and often impossible to use laboratory criteria whether  $VO_{2max}$  is reached or not. Instead, field tests are based on information derived from laboratory tests in which a large volume of subjects have been measured. Fitness level for each subject is gained from the laboratory test, which is used to create an average of oxygen consumption for any given speed. Field tests check the final stage (workload) or speed that the subject achieves and the achieved workload is checked against a point in a trend line (regression line) built from laboratory results. This gives an approximation of the fitness level of the subject. (Ramsbottom et al. 1988.)

### 6.1 Common field tests

Ramsbottom et al. (1988) correlated multi-stage fitness test (also known as the beep test or 20m shuttle run test) to direct uphill treadmill  $VO_{2max}$  test. They found out that multi-stage fitness test can be used to estimate  $VO_{2max}$  ( $r= 0.92$ ,  $p < 0.01$ ). Since then the validity of multi-stage fitness test in estimating  $VO_{2max}$  has been confirmed many times (Cooper et al. 2005; Leger & Gadoury 1989; McVeigh et al. 1995). In addition, multi-stage fitness test has been shown to predict endurance performance in running events (Noakes et al.1990; Scott & Houmard 1994).

Other field tests, such as, yo-yo intermittent test, cooper walk run 12-minute test and submaximal cycle ergometer test have proven to be good predictors of  $VO_{2max}$  (Castagna et al. 2006; Grant et al. 1995). However, predicting performance in sports requires a testing pattern to meet the demands of the activity being performed (Castagna et al. 2006). In practice, this means testing should take into account physiological demands of the activity, movement patterns should be similar to the ones used during the activity and technical skills should be included in the test patterns (Bangsbo & Lindquist 1992; Castagna et al 2006).

In multi-stage fitness test the subject runs between two markers placed 20m from each other with increasing speeds. Speed increases 0.14m/s in step-like fashion once every minute. The test is evaluated by based on which speed (level or stage) is obtained and how long the speed

can be maintained (number of shuttles). The original test by Leger and Lambert (1982) used 2-minute duration for stage, but after revision in 1984 a standard of 1-minute duration for each stage emerged (Leger et al. 1984). Billat et al. (1996) examined the differences between 1-minute stages to 2-minute stages in a treadmill protocol. They found out that there was no significant difference between the stages in the obtained  $VO_{2max}$  nor the velocity that the  $VO_{2max}$  was reached. However, they proposed that shorter stage might have an advantage in experimental settings for examining velocity at  $VO_{2max}$ . Shorter stage duration prevents the test from ending premature due to exhaustion or surrender by the subject. In addition, Astorino et al. (2000) stated that for most subjects maintaining workload at  $VO_{2max}$  or above is not feasible for 2-3 minutes and therefore shorter sampling intervals are required for demonstration of  $VO_2$  plateau. The validity of multi-stage fitness test and its ability predict endurance performance was the basis, which the protocol used in this thesis was built upon.

## **6.2 Modifying existing field tests for parkour fitness testing**

For designing a field test used in this thesis, the expertise of three long term parkour coaches and athletes were utilized. The coaches had an average of 7 years of parkour coaching (range 5-10 years) experience and more than 10 years of training experience (range 10-12 years). As no previous scientific enquiry to parkour fitness testing has been conducted, practical knowledge from experienced parkour coaches was used to build an understanding on the demands of the activity.

The ground rules were established based on previous literature for intensity of workloads (Leger et al. 1984, Leger & Lambert 1982), duration of workloads (Billat et al. 1996; Leger et al. 1984) and hypothesized test duration (Billat et al. 1996; Buchfuhrer et al. 1983). For the pilot protocol, distance between obstacles (for convenient gait), the height of the obstacles (so that good vaulting technique could be easily applied) and acceleration/deceleration distance from the obstacles was designed based on expertise from the coaches. The aim was to closely simulate the demands of the sport, which according to Castagna et al. (2006) and Bangsbo and Lindquist (1992) is a requirement for assessing endurance performance for the specific sport.

## 7 THE PURPOSE OF THE STUDY

Before conducting this study, there has not been any physiological research for parkour movement. This study serves as a pilot for a field test aimed to assess parkour athletes'  $VO_{2peak}$ . The aim was to develop a field test protocol suitable for assessing parkour athletes' cardiovascular fitness. A field test is a useful tool for coaches and athletes alike. The purpose is to understand the underlying physiology of parkour, but not to categorize or define parkour movement.

From a physiological perspective, measuring  $VO_2$  consumption during parkour movement (in this case vaulting) at different speeds was the main focus. This will increase the understanding of how demanding vaulting is at different velocities. Hopefully this will help parkour practitioners and coaches to better plan their exercise so that it actually improves performance.

Research questions are as follows:

1. Does the field test protocol provide a valid measurement of  $VO_{2peak}$  for vaulting?

Subjects are expected to achieve  $VO_{2max}$ , as confirmed by meeting  $VO_{2max}$  testing criteria defined by previous studies (Astorino et al. 2000; Howley et al. 1995). The following criteria will be achieved: a plateau in  $VO_2$ , high lactate values ( $\geq 8$ ), above 1.1 RER, maximal heart rate and voluntary exhaustion.

2. Do the results of the pilot-test validate the testing protocol?

Previous literature describes optimal testing protocols to last between 8-12 minutes (Buchfuhrer et al. 1983; Yoon et al. 2007). Here the test duration until exhaustion is compared to this recommendation. Billat et al (1996) found that an accurate resolution in  $VO_2$  sampling is dependent on small increments in workload and optimal workload duration. They suggested an optimal workload duration to be 1 minute and workload increment 0.5 km/h. The pilot protocol

of the present study was adapted to suit this recommendation. Here it is investigated if these parameters produce an accurate estimation for  $\text{VO}_2$ .

3. What kind of regression line is produced from oxygen consumption in relation to velocity? How steep is the slope and is the increase in oxygen consumption in relation to velocity linear?

Previous studies on running suggest that oxygen consumption increases linearly when the velocity increases and a regression line can be used to predict oxygen consumption on a given speed (for a review, see Leger & Mercier 1984). Leger and Mercier (1984) found that in running the average steepness of regression line is 3.163. Here it is investigated if the regression line obtained for vaulting is similar to studies on running. The slope is expected to be linear in vaulting, but it is expected that oxygen consumption is higher for any given speed in parkour when compared to running, because of higher energy demand of vaulting.

## **8 METHODS**

### **8.1 Subjects**

The subjects were recruited from all over Europe. Inclusion criteria for this study was at least five years of parkour practice with average of two training session of parkour in a week. These inclusion criteria were placed to make sure that the subjects would meet the sport specific requirements and be able to push themselves to exhaustion on the obstacle course  $VO_{2max}$  test. To ensure the best quality of subjects, the research team organized recruitment of subjects with Finnish Parkour Association. Finnish Parkour Association held an annual parkour event of year 2015, in which coaches were recruited from all over the Europe. The coaches volunteered for this study, and they were available for the sole purpose of research for one day.

Ten male volunteer subjects participated in this study. They were between 18 to 32 years of age (mean age  $26.3 \pm 4.2$ ). Their height varied between 171 cm to 194 cm and their weight was between 63 kg and 87 kg. The subjects had the right to terminate the test at any given time and also the right to refuse some parts or all of the testing. Before the  $VO_{2max}$  test to voluntary exhaustion, the subjects were briefed about the testing protocols and what data was collected from them. The subjects gave an informed consent to participation. In addition, they were advised to avoid excessive physical activity for two days prior to testing.

### **8.2 Testing protocol**

#### **8.2.1 Designing the protocol**

There were several key factors when designing the testing protocol for oxygen consumption in vaulting. Firstly, the safety of the subjects was of utmost importance. To accommodate the need for safety, we had to make sure that subjects were of adequate skill level in the sport to ensure a safe completion of the obstacle course. In addition, the measuring equipment was tested so

that it did not hinder a safe completion of the test and surrounding area from the test environment was cleaned from all obstructions.

Secondly, the testing was limited to one day, due to availability of participants being limited to one day. This prevented additional tests to be performed on different days, like a treadmill running test to exhaustion, which would have brought a greater understanding of energy demands of vaulting. Due to the nature of this unique opportunity (access to top level parkour athletes), it was also decided that concurrent tests would be done on the subjects while doing the test to a voluntary exhaustion. Concurrent tests involved biomechanical examination of vaulting at different speeds. This was accomplished by 3d motion capture tools and force plates that monitored jumping forces and landing forces from the obstacles. As a part of another research project conducted on the same day, the subjects had to undergo three maximal speed runs through the obstacle course before the test to a voluntary exhaustion. To mitigate the fatigue caused by this, the subjects had 15 minutes break before starting the test to voluntary exhaustion. In addition, after the test to voluntary exhaustion the subjects were taken blood lactate and after ten minutes, the subjects did one more maximal speed runs through the obstacle course. This designed allowed to see effects of fatigue in both maximal speed of the subjects and in vaulting technique. In this thesis, only the results from the test to a voluntary exhaustion is reported.

The voluntary test to exhaustion was modified from 20m shuttle-run test. Starting speed of the test was decided to be 6 km/h to make sure the test would start below lactate threshold 1. Increases in speed were kept the same as in 20m shuttle-run test. Each individual speed was maintained for at least one minute. Each speed consisted of at least two shuttles. If a shuttle was unfinished before the one-minute mark, the speed was maintained until 50 meters' shuttle was completed. In field testing environment, it is impractical or impossible to increase running speed in the middle of a shuttle, so before increasing speed the subject must finish whole shuttle. Therefore, stage duration was not constant due to nature of the field test. Stage duration and corresponding number of shuttles are presented in Table 1.

Increase in workload was more troublesome, as it was unclear how large increments of workloads are suitable in vaulting. In the end, it was decided that the increase in workload should be done similarly to 20m shuttle-run test and increase of 0.5km/h for each stage was decided on. However, increase in workload might or might not be linear with this testing protocol, because as the speed increases, the subjects have more obstacles to vault during each stage. Unlike 20m shuttle-run test, in this protocol a 50m shuttles were used. This allowed for more obstacle to be placed in each shuttle, instead of just having one in the middle of 20m track. In addition, this allowed for acceleration phase before first obstacle in each shuttle and deceleration phase after the last obstacle in each stage. After pre-piloting the obstacle course with expert parkour coaches, five obstacles were observed to work well in a 50m shuttle. Five obstacles placed evenly along the course allowed for examination of gait characteristics and provided enough variation from regular running tests. Five obstacles allowed for measuring oxygen consumption in vaulting.

After deciding the starting speed, increases of speed and the shuttle distance, an audio cue was required so that the subjects could pace their movement. Audio track was made with cues to start each shuttle and cues for each obstacle to keep even pace.

TABLE 1: Number of stage, stage duration, speed, number of shuttles and test duration (at the end of stage) on a 50m obstacle course.

Stage	Stage duration (s)	Speed (km/h)	# shuttles	Test duration (s)
1	60	6	2	60
2	83	6.5	3	143
3	77	7	3	220
4	72	7.5	3	292
5	68	8	3	360
6	64	8.5	3	423
7	60	9	3	483
8	76	9.5	4	559
9	72	10	4	631
10	69	10.5	4	700
11	65	11	4	765
12	63	11.5	4	828
13	60	12	4	889
14	72	12.5	5	960
15	69	13	5	1029
16	67	13.5	5	1097
17	64	14	5	1161
18	62	14.5	5	1222
19	60	15	5	1282
20	70	15.5	6	1352

Height of the obstacles was determined to be  $1\text{ m} \pm 12\text{ cm}$ , because these types of obstacles are typically found in many parkour gyms and also were familiar to all subjects participating in this study. Width of the obstacles were  $40\text{ cm} \pm 3\text{ cm}$ . The distance between the obstacles was 7 m (measured from the center of each obstacle) and acceleration and deceleration distance was 11 m both at the beginning and at the end of the shuttle. Shuttle length was 50 m (Figure 4).



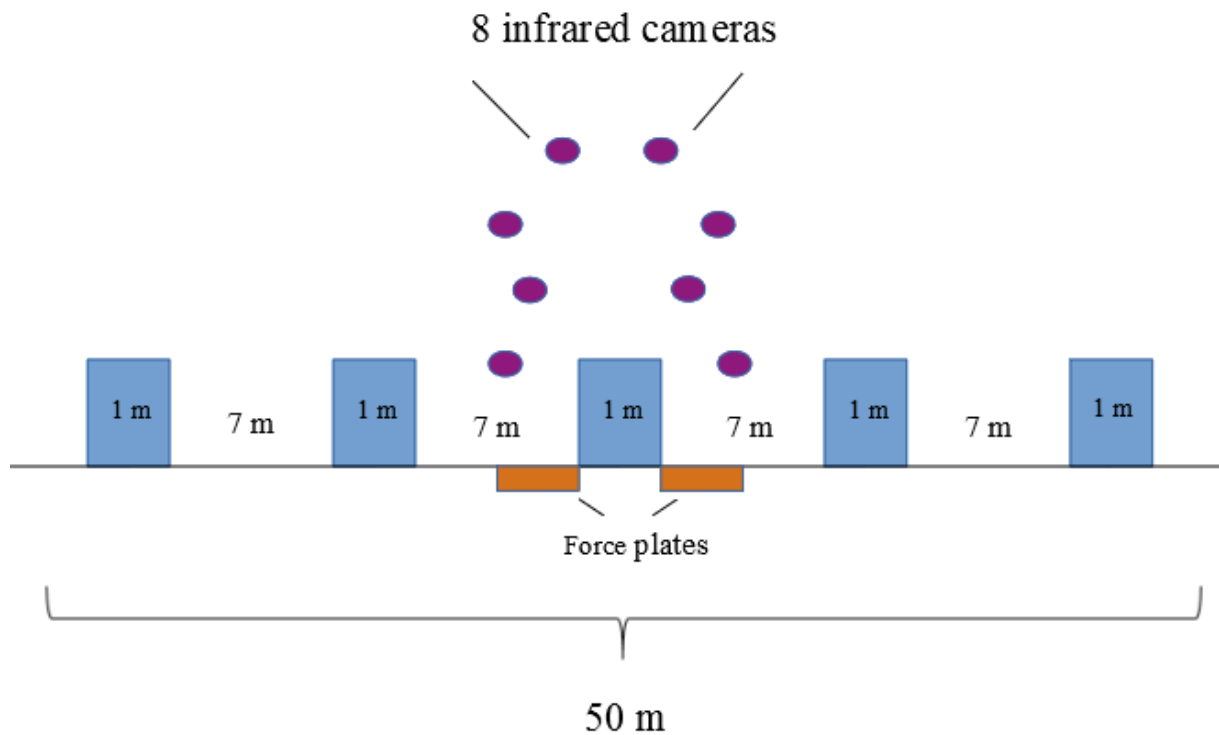


FIGURE 4: Illustration of the obstacle course and position of cameras and force plates.

### 8.2.2 The pilot test

The pilot test was done on a track and field arena (Hipposhalli, Jyväskylä, Finland), and it was part of a larger research project. On the testing day, the subjects were weighed and their height was measured. They had 30 minutes to familiarize themselves on the obstacle course, and they were instructed of the measuring protocols. They had the option to choose their preferred vaulting technique. They were allowed to adjust their technique in accordance to increases in velocity. Their joints and other body segments were marked using custom made markers. The placement of markers was done according to anatomical conventions. Joints were marked for 3d video analysis used in another research project, not reported here.

After preparation, the subjects ran through the obstacle course at maximal speed three times with 3-minutes rest in-between the runs. They were granted ten minutes of rest before adding mobile oxygen consumption measuring backpack to them. With oxygen consumption measuring devices in place, pre-lactate was taken and the voluntary test to exhaustion was

started. After the voluntary test to exhaustion, lactates were taken at post 0-minutes, post 5-minutes and post 10-minutes. The oxygen consumption measuring device was removed and after post 10-minutes lactate measurement, the subjects ran through the obstacle course at maximal speed once more. For the procession of the testing day see Figure 5.

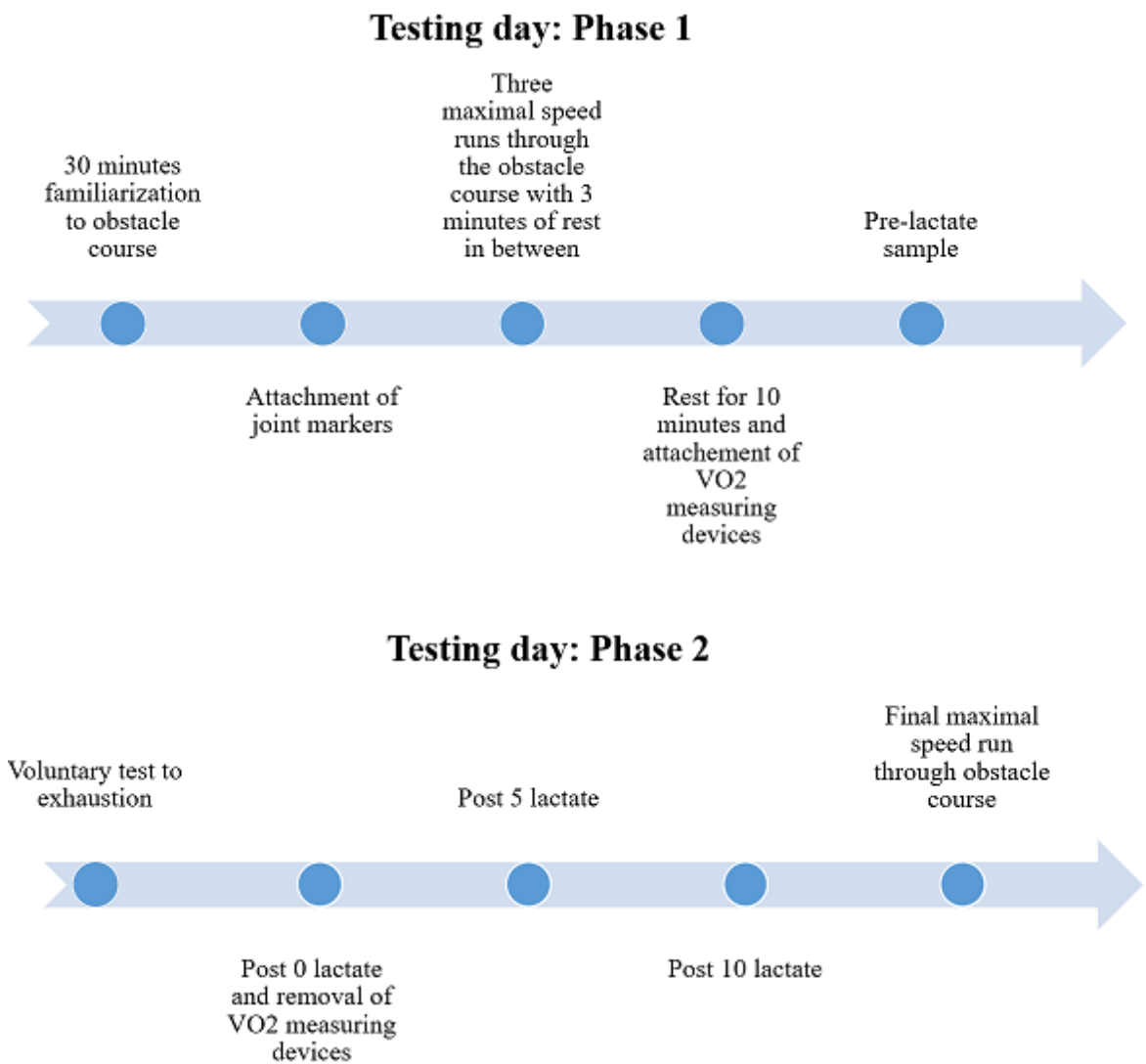


FIGURE 5: Timeline for the testing day. Phase 1 describes what happens before voluntary test to exhaustion. Phase 2 describes remainder of the testing day.

### 8.3 Measuring devices and outcome measures

Oxygen consumption was measured using ergospirometer (Oxycon Mobile jaeger, Viasys Healthcare, inc., Höchberg, Germany), which allowed for measurement of whole voluntary test to exhaustion. Ergospirometer consists of breathing mask, which attaches to a portable breath-by-breath data collector and wireless signal transmitter. Collector and transmitter is carried on person in a wearable body vest. The transmitted data from the breath-by-breath data collector is wirelessly transmitted to a computer for analysis of oxygen consumption. Before each measurement the breathing mask and its sensors were cleaned and dried, and the measuring devices were calibrated via calibrating gas. Oxygen consumption data was averaged over time period of 30 seconds and breath-by-breath data was not used for analysis. The highest reached  $\text{VO}_2$ -value was determined to be the  $\text{VO}_{2\text{peak}}$ . Term  $\text{VO}_{2\text{peak}}$  is used here to describe to maximal obtained oxygen consumption.  $\text{VO}_{2\text{peak}}$  is used instead of  $\text{VO}_{2\text{max}}$  to describe obtained results in this study to emphasize that there is uncertainty whether the values obtained represent the true  $\text{VO}_{2\text{max}}$ . RER-value was obtained from breath-by-breath data, and it was averaged for each speed for each individual. Maximal heart rate was gained from heart rate monitor (Suunto Quest, Amer Sports, OYJ., Vantaa, Finland). Lactate samples were drawn to capillaries and mixed into hydrolysate. Analysis of lactate samples were done on Biosen C-line Glucose and Lactate analyzer (EKF diagnostic, Cardiff, United Kingdom). The criteria for obtaining  $\text{VO}_{2\text{max}}$  was based on previous studies: I) a plateau (fluctuations smaller than  $\leq 1.5 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$  between  $\text{VO}_{2\text{peak}}$  and consequent  $\text{VO}_2$  values) in  $\text{VO}_2$ , II) Maximal RER-value  $>1.1$ , III) maximal heart rate within 10 beats per minute of age-predicted maximum ( $220 - \text{age}$ ) and IV) lactate values  $\geq 8$  (for review see Howley et al. 1995).

### 8.4 Statistical analysis

SPSS-program (version 24.0.0, SPSS, Inc., Chicago, US) was used for statistical analysis. Means and standard deviations were calculated over the participants for oxygen consumption and RER. A linear regression was calculated to investigate whether oxygen consumption linearly increases with the increase of workload. Regression was calculated by fitting a regression curve over oxygen consumption derived from all the participants and speeds. In

addition, a Spearman correlation was calculated between  $\text{VO}_2$  and velocity. To investigate the anaerobic demands of the activity, a Spearman correlation was calculated between RER and velocity. The Spearman correlation was used because the variables were not normally distributed. For significance values lower than 0.05 were considered significant.

## 9 RESULTS

Average test duration was 12 minutes and 12 seconds ( $\pm 1$  minutes 5 seconds), ranging from 10 minutes and 50 seconds to 14 minutes and 3 seconds. Mean  $\text{VO}_{2\text{peak}}$  was  $44.0 \pm 1.65$  ml/kg/min. Details for individual participants are reported in Table 2. One participant had missing data for final  $\text{VO}_2$ -values, due to malfunction of measuring device. Therefore,  $\text{VO}_{2\text{peak}}$  is unavailable for one participant. Eight out of nine participants reached  $\text{VO}_2$ -plateau.

TABLE 2.  $\text{VO}_2$  measurement test duration until exhaustion, measured  $\text{VO}_{2\text{peak}}$ , lactate values pre-test, immediately after test, post 5-minutes of testing, post 10 minutes of testing and maximal heartrate for each individual participant

Participant	Duration (min:s)	$\text{VO}_{2\text{peak}}$ (ml/kg/min)	Lactate values (mmol/l)				$\text{HR}_{\text{max}}$
			Pre	Post 0	Post 5	Post 10	Bpm
P1	11:23	42.4	5.69	11.68	14.58	9.89	193
P2	11:55	42.3	5.84	9.60	8.66	6.34	202
P3	12:04	44.5	1.97	10.57	9.81	6.36	207
P4	10:50	42.5	1.45	6.36	7.18	6.17	200
P5	13:52	46.3	2.34	13.95	15.99	13.05	199
P6	12:09	Missing data	2.02	9.99	9.62	9.24	202
P7	12:48	46.5	5.00	7.99	7.79	-	196
P8	11:42	42.7	4.94	11.96	11.99	-	194
P9	11:10	43.8	6.21	12.01	9.36	-	209
P10	14:03	44.7	3.83	10.03	11.07	-	196

Mean oxygen consumption for starting speed (6 km/h) was  $14.4 \pm 4.1$  ml/kg/min and oxygen consumption for final speed of 12 km/h was  $43.9 \pm 0$  ml/kg/min, and only one participant made it this far. For mean oxygen consumption and respiratory exchange ratio for each speed see Table 3.

TABLE 3. Mean ( $\pm$ SD) oxygen consumption ( $\text{VO}_2$ ) and Respiratory Exchange Ratio (RER) for each velocity.

Speed (km/h)	$\text{VO}_2$ (ml/kg/min)	RER
6	$14.4 \pm 4.1$	$0.99 \pm 0.08$
6.5	$25.4 \pm 3.0$	$0.94 \pm 0.07$
7	$31.0 \pm 2.2$	$1.02 \pm 0.07$
7.5	$32.8 \pm 2.1$	$1.08 \pm 0.08$
8	$34.5 \pm 1.8$	$1.16 \pm 0.09$
8.5	$36.5 \pm 1.8$	$1.16 \pm 0.03$
9	$38.7 \pm 1.3$	$1.20 \pm 0.02$
9.5	$40.7 \pm 1.4$	$1.26 \pm 0.03$
10	$42.0 \pm 1.0$	$1.33 \pm 0.04$
10.5	$42.9 \pm 1.2$	$1.37 \pm 0.05$
11	$43.5 \pm 1.9$	$1.37 \pm 0.06$
11.5	$45.8 \pm 1.0$	$1.39 \pm 0.04$
12	$43.9 \pm 0.0$	$1.38 \pm 0.00$

Oxygen consumption followed increase in workload linearly for each participant (see Figure 6), and there was a positive correlation with the mean oxygen consumption and velocity  $r = 0.995$  and  $p < 0.001$ . Respiratory exchange ratio was elevated for most subjects before beginning the voluntary test to exhaustion (see Figure 7) as was pre-test lactate (eight out of ten subjects had  $>2$  pre-lactate values and four out of the eight had  $>5$  pre-lactate values). After settling into the testing RER-values followed a linear increase as the workload increased.

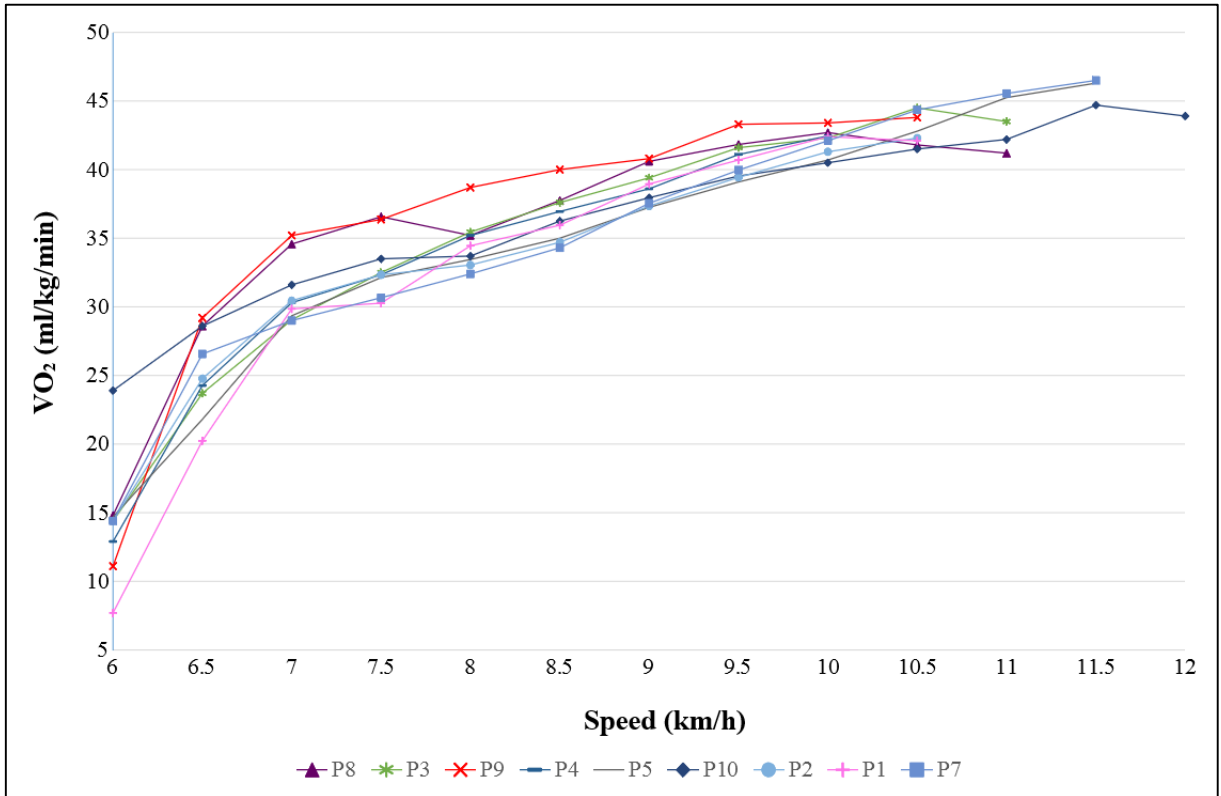


FIGURE 6. The measured oxygen consumption for each individual at each speed.

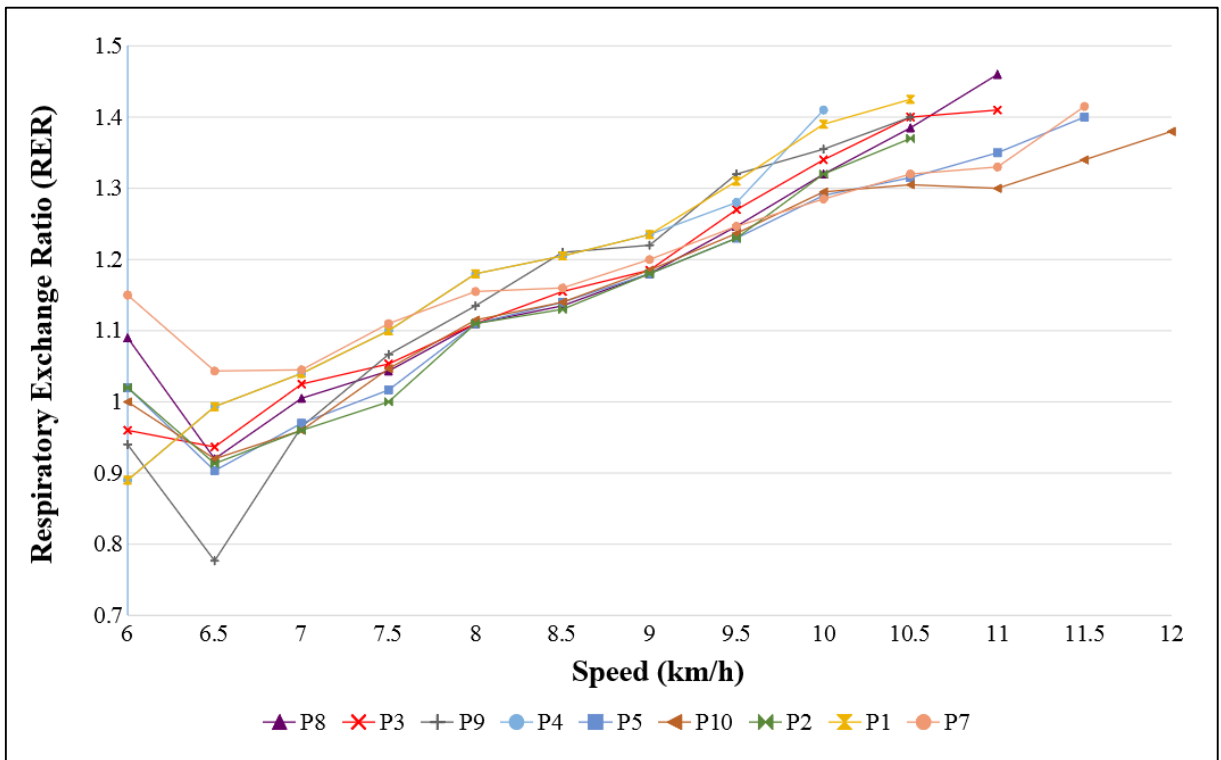


FIGURE 7. Change of Respiratory Exchange Ratio per velocity for each participant (n = 9).

Participants' predicted  $\text{VO}_2$  was equal to  $4.15 + 3.73(\text{velocity})$  ml/kg/min when velocity is measured in km/h. This prediction equation is based on 89 observations from 9 subjects. Participants  $\text{VO}_2$  increased by 1.87 ml/kg/min for each 0.5 km/h increase of velocity. The regression is presented in Figure 8.

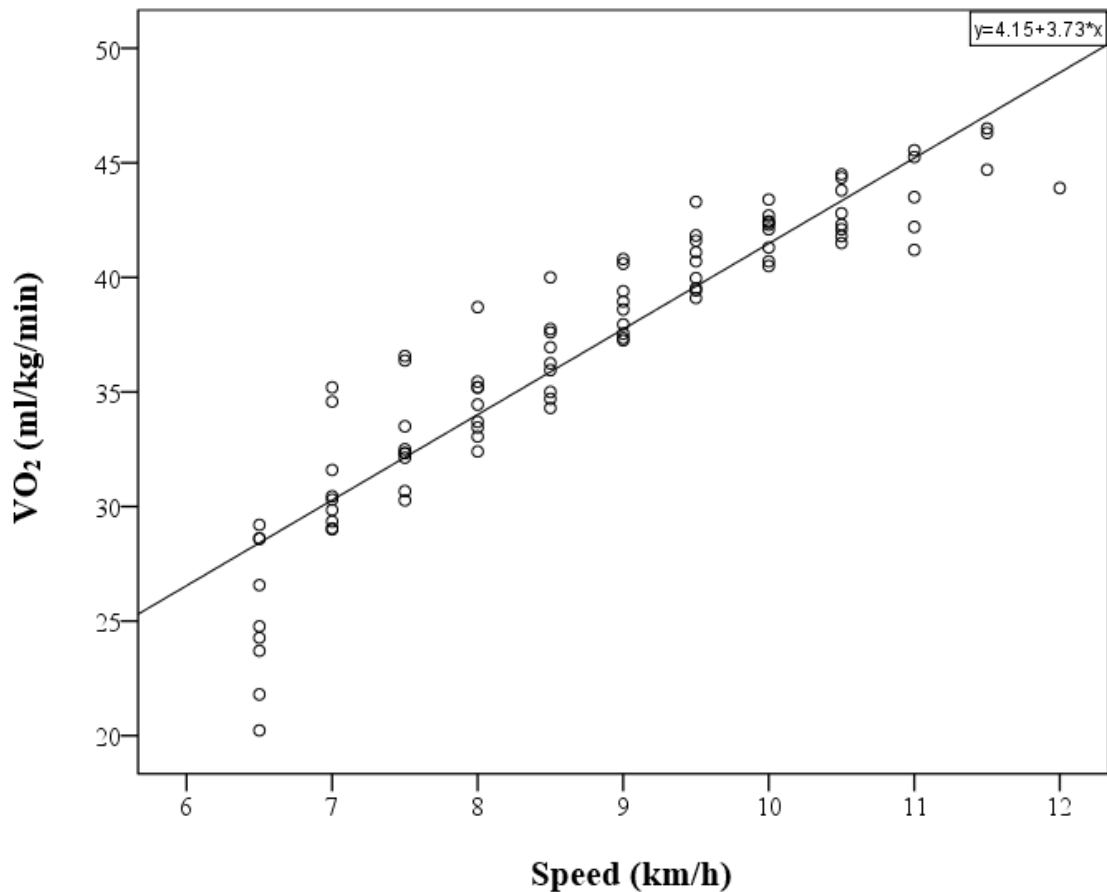


FIGURE 8. Mean  $\text{VO}_2$  for velocities 6.5 km/h – 12 km/h with added regression line. Regression line  $y = 4.15 + 3.73x$ .

Mean respiratory exchange ratio had a positive correlation with velocity,  $r = 0.99$ ,  $p < 0.001$  (See Figure 9). Mean respiratory exchange ratio first raised above 1.00 at the speed of 7 km/h. Highest mean RER values were recorded at 11.5 km/h and were  $1.39 \pm 0.04$ .



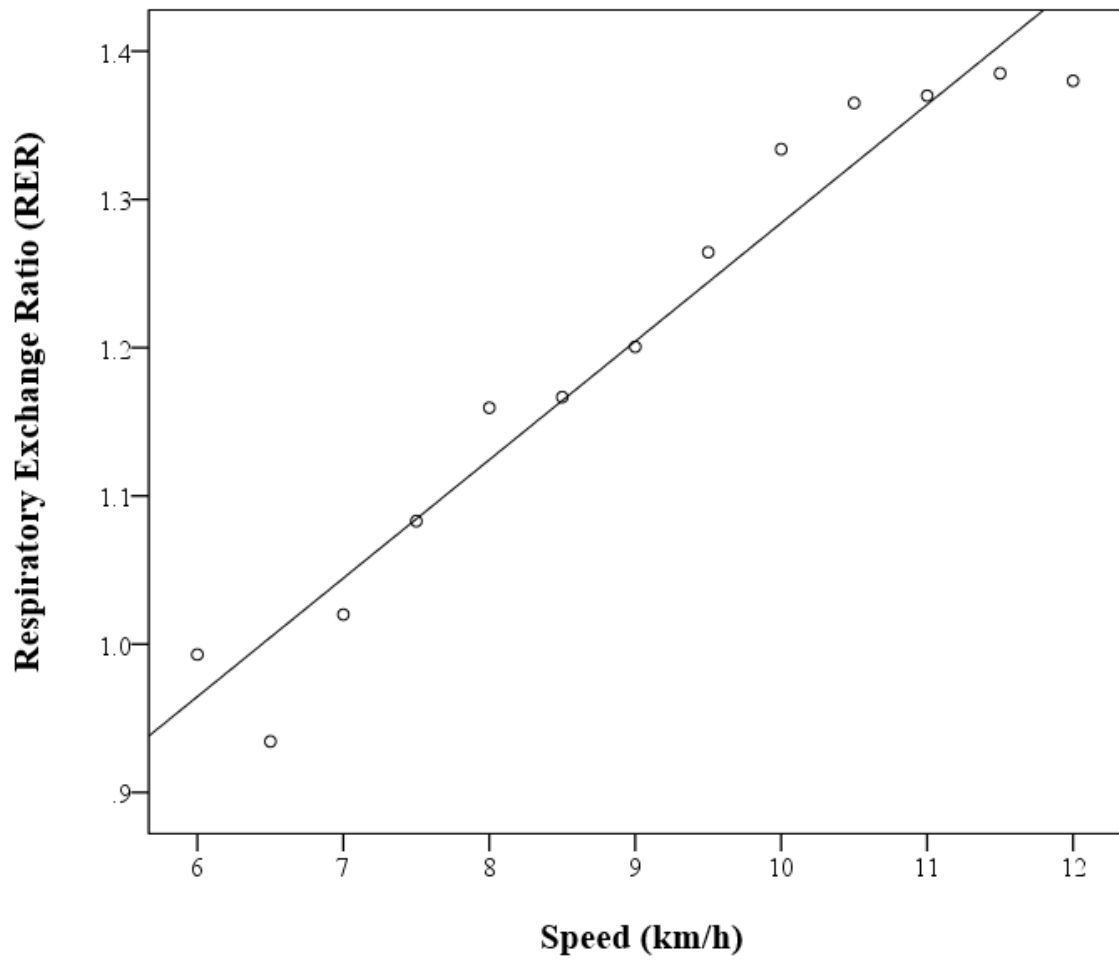


FIGURE 9. Mean respiratory exchange ratio for each velocity with added trend line.

## 10 DISCUSSION

This is the first study to examine cardiovascular fitness in parkour athletes on an obstacle course. The main finding indicated that the pilot protocol was suitable for  $\text{VO}_{2\text{max}}$  testing as validated by the achievement of traditional  $\text{VO}_{2\text{max}}$  criteria. The study deepens the understanding of how movement modality is reflected in energy metabolism, since aerobic capacity is rarely tested in other activities besides running. Previous studies employing different testing protocols, have shown that  $\text{VO}_{2\text{max}}$  is task specific (Buchfuhrer et al. 1983; Hermansen et al. 1970; Holmer et al. 1974; Tanner et al. 2014) and thus it is important to develop testing protocols to suit different tasks. In addition, preliminary norms were obtained for estimating  $\text{VO}_{2\text{max}}$  based on vaulting performance on an obstacle course.

### 10.1 Validity of pilot test for $\text{VO}_{2\text{max}}$ testing

In the pilot test, all subjects reached maximal heart rate and RER values above 1.1. In addition, 8 out of 9 subjects reached post-test lactate values  $\geq 8$ . Furthermore, 8 out of 9 subjects (89%) reached a plateau in oxygen consumption, as defined by a change less than  $\leq 1.5 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ . Meeting these criteria indicates that  $\text{VO}_{2\text{max}}$  was achieved in the pilot test (Docherty et al. 2003; Howley et al. 1995). The appearance of plateau in this high percentage of subjects is uncommon. Froelicher et al. (1974) report as low as 7-33% of tests to voluntary exhaustion ending in a plateau in running when comparing different testing protocols. More recently, Edvardsen et al. (2014) measured 861 subjects to voluntary exhaustion and found out that in only 42% of tests a plateau in oxygen consumption was reached. One explanation for the results of the pilot test could be that in this study a short sampling interval (30s) was used and it might have proved to be beneficial for obtaining  $\text{VO}_2$  plateau as suggested by Astorino et al. (2000). However, according to Beltz et al. (2016) an existence of plateau in oxygen consumption is an inconsistent phenomenon and thus its validity as a  $\text{VO}_{2\text{max}}$  criteria can be questioned.

However, these results should be interpreted with caution. It is unclear whether acidosis from vaulting over the obstacles prevented the subjects from reaching their true capabilities of oxygen consumption. Acidosis has been shown to hinder energy metabolism, by inhibiting

glycolysis and thus resulting in less substrates for oxidative phosphorylation (Dietl et al. 2010; Heisler 2004; Suleymanlar et al. 1992). Increased metabolic acidosis has also been linked to peripheral fatigue, which in turn could also terminate the test before true  $VO_{2max}$  has been reached (Robergs 2001a).

The mean test duration was 12 minutes and 12 seconds, which is approximately within 8-12 minutes as suggested by Buchfuhrer et al. (1983) to be the best length for measuring maximal oxygen uptake. This indicates that the starting speed of 6 km/h suited this set of subjects perfectly. However, a higher starting speed would be more appropriate for subjects that are known to be in good cardiovascular fitness level. It must also be noted that RER values increased rapidly to a level above 1.0. In some subjects this happened already at the second workload (speed 7 km/h). Therefore, to make sure there is an aerobic phase in the testing protocol, a starting speed of 6 km/h is recommended based on these results. Duration for each workload, 1-minute to 1.5-minutes, was within good testing protocol parameters as suggested by Billat and Koralsztein (1996).

The increment for the increase in workload was 0.5km/h which resulted in average  $VO_2$  increase of 1.87 ml/kg/min. This step increment was recommended by Billat and Koralsztein (1996) to obtain good accuracy in determining  $VO_{2max}$  in running. The obtained resolution is very precise indicating that the increment was suitable for vaulting. In contrast, if a very large  $VO_2$  increase would have been found, it could indicate too sharp increase in the workload and therefore imprecise  $VO_{2peak}$  measurement. However, if the increase were smaller than 1.05 ml/kg/min for 0.5 km/h increase in speed, the result could be mistaken for plateau in oxygen consumption, even though the subjects could still increase their oxygen consumption (Taylor 1955).

## **10.2 Oxygen consumption in vaulting**

Analysis of the oxygen consumption-velocity regression indicated that the increase in velocity predicted increase in oxygen consumption. Based on data of the present study the oxygen consumption of vaulting on an obstacle course can be estimated with the following equation:  $VO_2$  (ml/kg/min) = 4.15 + 3.73 x speed (km/h). In contrast, Leger and Mercier (1984) showed

that in running, the oxygen consumption can be estimated with the formula  $VO_2$  (ml/kg/min) =  $2.209 + 3.163 \times \text{speed}$  (km/h). The slope of the increase seems to be similar in vaulting and running. However, the larger constant in the equation of vaulting, indicates that vaulting does indeed require more oxygen than running at the same speed, as was expected. The differences between oxygen consumption of running and vaulting is visually represented in Figure 10.

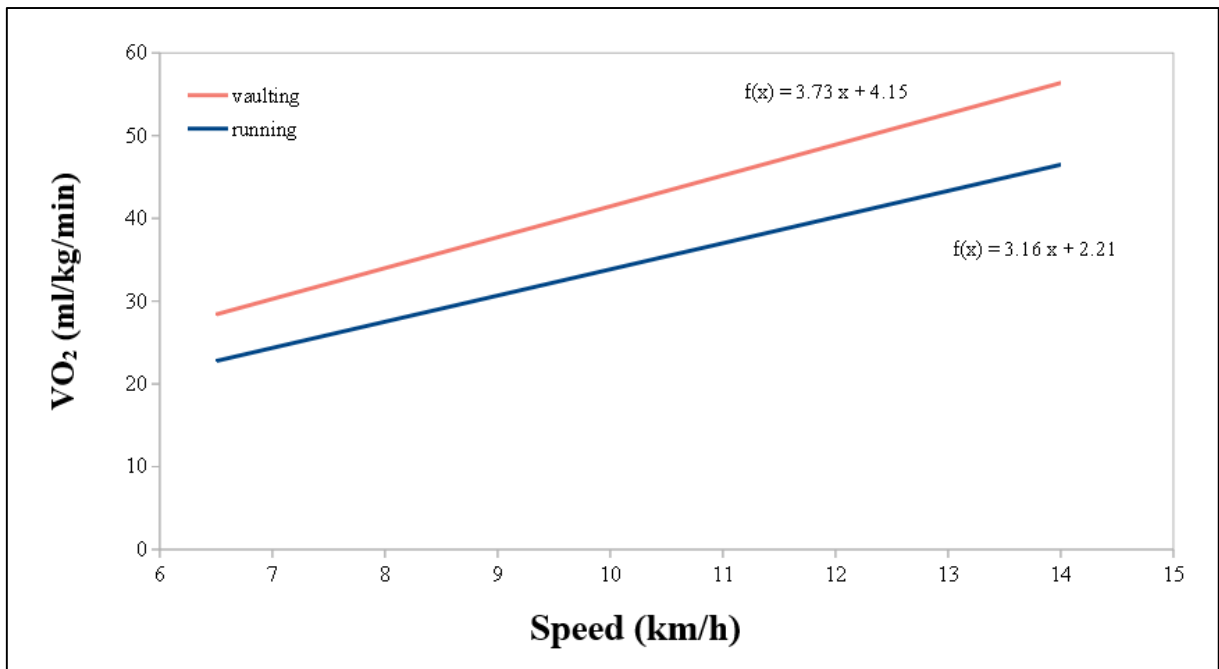


FIGURE 10. The difference between oxygen consumption at varying speed between vaulting and running on a treadmill as presented by regression lines. Regression line for running is based on Leger and Mercier (1984) and regression line for vaulting is based on data from present study.

In practice, oxygen consumption of running is enhanced by additional energy demands from vaulting the obstacles. It is likely that vaulting requires more work to be performed in comparison to just running. Increase in workload results in linearly increased oxygen consumption (Boone & Bourgois 2012). Comparison of oxygen consumption in vaulting to results obtained previously from running (Leger & Mercier 1984) show that the difference remains fairly constant even as the workload increases, which indicates that vaulting has a fixed energy cost that is not affected by speed. However, the energy producing mechanisms of vaulting remain unclear, as anaerobic energy metabolism was not directly measured in this

study. This study aimed to develop means to assess  $VO_{2peak}$  in field environment and thus was not suited for anaerobic power assessment. In the future, energy demands of vaulting should be assessed separately. Data from present study seems to indicate a large demand for anaerobic energy production. This is demonstrated by high ending lactates and more importantly quick rise of RER values to above 1.0 (the mean RER is higher than 1.0 at speed 7.0 km/h). RER values above 1.0 indicate that energy is being produced anaerobically (Issekutz et al. 1962).

Further comparison to 20m shuttle-run test support the notion that vaulting requires more oxygen than running at similar speeds. Leger et al. (1988) lists estimated  $VO_{2max}$  values for each individual speed obtained from 20m shuttle-run test (Table 4). Comparison to 20m shuttle-run test is meaningful as the field test protocol is very similar to one used in this study, the main difference coming from the modality of movement (vaulting over obstacles versus running).

TABLE 4. Predicted  $VO_{2max}$  for 20m shuttle-run test derived from Leger et al. (1988) and mean oxygen consumption for vaulting for each individual speed. Difference is calculated between vaulting  $VO_2$  and 20m shuttle-run  $VO_{2max}$ .

Speed (km/h)	20m shuttle-run $VO_{2max}$	Vaulting $VO_2$	Difference
8.5	23.60	36.50	12.90
9	26.60	38.72	12.12
9.5	29.60	40.73	11.13
10	32.60	41.98	9.38
10.5	35.60	42.89	7.29
11	38.60	43.54	4.94
11.5	41.60	45.83	4.23

Individual variation in measured oxygen consumption in vaulting, as expressed by standard deviation, is relatively small between the subjects. When individual regression lines were inspected, oxygen consumption increased linearly with the increases in workload for all subjects. This finding indicates that an averaged regression line between  $VO_2$  and speed represent data from individual subjects quite well.

### 10.3 Strengths and limitations

This study demonstrated that  $VO_{2peak}$  can be measured in Parkour. The designed testing protocol produced seemingly valid measurement of individual subjects  $VO_{2peak}$  and the obtained data allowed the synthesis of regression line. This regression line allows for estimation of  $VO_{2max}$  in parkour athletes, without the need of laboratory testing equipment or expensive measuring devices. However, this should be approached with caution, since the pilot test and subsequent regression line suffers from small sample size. In addition, the obtained  $VO_{2peak}$  was not confirmed with a verification phase nor was a comparison done with results from different testing protocols. In the future, to combat these limitations, a verification phase could be done in addition to the pilot protocol. Verification phase could be similar to what is commonly done in running tests (for review see Beltz et al. 2016). In practice, this would mean going through the obstacle course at a supramaximal speed, as determined from the initial testing protocol, and comparing the obtained  $VO_2$ -values to the  $VO_{2peak}$  obtained from the final workload from the initial protocol. In addition, a direct comparison between another  $VO_{2max}$  testing protocol and this pilot protocol should be done. This kind of comparison would result in greater understanding of how the energy demands vary in parkour compared to running.

The study was also limited to measuring oxygen consumption. To better understand the energy demands of vaulting, a testing protocol that takes into account anaerobic energy production should be designed.

In future, the pilot protocol needs to go through series of scrutiny. This involves, doing the test for a large population of parkour athletes and more direct comparisons to other testing protocols. Furthermore, to ensure the reliability of the protocol, the same test should be repeated with same individuals on different occasions. Also differences between individual subjects could be illustrated for example by analyzing their economy of vaulting or conducting maximal anaerobic power test. It is possible that the economy and efficiency of vaulting varies greatly between subjects and therefore, the obtained velocity in the pilot protocol could be affected by other factors than  $VO_{2max}$ .

Due to being part of a bigger research project, the subjects did not start the pilot protocol totally recovered. Prior to pilot protocol the subjects completed three maximal speed runs through the obstacle course, after which the subjects had 15 minutes of rest before starting the pilot protocol. Subjects showed signs of insufficient recovery before testing, as demonstrated by elevated resting lactate and RER-values. However, as the testing started the oxygen consumption stabilized to a steady-state and RER-values dropped to aerobic range. Due to these factors, it can be concluded that the prior exhaustion did not play a major role in the results of the  $\text{VO}_{2\text{max}}$  test.

The pilot protocol was planned in detail based on previous literature and ethical considerations. The testing was conducted with high safety standards, which guided subject recruitment and obstacle course design. For example, only experienced athletes were recruited to minimize hazardous accidents during testing. In addition, the athletes were briefed thoroughly and they had time to practice on the obstacle course prior to testing.

#### **10.4 Conclusion and practical implications**

The study showed that oxygen consumption can be measured in a field test with parkour movement. However, the oxygen consumption captures only one aspect of energy demands in parkour movement while anaerobic energy production and its contribution to parkour performance remains unclear. The protocol used in this thesis describes a very simple parkour movement (vaulting or going over obstacles), future protocols should aim to incorporate climbing, jumping, change of direction and other unique movements typical to parkour. Doing this would grant a better approximation what energy metabolism is actually like during bouts of parkour practice.

The subjects in this thesis were recruited from all over Europe, therefore representing athletes from various training cultures. Surprisingly, there was not much individual variation in oxygen consumption. Overall the athletes in this study portrayed mediocre to good cardiovascular fitness and they were not in excellent endurance shape as could have been expected based on a long training history in parkour. The subjects had at least 5 years of parkour experience and in

this case their practice had not made them elite endurance athletes. Therefore, if the aim for parkour athlete is to improve physical performance in all its aspects, it can be suggested that practitioners should train cardiovascular fitness separately from regular training. Regular parkour training does not seem to induce endurance adaptations beyond a certain point. However, all subjects were highly motivated and achieved exhaustion in the pilot testing. This could indicate familiarity with training until exhaustion.

To further enhance the understanding on limiting factors in parkour movement, a new testing protocols needs to be developed. New protocols should take into consideration lactate measurements during the testing phases and observe at lower speeds whether a steady state of oxygen consumption is actually achieved. It is possible that even at low speeds, going over obstacles causes anaerobic energy metabolism which could result in inability to sustain even low speeds for long durations.

In summary, the achievement of  $VO_{2max}$  criteria indicates that the field test protocol is well suited for assessing cardiovascular fitness. The linear increase in oxygen consumption with increasing velocity, suggests that the achieved final speed could be used to estimate oxygen consumption in parkour field test. The observation that oxygen consumption was high for any given speed, indicates that vaulting requires more oxygen than what is usually observed in running at similar speeds. Results also indicate a large demand for anaerobic energy production in vaulting, even at low speeds



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