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BIOMECHANICAL CORRELATION BETWEEN LINEAR AND CYCLIC MOVEMENT PATTERNS  
OF THE LOWER LIMBS IN ELITE **BMX** ATHLETES

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## ABSTRACT

Maximal power depends on two parameters: force and velocity. The relation between the two parameters, also known as the force-velocity relationship, has been studied in linear as well as cyclic movement patterns. In both types of motion similar linear regressions were reported. To date, the correlation between the force-velocity relationships of linear and cyclic movements remains unknown. The aim of this study is to describe this correlation and to identify power parameters of the force-velocity relationships that favour sprint and start performances on a BMX bike. Thirteen junior and elite BMX athletes performed squat jumps in five loading conditions, five BMX starts on a supercross ramp and three 30-meter maximal BMX sprints on level ground. Using data from a force plate and on-bike powermeters, individual force-velocity profiles for each test were generated. Theoretical maximal force ( $F_0$ ) and torque ( $T_0$ ), velocity ( $v_0$ ) and cadence ( $Cad_0$ ), cycling power ( $cP_{max}$ ) and jumping power ( $jP_{max}$ ), as well as slope ( $S_{F-v}$  and  $S_{T-Cad}$ ) were determined from the force-velocity relationships. The correlation between the force-velocity parameters of the squat jump test and the two other BMX tests, as well as their relation to the sprint and start performances, were calculated. Squat jump  $P_{max}$  and  $F_0$  were related to sprint and start  $cP_{max}$  and  $T_0$  ( $p \leq 0.01$ ), suggesting a positive transfer from a simple linear movement onto a complex, sport-specific cyclic movement. In Addition,  $F_0$  and  $jP_{max}$  correlated with mean start and sprint power and start and sprint time ( $p \leq 0.05$ ) and therefore proved to be good indicators of sprint performance, but more importantly competition-specific start performance. These findings have major implications for coaches and athletes regarding the design of training plans.

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## LIST OF ABBREVIATIONS

|                   |   |
|-------------------|---|
| BM                | Body mass   |
| $Cad_0$           | Theoretical maximal cadence                               |
| $cP_{max}$        | Theoretical maximal cycling power                         |
| CV                | Coefficient of variation                                  |
| $F_0$             | Theoretical maximal force                                 |
| F-v               | Force – velocity  |
| FP                | Force plate   |
| ICC               | Interclass correlation coefficient                        |
| $jP_{max}$        | Theoretical maximal jumping power                         |
| LPT               | Linear position transducer                                |
| P-v               | Power – velocity  |
| $P_{mean\ 30}$    | Average power output over 30 m BMX sprint on level ground |
| $P_{mean\ start}$ | Average power output of a BMX start                       |
| $r$               | Correlation coefficient                                   |
| $r^2$             | Coefficient of determination                              |
| rpm               | round per minute  |
| SD                | Standard deviation  |
| $S_{F-v}$         | Slope of the force – velocity curve                       |
| SJ                | Squat jump  |
| $S_{T-Cad}$       | Slope of the torque – cadence curve                       |
| $T_0$             | Theoretical maximal torque                                |
| T-Cad             | Torque – cadence  |
| $v_0$             | Theoretical maximal velocity                              |
| $v_{mean\ 30}$    | Average speed over 30 m BMX sprint on level ground        |
| $v_{mean\ start}$ | Average speed of a BMX start                              |

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## 1. Introduction

Muscular power is a major determinant of performance in many sports. It is the ability to accelerate a system as much as possible in the shortest possible time. The underlying parameters of power output are (i) the capability of the neuromuscular and osteoarticular systems to generate high force level and (ii) the capacity to do it at a high contraction velocity. These two are however not unrelated, and thus, the force-velocity (F-v) relationship describes neuromuscular capacity of generating power.

Many researchers have described this relationship choosing different approaches. Some analysed single muscles *in vitro* (Fenn & Marsh, 1935; Hill, 1938) while others described single joint movements (Perrine & Edgerton, 1978; Rahmani et al., 1999; Wickiewicz et al., 1984) or functional movements (Gardner et al., 2007; Hautier et al., 1996; Meylan et al., 2015; Rahmani et al., 2001; Samozino et al., 2012; Vandewalle et al., 1987). Most studies showed a strong curvilinear or linear F-v relationship. In addition, similar F-v relationships were found resulting from cycle ergometer sprints and squat jump tests. However, to the best of our knowledge, there is no study in literature that describes the relation between linear and cyclic movement F-v profiles. Nonetheless, such information could help coaches better understand the relationship between off-bike training exercises and on-bike performance in BMX or sprint cycling.

Therefore, the objective of this work is to analyse the correlations between the parameters of the F-v profiles of linear and cyclic movement patterns. By performing a squat jump test, a BMX sprint test on level ground and a start test on a BMX supercross ramp, the participant's three individual F-v profiles are generated. The parameters of the F-v profiles are then extracted and compared in order to find any correlations. Performance time in the sprint and start tests are also recorded in an attempt to identify specific parameters of the squat jump test, which can favour BMX performance.

An extensive literature review will set the context of this present research and explain the significance of the F-v profile assessment. Then, a pilot study will test the reliability of two measurement systems and evaluate the protocol ahead of the main study. The BMX study will follow a standard structure. The goals and research questions of the study will be presented first followed by the methods and results.

The discussion will put the obtained result in context and present the limitations of the study. Finally, the conclusion will address the practical implications of our findings and suggest possible future work.

## 2. Review of literature

### 2.1. In vitro animal muscle

The first to study this force-velocity relationship were Fenn and Marsh in 1935. They discovered an exponential force-velocity relationship in isolated frog and cat gastrocnemius muscles in isotonic shortening conditions (Fenn & Marsh, 1935). Three years later Hill (1938) published a similar experiment on an isolated frog muscle, in which he describes the force-velocity relationship as hyperbolic (Figure 1). That means that the rate of change of force increases or decreases with changing velocity. At low velocity, a small increase in speed results in a large decrease of force. At high velocity, this same small increase in speed results in a very small decrease of force. This hyperbolic force-velocity relationship characterizes the relationship of force production and contractile velocity of a single isolated *in vitro* muscle while shortening. However, it does not necessarily explain the force-velocity relationship of a functional movement.

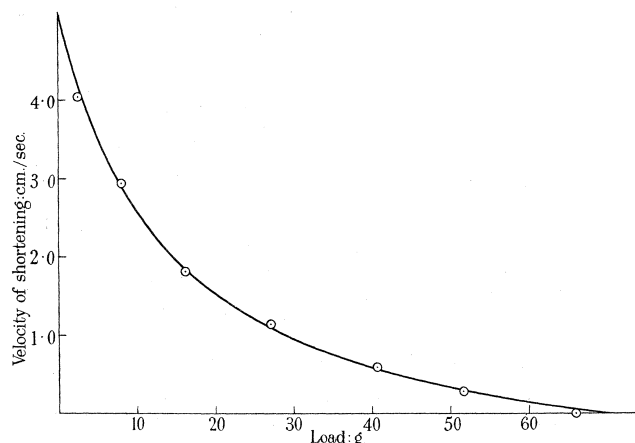


Fig. 1 : Relation between load and speed of shortening in isotonic frog muscle contraction (Hill, 1938)

### 2.2. In vivo human muscle

#### 2.2.1. Single joint movement

Studies on single joint movements have come to contrasting conclusions. Some research indicates similarities with Hill's results (Perrine & Edgerton, 1978; Wickiewicz et al., 1984), while others discovered a linear relationship between force and velocity (Rahmani et al., 1999).

Perrin & Edgerton's (1978) experimental design was as follows: fifteen participants performed knee extensions with various angular velocities on an isokinetic dynamometer (Cybex II). By using the isokinetic device, it was possible to register the torque production of a muscle group at any desired velocity. Thus, with this device, velocity of muscle shortening is the controlled variable, whereas in normal muscle strength testing, velocity is the consequence of load. Seven angular

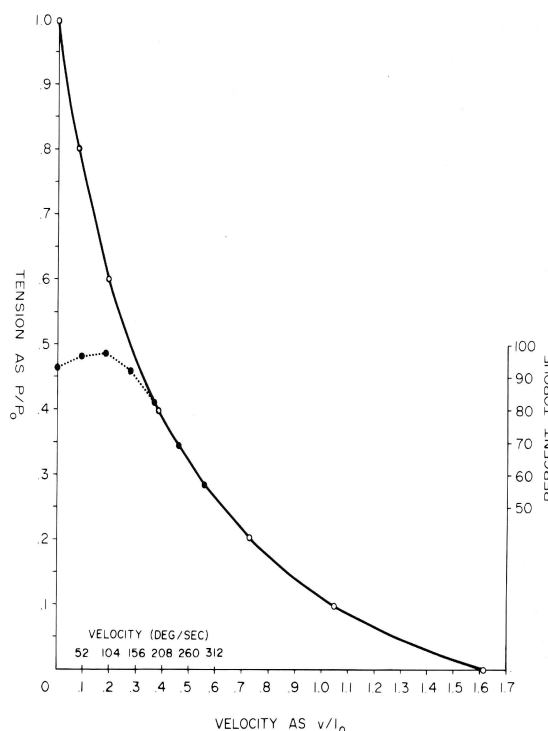


Fig. 2 : Experimental force-velocity relationship of isolated frog muscle (Hill, 1938) and in vivo human muscles (Perrine & Edgerton, 1978) as determined in two separate experiments.

velocities were tested. The results were similar to Hill's hyperbolic single isolated muscle curve except for the lower velocities (Figure 2). While the *in vivo* muscle relationship follows a hyperbolic shape over the three highest velocities ( $192^{\circ}\cdot\text{sec}^{-1}$  to  $288^{\circ}\cdot\text{sec}^{-1}$ ), it clearly departs from that curve at  $192^{\circ}\cdot\text{sec}^{-1}$  and shows a decreasing rate of rise in force as velocities lowers.

Wickiewicz et al. (1984) found very similar results with twelve subjects performing knee extensions, knee flexions, ankle plantarflexions and ankle dorsiflexions on a isokinetic dynamometer (Cybex II). They also noted lower torque values than what would be predicted by the Hill's hyperbolic curve at low velocities (Figure

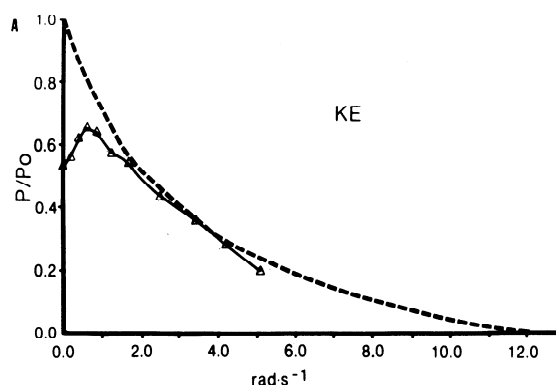


Fig. 3 : Normalized torque-velocity curve for knee extensors fitted to Hill's hyperbolic curve (Wickiewicz et al., 1984).

3). A possible explanation proposed by

the authors for this difference in results at lower velocities may be a neural regulatory mechanism. This neural mechanism would be restricting the maximal voluntary concentric force production to a maximum safe tension level of the *in vivo* muscle. This idea is supported by the fact that eccentric contractions obtain fairly higher

tension levels than maximal voluntary concentric tensions. So, at low velocities and high forces, there might be a functional maximum-tension limiting mechanism, which would explain the biphasic force-velocity relationship (Perrine & Edgerton, 1978; Wickiewicz et al., 1984).

In contrast to the two mentioned studies, Rahmani et al. (1999) discovered a linear relationship between force and velocity in a single joint movement (Figure 4). In their study, they tested 20 healthy elderly men on a series of maximal ballistic knee extensions at different loads. They used an inverse dynamic method allowing force and velocity to be deduced from the load displacement. This method has the advantage of allowing ballistic movements, which are closer to everyday life than isokinetic movements,

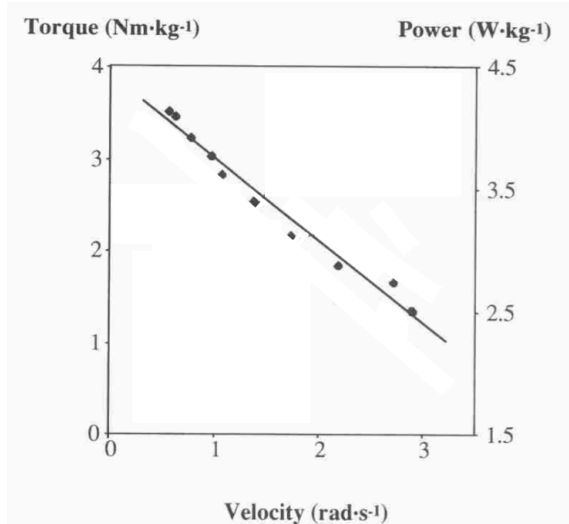


Fig. 4 : Average torque and average power developed during leg extension exercises plotted against the average velocity (Rahmani et al., 1999).

according to the authors. Their results showed a strong linear relationship for every subject ( $r = 0.92 - 0.99$ ,  $p < 0.001$ ). The lower force and higher velocity portion of the curves shows similarities with the previously describes biphasic curve, however the high force and low velocity portion does not. It is unclear if this discrepancy in the lower velocity part of the curve is due to the measuring method used or the protocol itself. Although isokinetic contraction of the leg extender muscle has a strong correlation with ballistic types of muscle activation, from a functional point of view, isokinetic movements represent an unnatural muscular activity (Bosco et al., 1983). This might be a possible explanation for this force-velocity disparity.

### 2.2.2. Multi-joint movement

Since pluriarticular movements are more important in many aspects than single joint movements, evaluation of their muscular dynamic properties seems only logical. Many studies have been conducted on the force-velocity relationship in multi-joint movements. To allow a better overview, it may be useful to structure the work

accomplished so far into two separate sections: one section focusing on linear multi-joint movement and the other on a cyclic movement pattern.

### **2.3. Linear movements**

Linear movements of the lower limbs have been studied using different methods. Some researchers favoured a horizontal testing method (Meylan et al., 2015; Samozino et al., 2012; Yamauchi & Ishii, 2007) while others investigated vertical squatting or jumping (Bosco et al., 1995; Giroux et al., 2015b; Rahmani et al., 2001).

#### **2.3.1. Horizontal push-offs**

In order to understand the impact of maximal average power and F-v relationship on the performance of the leg extension neuromuscular system, Samozino et al. (2012) used a theoretical integrative approach. According to these authors, “jumping performance can be expressed as a function of some mechanical characteristics of the lower limbs” (Samozino et al., 2012). These mechanical characteristics are theoretical maximal force ( $F_0$ ) and theoretical maximal velocity ( $v_0$ ) extrapolated from the force-velocity relationship and theoretical maximal jumping power ( $jP_{max}$ ) being the apex of the power-velocity 2<sup>nd</sup>-degree polynomial relationship. In their study, they predicted theoretical performance and compared this with measured experimental performance. An Explosive Ergometer, consisting of a seat fixed on a carriage, which is free to move on a rail, was used. This apparatus can be inclined to a maximal angle of 30°. At the bottom of the ergometer, two force plates (FP) were fixed perpendicularly to the rail. The participants would accelerate themselves and the sled by pushing onto the FP. An electric motor was used to impose certain resistive forces onto the sled. These braking forces varied between 0% and 240% of the participants body mass (BM). Fourteen young athletic subjects took part in the experiment. All participants practiced physical activities including explosive movements. The participants were seated and strapped on the carriage seat. Starting position was set at 90° knee angle and the participants were instructed to perform maximal push-offs. Two trials were performed at each braking force separated by two minutes of recovery. The best trial of each braking force condition was used to determine average force, velocity and power during the entire push-off phase. These values



were then used to construct the F-v and P-v relationship for each participant in order to determine  $F_0$ ,  $v_0$  and  $jP_{\max}$ . The collected data from the inclined push-offs were then used to compare to the predicted ones in order to validate the theoretical integrative approach. The results showed a linear fit of the F-v relationship ( $r^2 = 0.75\text{--}0.99$ ,  $p \leq 0.012$ ) which is in agreement with the aforementioned ballistic knee extension study (Rahmani et al., 1999). There was no significant difference between the theoretical predicted values and the measured values and the theoretical approach was therefore validated. The F-v relationship has usually been described as exponential or hyperbolic for isolated muscle (Fenn & Marsh, 1935; Hill, 1938), but in mono- and pluriarticular movements the F-v relationship, and thereby  $F_0$ ,  $v_0$  and  $jP_{\max}$ , refers to an entire *in vivo* neuromuscular system. This is a complex system consisting of many different muscles with different fibre types, architectural characteristics, tendon properties and also different neuronal activation abilities (Cormie et al., 2011). This may explain the different F-v curve in isolated and *in vivo* muscle.

Yamauchi & Ishii (2007) have shown that  $jP_{\max}$  is the greatest muscular characteristic to affect push-off performance, but it has been demonstrated that it isn't the only one. Indeed, Rahmani et al. (1999) showed that two participants with the same  $jP_{\max}$ , don't necessarily attain the same push-off performance. Their respective F-v profiles play an important role especially the slope of the F-v curves ( $S_{F-v}$ ).  $S_{F-v}$  is the ratio between  $F_0$  and  $v_0$ . Samozino et al. (2012) found that for each subject, there is an optimal F-v profile. The greater the difference between the optimal F-v profile and the real one, the lower the performance will be. Differences ranging from 36 to 104% have been reported between individual F-v profiles and optimal ones. Unfavourable F-v profile can make up to 30% in push-off performance between participants with similar  $jP_{\max}$ . This shows the importance of F-v profile assessment, not only for scientists who are studying muscle function and its' characteristics, but also for coaches who are monitoring athletes' training.

Yamauchi and Ishii (2007) and Meylan et al. (2015) used a very similar approach to construct individual F-v profiles. They also used horizontal ballistic push-offs against different loads or braking forces on a sled: Yamauchi & Ishii (2007) with the purpose of comparing the different F-v parameters to vertical jump performance, and Meylan et al. (2015) in order to quantify the reliability of F-v and P-v profiles and estimate

maximal strength expressed as a one repetition maximum (1RM). In Yamauchi & Ishii's (2007) study, 67 untrained young subjects performed ballistic push-offs with various loading, maximum isometric measurements, and vertical countermovement jumps. The ballistic push-offs resulted in linear and parabolic relationships for F-v and P-v, respectively, which are in line with previous results (Samozino et al., 2012). Furthermore, the maximum isometric force was not significantly different from  $F_0$ . This shows that  $F_0$  can be associated with maximal isometric force performance (Cormie et al., 2011; Yamauchi & Ishii, 2007). By comparing F-v parameters to vertical jump performance, a positive correlation was found for  $F_0$ ,  $v_0$  and  $jP_{\max}$  ( $r = 0.48, 0.68$ , and  $0.76$ ;  $p < 0.001$ ). Although there is a strong correlation between  $jP_{\max}$  and vertical jump performance, it is not possible to predict  $jP_{\max}$  from vertical jump height with enough accuracy. This is due to the fact that the optimal load at which  $jP_{\max}$  is attained during the push-off is not equal to the body weight during vertical jumps (Yamauchi & Ishii, 2007).

In their study with 36 youth males Meylan et al. (2015) also employed ballistic push-offs against various loads (80 - 160% BM) on three separated occasions using a horizontal leg press. Instead of using two FP like in other studies (Samozino et al., 2012; Yamauchi & Ishii, 2007), they used a linear position transducer. The results showed a linear F-v relationship ( $r^2 = 0.90$ ), which is in accordance with the aforementioned research (Samozino et al., 2012; Yamauchi & Ishii, 2007). A much stronger reliability of the F-v parameters was found between sessions 2-3 compared to sessions 1-2. This variability is due to a learning effect and it is recommended to conduct a familiarization session prior to the testing in order to confidently assess athletes' F-v profiles. It was also confirmed that the 1RM prediction method by Jidovtseff (2011) based on the load-velocity profile is a reliable method to assess maximal strength. This method predicts 1RM at  $0.23 \text{ m}\cdot\text{s}^{-1}$  on the individual load-velocity curve and "could be a preferred method to determine maximal strength in untrained or youth athletes" (Meylan et al., 2015).

Overall, the studies that analysed the characteristics of the F-v relationship in horizontal pluriarticular ballistic movements showed a strong linear relation between force and velocity, as well as a strong parabolic relation between power and velocity. The testing method was revealed to be reliable for assessing F-v profiles, although a familiarization trial is recommended for untrained people. Furthermore, this horizontal

testing method has the advantage of assessing neuromuscular characteristics with resistance which is greater or less than body mass, and allows a population with poor squatting or landing skills to avoid any overloading of the spine (Faigenbaum et al., 2009). However horizontally performed push-offs are unusual movements; therefore, vertical squatting would represent a more functional movement.

### 2.3.2. Vertical jumps

Many researchers choose squatting to study mechanical behaviour of the lower limb muscles, because it is a basic and widely used training exercise among athletes. Several works concentrated on the F-v relationship in vertical squat jumps (Bosco et al., 1995; Cuk et al., 2014; Giroux et al., 2015a, 2015b; Rahmani et al., 2001; Samozino et al., 2014). Most of them performed the squat jump (SJ) with additional loads on their shoulder over a force plate (Bosco et al., 1995; Rahmani et al., 2001; Samozino et al., 2014) or with a pulley device, which simulated an increase or decrease in body weight (Cuk et al., 2014).

Rahmani et al. (2001) studied the F-v and P-v relationships from loaded SJ performed with a guided barbell over a FP. Fifteen international alpine ski racers took part in the study. The loading conditions ranged from 60 – 180 kg with an increment of 20 kg. In addition to the loaded dynamic tests, the participants also performed maximal isometric contractions at a knee angle of 90°. The results showed a strong linear relationship between force and velocity for each individual ( $r^2 = 0.83 - 0.98$ ). These findings are in line with the F-v relationship from horizontal push-off movements (Meylan et al., 2015; Samozino et al., 2012; Yamauchi & Ishii, 2007) but also with other vertical SJ studies using a larger range of loads (Bosco et al., 1995) or lighter loads (Samozino et al., 2014). Researchers (Giroux et al., 2015a; Samozino et al., 2014) using a simple computation method proposed by Samozino et al. (2008) in which  $F_0$ ,  $v_0$  and  $jP_{\max}$  are computed from SJ height, push-off distance and body mass, have found the same linear correlation between force and velocity ( $r^2 = 0.83 - 1.00$ ). This was also the case for Cuk et al. (2014) with their method of measuring SJ with positive and negative loading. They used a pulley device, which simulated either an increase or decrease in bodyweight up to 30%. Their result showed a strong linear F-v relationship in addition to high reliability indices for  $F_0$ ,  $v_0$ ,  $jP_{\max}$  and  $S_{F-v}$

(ICC = 0.80 – 0.98). This suggests that negative loading doesn't affect the F-v profile and could therefore be used with untrained subjects or rehabilitating athletes.

In contrast to other studies (Cormie et al., 2011; Yamauchi & Ishii, 2007), the results of Rahmani et al. (2001) showed that the  $F_0$  extracted from the F-v curve, couldn't be associated with the maximal isometric contraction. Indeed,  $F_0$  was 23% higher than the measured isometric contractions. This overestimation is partly attributed to the position of the subject. Isometric contractions were performed at 90° knee angle, whereas in dynamic contractions, the knee angle range from 90 to 180° with a maximal force production at 110°. It is therefore hypothesised that isometric contractions performed at 110° are more likely to give a closer result to  $F_0$ .

$S_{F-v}$  is an important parameter of the F-v relationship, because it has a great influence on the jump performance (Samozino et al., 2012). The results of Rahmani et al. (2001) exhibit a major variability between participants (CV% = 25.8%) for the  $S_{F-v}$ . This might be surprising in such a homogenous group of athletes, but since  $S_{F-v}$  is the ratio of  $F_0$  and  $v_0$ , a small variability in those two parameters results in a major variability of the  $S_{F-v}$ . Other research on the significance of the  $S_{F-v}$  parameter in squat jump showed that the slope of the F-v curve varies greatly from one sport to another due probably to the specific adaptations from chronic sport practice (Giroux et al., 2015a).

The research of Samozino et al. (Samozino et al., 2014) using the computation method based on jump height, BM and push-off distance, confirmed their earlier findings (Samozino et al., 2012) that not only  $jP_{max}$  but also  $S_{F-v}$  had an impact on jump performance. This time, the subjects performed vertical squat jumps with additional load (0, 25, 50 and 75% of BM). To quantify the impact of  $S_{F-v}$  on performance, the individual F-v imbalance was computed from actual and optimal F-v profiles. An average performance loss of  $6.49 \pm 6.25\%$  was reported due to the individual F-v imbalance. These results are in line with the aforementioned findings from Samozino et al. (2012). In addition, the results again showed a strong and linear relationship between force and velocity ( $r^2 = 0.87-1.00$ ;  $p \leq 0.05$ ). Moreover, the results supported what has been previously demonstrated (Samozino et al., 2012; Yamauchi & Ishii, 2007) that  $jP_{max}$  was significantly related to jump performance ( $r^2 = 0.78$ ;  $p \leq 0.001$ ). This was also found by Bosco et al. (Bosco et al., 1995) who compared F-v and P-v relationships to jump and sprint performance.  $jP_{max}$  correlated

with SJ and countermovement jump performance (SJ:  $r^2 = 0.80$ ;  $p \leq 0.01$ , CMJ:  $r^2 = 0.80$ ;  $p \leq 0.01$ ).

Overall, the studies assessing F-v relationship and P-v relationship in vertical multi-joint ballistic movement showed, despite different research methods, similar results to the above-mentioned single joint and horizontal multi-joint movement studies. A clear linear F-v relationship was reported and the importance of  $jP_{\max}$  and  $S_{F-v}$  was reinforced. Ballistic jump squat is therefore a valid and reliable exercise to evaluate individual F-v and P-v relationship.

## **2.4. Cyclic movement**

The muscle F-v relationship demonstrated in linear movement patterns was also studied in cyclic movement patterns (Bertucci & Hourde, 2011; Bertucci et al., 2007; Bertucci et al., 2005; Debraux & Bertucci, 2011b; Dorel et al., 2005; Driss et al., 1998; Gardner et al., 2007; Hautier et al., 1996; Martin et al., 1997; Sargeant et al., 1981; Seck et al., 1995; Vandewalle et al., 1987). The force-velocity test as its name suggests, was commonly used to assess the relationship between torque and pedalling cadence. The test consists of one or multiple short, all-out sprints against a resistance, which allows subjects to produce maximal torque while accelerating through a full range of cadences in approximately 6 seconds. It enables the description of the torque-cadence (T-Cad) and the power-cadence (P-Cad) relationships and the assessment of its components ( $T_0$ ,  $Cad_0$ ,  $S_{T-Cad}$ ,  $Cad_{opt}$  and  $cP_{\max}$ ).  $T_0$  and  $Cad_0$  are the theoretical maximal torque and cadence and  $Cad_{opt}$  is the optimal cadence at which maximal cycling power ( $cP_{\max}$ ) is obtained.

Several methods were used to perform the force-velocity test. One of them uses a friction braked ergometer, where different resistive loads are applied onto the flywheel (Arsac et al., 1996; Bertucci et al., 2007; Driss et al., 1998; Hautier et al., 1996; Vandewalle et al., 1987). This method uses standard equipment, but does not account for the flywheel acceleration and therefore may underestimate maximal power (Lakomy, 1986). Furthermore, it requires participants to perform multiple sprints. The isokinetic method on the other hand, controls pedalling rate and measures the force applied on the pedals (Sargeant et al., 1981). It generates valid measurement of instantaneous average and maximal power but also requires

multiple sprints at different pedalling rate and necessitates highly modified equipment (Martin et al., 1997). Then, there is the method using both friction resistance and flywheel inertia, which allows maximal power measurement in a single sprint, but requires important ergometer modification and doesn't measure instantaneous power (Seck et al., 1995). Finally, the inertial-load method uses only the resistance provided by the moment of inertia of the flywheel. By adding an intermediate gear drive onto the ergometer between the crank and the flywheel, gear-ratio is increased (Driss & Vandewalle, 2013). This method allows measurement of instantaneous and average power and produces valid measure of maximal power in only one single sprint (Gardner et al., 2007; Martin et al., 1997).

Strong linear T-Cad relationships haven been found in numerous studies (Bertucci et al., 2005; Dorel et al., 2005; Gardner et al., 2007; Sargeant et al., 1981; Vandewalle et al., 1987) and is nowadays well accepted among researchers. Sargeant et al. (1981) measured power output and T-Cad relationship with the isokinetic method. They found strong linearity in the maximum peak force - cadence profiles ( $r > 0.97$ ,  $p < 0.002$ ) for all participants. The large intersubject difference was resolved when maximum peak torque was standardized to the upper leg volume. A parabolic relationship was displayed, when maximum peak power was plotted against cadence. This showed a decrease in power at higher cadence. Similar results have been shown by Vandewalle et al. (Vandewalle et al., 1987) in their study using a friction braked ergometer. Their research focused on the T-Cad relationship in different populations of elite and recreational athletes. Like reported by Sargeant et al. (1981), the individual T-Cad data were well described by a linear relationship for cadence values between 100 – 200 rpm ( $r > 0.99$ ) as was the P-Cad by a parabolic relationship. This was also the case for the results of twelve elite track cyclists, where the coefficient of determination averaged  $0.981 \pm 0.01$  for the T-Cad profiles and  $0.957 \pm 0.015$  for the P-Cad profiles (Dorel et al., 2005). Gardner et al. (2007), in their attempt to compare laboratory and field measured power with elite track cyclists, found similar results for both tests to the aforementioned studies. For the laboratory test, the inertial-load method was used and for the field test, an SRM powermeter was fitted to the athlete's bicycle. The laboratory and field T-Cad data showed also good linear fit ( $r^2 = 0.990 \pm 0.01$ ;  $r^2 = 0.983 \pm 0.02$ , respectively) as previously reported.

The linear T-Cad relationship is described by three parameters;  $T_0$ ,  $Cad_0$  and  $S_{T-Cad}$ .  $T_0$  represents the theoretical maximal torque of the cyclist and is the intercept of the T-Cad curve with the torque axis.  $T_0$  was reported to be an index of maximal leg strength, since a correlation was found between  $T_0$  and maximal isometric force [ $r = 0.73$ ,  $p < 0.05$  (Driss et al., 2002)]. In elite track cyclists this power parameter was reported to be  $235.9 \pm 19.1$  Nm (Dorel et al., 2005). This is in agreement with the results of Martin et al. (1997) and Driss et al. (1998) with average  $T_0$  values of  $203 \pm 9$  Nm and  $183.4 \pm 15.1$  Nm, respectively. The slightly lower values are certainly due to the tested subjects, which were volleyball players (Driss et al., 1998) and active males (Martin et al., 1997), but not cyclists who were specifically trained for maximal power production. Gardner et al. (2007) also tested track cyclists and found higher  $T_0$  values for the laboratory test ( $266 \pm 20$  Nm) and the field test ( $266 \pm 13$  Nm). These higher values were partly due to the fact that the cyclists were allowed to stand out of the saddle for both tests, which generates greater power and torque values (Bertucci et al., 2005; Reiser et al., 2002). Not in line with the described results were the results of Bertucci et al. (2005), who compared field power on a road bicycle in a gymnasium to laboratory power on the same road bike mounted on an ergo-trainer.  $F_0$  for the field test was  $857 \pm 154$  N and  $745 \pm 100$  N for the laboratory test. Assuming a crank arm length of 175 mm, it can be expected that  $T_0$  was  $150 \pm 27$  Nm for the field test and  $130 \pm 17$  Nm for the laboratory test. These values are relatively low it may be that the data collection had been compromised.

$Cad_0$  is the theoretical maximal pedalling rate of the cyclist and is the intercept of the T-Cad curve with the cadence axis. Its values have been reported to be  $220 \pm 8$  rpm for active people (Sargeant et al., 1981),  $233 \pm 9.7$  rpm for volleyball players and between 248 and 281 rpm for competitive cyclists in different test conditions [laboratory and field tests; seated and standing position (Bertucci et al., 2005)]. Vandewalle et al. (1987) showed various values for different populations. Among eight sport disciplines, endurance runners had the lowest  $Cad_0$  ( $212 \pm 19$  rpm). On the other hand, track cyclists and sprint runners had the highest values ( $249 \pm 12$  rpm;  $247 \pm 13$  rpm, respectively). This is in line with the aforementioned studies and with Dorel et al. (2005), who tested elite track cyclists ( $260 \pm 8.6$  rpm). These reported results show that power athletes exhibit greater  $T_0$  and  $Cad_0$  than endurance athletes or untrained active subjects. This is not surprising since the

power production capacity is dictated by the T-Cad relationship, which is given by the two parameters  $T_0$  and  $Cad_0$  (Cormie et al., 2011).

$S_{T-Cad}$  is a further parameter of the T-Cad relationship, which describes the slope of the curve. Its value is given by the  $T_0$  and  $Cad_0$ . From the data of Vandewalle et al. (Vandewalle et al., 1987), the  $S_{T-Cad}$  of different sport disciplines was calculated. Not surprisingly steeper average  $S_{T-Cad}$  values were found for power athletes (rugby players: -0.847; sprint runners: -0.784; track cyclists: -0.727) compared to endurance athletes (endurance cyclists: -0.634; endurance runners: -0.659). These values differ from elite track cyclists in laboratory and field conditions [ $-1.040 \pm 0.09$  and  $-1.035 \pm 0.10$  (Gardner et al., 2007)]. Possible explanations for this discrepancy may be the level of the track athletes or the measuring method used. Unfortunately, the importance of  $S_{T-Cad}$  has, as of yet, received little attention from the scientific literature.

$cP_{max}$  is the theoretical maximal power and corresponds to the apex of the parabolic P-Cad relationship. It is the most researched power parameter, because it has been directly linked to sports performance (Giroux et al., 2015a).  $Cad_{opt}$  is the pedalling rate at which  $cP_{max}$  occurred and corresponds to  $0.5 \cdot Cad_0$  (Vandewalle et al., 1987). Sargeant et al. (1981) were among the first to describe the T-Cad and P-Cad relationship. They reported maximal power output averaged over a complete pedal revolution for active untrained subjects of  $840 \pm 153$  W at 110 rpm. Similar results were discovered by Hautier et al. (1996) in their study on the P-Cad relationship and muscle fibre composition. Ten trained subjects performed a force-velocity test on an isokinetic ergometer.  $cP_{max}$  and  $Cad_{opt}$  were  $940 \pm 155.5$  W and  $120 \pm 8$  rpm. Furthermore,  $Cad_{opt}$  and  $cP_{max}$  standardized to body weight were related to the percentage of the cross-sectional area of fast twitch muscle fibres ( $r = 0.88$ ,  $p < 0.001$ ; and  $r = 0.60$ ,  $p < 0.06$ , respectively). Therefore, when the percentage of type II fibres is high,  $Cad_{opt}$  should be high. On the contrary, when the percentage of slow twitch fibres is high,  $Cad_{opt}$  should be lower. This confirms what has been reported previously, namely that power athletes exhibit greater  $Cad_0$  (which is directly linked to  $Cad_{opt}$ ) than endurance athletes. Vandewalle et al. (1987) confirmed this with the following  $cP_{max}$  and  $Cad_{opt}$  values in different sports; rugby players: 1257 W at 119 rpm ; track cyclists: 1180 W at 125.5 rpm; sprint runners: 1252 W at 123.5 rpm; endurance runners: 776 W at 106 rpm and road cyclists: 870 W at 114.5 rpm. Driss



et al. (1998) and Arsac et al. (1996) found comparable result for trained athletes and volleyball players with the friction load method ( $cP_{\max}$ :  $868 \pm 132$  W and  $1090 \pm 96.6$  W  $Cad_{\text{opt}}$ :  $125 \pm 9$  rpm and  $116.5 \pm 4.8$  rpm). In high-level track cyclists,  $cP_{\max}$  is expected to be greater due to the specific demands of the sport. This is the case, as has been demonstrated by Gardner et al. (2007) and Dorel et al. (2005) with greater values than previously reported ( $1791 \pm 169$  W and  $1600 \pm 116$  W, respectively).  $Cad_{\text{opt}}$  was also slightly higher for elite track cyclists ( $128 \pm 7$  rpm and  $129.8 \pm 4.7$  rpm). Like in the other T-Cad parameters, Gardner et al. (2007) found no significant differences between field and laboratory  $cP_{\max}$  and  $Cad_{\text{opt}}$ . This indicates that maximal T-Cad values may provide an accurate means of modelling cycling performance. When comparing the two P-Cad parameters to performance (speed over 200 m), Dorel et al. (2005) showed that  $Cad_{\text{opt}}$  was significantly related to performance ( $r = 0.77$ ,  $p < 0.01$ ) but, interestingly,  $cP_{\max}$  was not. However, when scaling  $cP_{\max}$  to frontal surface area, a correlation with performance was shown ( $r = 0.75$ ,  $p = 0.01$ ). Frontal surface area of the bike and the rider affects the air resistance, which makes up 90% of the resistive force when cycling on a track. In reducing the frontal surface area, air resistance will also decrease leading to an increase in speed at the same power output. Several other BMX studies (Bertucci & Hourde, 2011; Bertucci et al., 2007; Debraux & Bertucci, 2011b) also found correlations between  $cP_{\max}$  and performance. Bertucci et al. (2007) performed a force-velocity test using the friction-load method and BMX starts or sprints with 35 regional and national BMX riders. The results showed a strong correlation between maximal power output and BMX time performance over 30 m ( $r = 0.85$ ,  $p < 0.01$ ). This is in line with Bertucci (2011), who found a significant relationship between BMX race time over 25 and 27 m and maximal power output on an ergometer ( $r = 0.59$ ,  $p < 0.05$  and  $r = 0.61$ ,  $p < 0.05$ , respectively). Debraux and Bertucci (2011a) studied the determining factors of the sprint performance in BMX riders. Seven elite BMX riders performed 30 m sprints on level ground from a stationary start. Their results were similar to the aforementioned study when comparing  $cP_{\max}$  to average velocity over 80 m ( $r = 0.99$ ,  $p < 0.05$ ). Interestingly  $cP_{\max}$  was not significantly related to time performance after 20 m but  $T_0$  was ( $r = 0.98$ ,  $p < 0.05$ ).  $T_0$  being a good indicator of maximal force (Driss et al., 2002) suggests that  $T_0$  could be an important factor for the start and acceleration phase in a BMX sprint.

Many researchers have also investigated the link between power in linear movement, such as the vertical jump and in cyclic movement, such as short all-out sprint on a cycle ergometer or a bicycle (Bertucci & Hourde, 2011; Bertucci et al., 2007; Debraux & Bertucci, 2011b; Driss et al., 1998; Hautier et al., 1996; Vandewalle et al., 1987). Vertical jump height has been reported to be highly correlated with the peak jumping power measured with a force platform (Davies & Young, 1984) and with  $jP_{\max}$  extracted from the P-v relationship (Bosco et al., 1995; Samozino et al., 2012; Yamauchi & Ishii, 2007). Therefore measurement of vertical jump height can be considered as an effective field method of evaluating muscle power. Vandewalle et al. (1987) used this method and compared jump height results with  $cP_{\max}$  obtained on a cycle ergometer. A significant correlation between jump height and  $cP_{\max}$  scaled to body mass was shown ( $r = 0.85$ ). However the correlation coefficient wasn't particularly high. Similar results were shown by Hautier et al. (1996) and Driss et al. (1998) with correlation coefficient  $r$  being 0.87 and 0.754, respectively. More recently, Bertucci (Bertucci & Hourde, 2011) came to the same conclusion when comparing  $cP_{\max}$  values collected on a bicycle in laboratory and field conditions with squat jump height ( $r = 0.79$ ,  $p < 0.05$  and  $r = 0.69$ ,  $p < 0.05$ ). Bertucci et al. (2007) went even further and compared maximal power of a single SJ to BMX start performance. SJ maximal power was significantly related to time after 5 m and 30 m ( $r = 0.75$ ,  $p < 0.01$  and  $r = 0.83$ ,  $p < 0.01$ ). These different correlations obtained between brief cyclic and linear movements all show that they characterize related functional properties, namely instantaneous leg muscle power (Hautier et al., 1996). Debraux et al. (2011b) chose a different approach to compare cyclic and linear movements. Ten national elite BMX riders performed a series of loaded SJ in order to obtain the F-v profile and a force-velocity test on a cycle ergometer. From the F-v profile,  $jP_{\max}$ ,  $F_0$  and  $v_0$  were extracted and from the force-velocity test  $cP_{\max}$  was calculated. The relationships between the tests were studied. The major finding of the study was the significant correlation between  $F_0$  and  $cP_{\max}$  ( $r = 0.65$ ,  $p < 0.05$ ). Therefore theoretical maximal force in SJ is a determining factor of the power output in short all-out cycling sprints. Maximal leg strength is thus an important parameter during the start phase of a cycling sprint.

Overall, the findings of studies describing the torque and power-cadence relationship show numerous similarities with the previously described force and power-velocity

relationship studies, not only in regards to their linear and parabolic nature, but also to the similarities found between the various parameters of the power profiles. But no study has yet analysed the correlation between the slopes and endpoints of the linear and cyclic movement profiles and therefore it remains unknown if there is any transfer mechanism.

### **3. Reliability study**

#### **3.1. Goals and research questions**

The aim of the test-retest reliability study is to ensure that the T-Force (Ergotech, Spain), a linear position transducer (LTP), is an adequate measuring system by comparing it to a general accepted measuring system, the Quattro Jump (Kistler, Switzerland) force plate. Its results will aid the decision as to which measuring system will be used for the main BMX force-velocity relationships study. Furthermore, it serves as a pilot study to the main study, in which the protocols will be tested and gain experience in the manipulation of the measuring tools and software will be gained.

The research question is the following:

- How reliable are the measurements of concentric jump height obtained from a linear position transducer (T-Force) and force plate (Quattro Jump,) measuring systems?

#### **3.2. Methods**

##### **3.2.1. Subjects**

To recruit participants for this reliability study, an ad (see Appendix A) was published in the different gymnasiums and sent to all sport students at the University of Fribourg. Twelve students replied to the ad and agreed to take part in the study. Their mean ( $\pm$  SD) age, height, body mass and body mass index (BMI) were  $24.6 \pm 2.6$  years,  $178.5 \pm 8.7$  cm,  $73.2 \pm 11.0$  kg and  $22.9 \pm 2.3$  kg·m<sup>2</sup> respectively. Two participants were not familiar to squat training. They underwent a brief introduction followed by a familiarization period. All participants were healthy and no injuries were reported.

##### **3.2.2. Study design**

The procedure included two tests (test and re-test) of maximal ballistic squat jumps with additional load separated by a week. After arriving at the university laboratory, the participants filled out a form provided by Swiss Olympic, where anthropometric,

training load, nutritional and physical data were collected, as well as the current motivation and mood (see Appendix B). Before doing a 10-minute warm up on a bicycle at a self-selected intensity, a brief instruction of the following test was given to the participants. Subjects' weight was determined with the FP and this was used to calculate the different additional loads. After that, the exact squat depth was established. Participants were asked to assume a position with a knee angle of 90° while an apparatus was placed underneath their hip, which would help maintain the same start position throughout the trials. In addition, push-off distance was calculated. It corresponded to the distance from the ground to the iliac crest in the fully extended position subtracted to the same distance in the start position.

After the warm up, dynamic tests were conducted. Participants performed squat jumps under five loading conditions (0%, 25%, 50%, 75% and 100% of BM). The additional load was placed on a 8-kg barbell placed on participants shoulder. For the 0% BM condition, the barbell was replaced with a wooden stick, which weighed 0.3 kg. Subjects were instructed to maintain the barbell in contact with their shoulder throughout the motion. Upon an auditory command, the participants went in the start position and after about two seconds jumped as fast and as high as possible. Three SJ were performed for each randomly assigned load condition, plus a fourth or fifth in the case of a 10% height difference between the three jumps. In between each jump, the barbell was taken off their shoulders for a 30 second break and between each load condition the subjects had approximately 3 minutes pause.

### 3.2.3. Data collection

The data were collected from both devices simultaneously. The FP, which was positioned underneath the participants and the LPT, which mobile portion was attached to the barbell.

The FP was setup according to the manufacturer's specifications. Before each test, the FP was calibrated. The natural frequency is approximately 150 Hz and the force range is 0 – 10 kN at a linear force signal ( $\leq \pm 0.5$ ), according to the manufacturer. Data is sampled at a rate of 500 Hz and stored on a PC. The Quattro Jump software (Kistler, Switzerland) processes the signal from the FP. Various variables from the vertical force component are calculated from the ground reaction force, but only the

jump height was used for further calculation using a simple computation method proposed by Samozino et al. (2008).

The LPT is composed of a two meter wire attached to the barbell and winding into a sensor unit placed on the floor. Inside the sensor unit, a tachogenerator measures the speed of the extension of the wire. The sampling rate is 1000 Hz. The sensor is connected to an electronic data acquisition board, which allows the data transfer to the software (T-Force System Software, Ergotech, Spain). The software calculates various variables from the measured displacement time of the wire, but only jump height was used for further calculations.

The Samozino computation method is a simple and accrued field method to evaluate force, velocity and power of the lower limbs during squat jumps (Samozino et al., 2008). This method is solely based on three parameters; total mass (BM + additional load), push-off distance and jump height. For each trial the mean vertical force ( $\bar{F}$ ) and the mean vertical velocity ( $\bar{v}$ ) were determined as following:

$$\bar{F} = mg \left( \frac{h}{h_{PO}} + 1 \right) \quad (1)$$

$$\bar{v} = \sqrt{\frac{gh}{2}} \quad (2)$$

with  $m$  being the total mass (BM + additional load),  $g$  being the gravitational acceleration ( $9.81\text{m}\cdot\text{s}^{-2}$ ),  $h$  the vertical jump height and  $h_{PO}$  the vertical push-off distance.  $h$  was obtained from the ground reaction force being measured by the FP and from the velocity measured by the LPT. The mean power ( $\bar{P}$ ) is the product of the mean vertical force ( $\bar{F}$ ) and the mean vertical velocity ( $\bar{v}$ ), obtained from (1) and (2):

$$\bar{P} = \bar{F} \cdot \bar{v} \quad (3)$$

Individual force-velocity relationships were obtained from the linear regression of force and velocity values (Rahmani et al., 2001; Yamauchi & Ishii, 2007). The following components were extracted from these individual F-v profiles: slope of the F-v line ( $S_{F-v}$ ), theoretical maximal force produced at null velocity ( $F_0$ ), which corresponds to the extrapolated intercept with the force-axis, theoretical maximal velocity produced at zero load ( $v_0$ ), which corresponds to the extrapolated intercept with the velocity-axis, and the theoretical maximal jumping power ( $jP_{max}$ ) computed by:

$$jP_{max} = \frac{F_0 \cdot v_0}{4} \quad (4)$$

A spreadsheet was created in order to calculate the F-v and P-v profiles for each individual (see Appendix C). Total mass, push-off distance and jump height had to be entered in order to become the profile's specific parameters ( $F_0$ ,  $v_0$ ,  $S_{F-v}$  and  $jP_{max}$ )

#### 3.2.4. Statistical analysis

The profile's specific parameters from the test and re-test were compared to determine the reliability between the 2 sessions. The samples mean and standard deviation (SD), as well as the coefficient of variation (CV) and the interclass correlation coefficient (ICC) were determined for  $F_0$ ,  $v_0$ ,  $S_{F-v}$  and  $jP_{max}$ . The confidential interval was set at 95% (Hopkins et al., 2001).

### 3.3. Results

The four parameters from the F-v relationship for each measurement system and each session are represented in Table 1. Higher force values were attained with the LPT compared to the FP. However LTP measured lower  $v_0$  and  $jP_{max}$  parameter than the FP. Finally the results showed steeper  $S_{F-v}$  for the LTP measurements.

Tab. 1 : Mean absolute values and standard deviation of the F-v parameters for each session measured with the linear position transducer (LTP) and the force plate (FP).

|            |  | Session 1 |        | Session 2 |       |
|------------|--|-----------|--------|-----------|-------|
|            |  | Mean      | SD     | Mean      | SD    |
| <b>LPT</b> | $F_0$ [N]                              | 3312.8    | 580.0  | 3352.1    | 613.0 |
|            | $v_0$ [ $\text{m}\cdot\text{s}^{-1}$ ] | 2.8       | 0.6    | 2.7       | 0.5   |
|            | $jP_{\max}$ [W]                        | 2250.3    | 436.4  | 2200.9    | 378.1 |
|            | $S_{F-v}$                              | -1269.4   | 440.3  | -1318.9   | 420.9 |
| <b>FP</b>  | $F_0$ [N]                              | 3178.6    | 731.4  | 3014.5    | 756.9 |
|            | $v_0$ [ $\text{m}\cdot\text{s}^{-1}$ ] | 3.7       | 1.9    | 3.7       | 1.2   |
|            | $jP_{\max}$ [W]                        | 2737.4    | 1126.3 | 2650.5    | 667.6 |
|            | $S_{F-v}$                              | -1080.4   | 546.3  | -923.6    | 411.3 |

Table 2 shows the typical error, CV and ICC for the parameters for both measuring systems. The within-subject variability was higher when performance was measured with the force plate than with the linear transducer. In addition, the ICC values were much lower when measured with the FP (0.28 – 0.59) compared to the LPT (0.74 – 0.90).

Tab. 2 : Within-subject variability and interclass correlation coefficient of the F-v parameters for each measurement system.

|             | Linear position transducer        |        |      | Force plate                       |        |      |
|-------------|-----------------------------------|--------|------|-----------------------------------|--------|------|
|             | Typical error                     | CV (%) | ICC  | Typical error                     | CV (%) | ICC  |
| $F_0$       | 206.5 N                           | 6.2%   | 0.90 | 500.6 N                           | 16.2%  | 0.59 |
| $v_0$       | 0.31 $\text{m}\cdot\text{s}^{-1}$ | 11.3%  | 0.74 | 1.37 $\text{m}\cdot\text{s}^{-1}$ | 37.5%  | 0.28 |
| $jP_{\max}$ | 159.9 W                           | 7.2%   | 0.87 | 672.6 W                           | 25.0%  | 0.51 |
| $S_{F-v}$   | 199.5                             | -15.4% | 0.82 | 397.2                             | -39.6% | 0.36 |

The F-v relationships were found to be linear for all trials, but great inconsistencies were revealed in the profiles derived from the FP data as shown in Figure 5. The coefficient of determination  $r^2$  averaged  $0.92 \pm 0.10$  for the LPT and  $0.63 \pm 0.27$  for the FP.



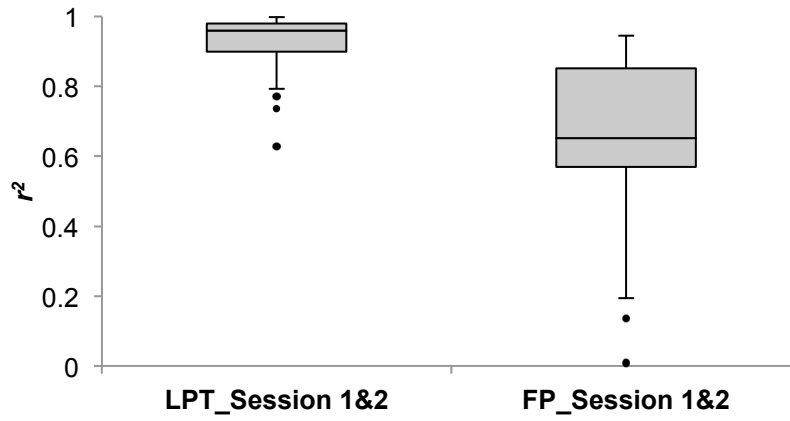


Fig. 5 : Distribution of  $r^2$  values of the linear regression obtained with the linear position transducer (LPT) and the force plate (FP). Any outliers are illustrated with a black dot.

Figure 6 shows the F-v profile for a typical subject for the same sessions. Differences between LPT and FP are observed for the slopes of the regressions, which influences  $F_0$  and  $v_0$ . Furthermore, the results of this subject vary much more when recorded with the FP than the LPT. This was also representative of the whole group, as shown in Table 2.

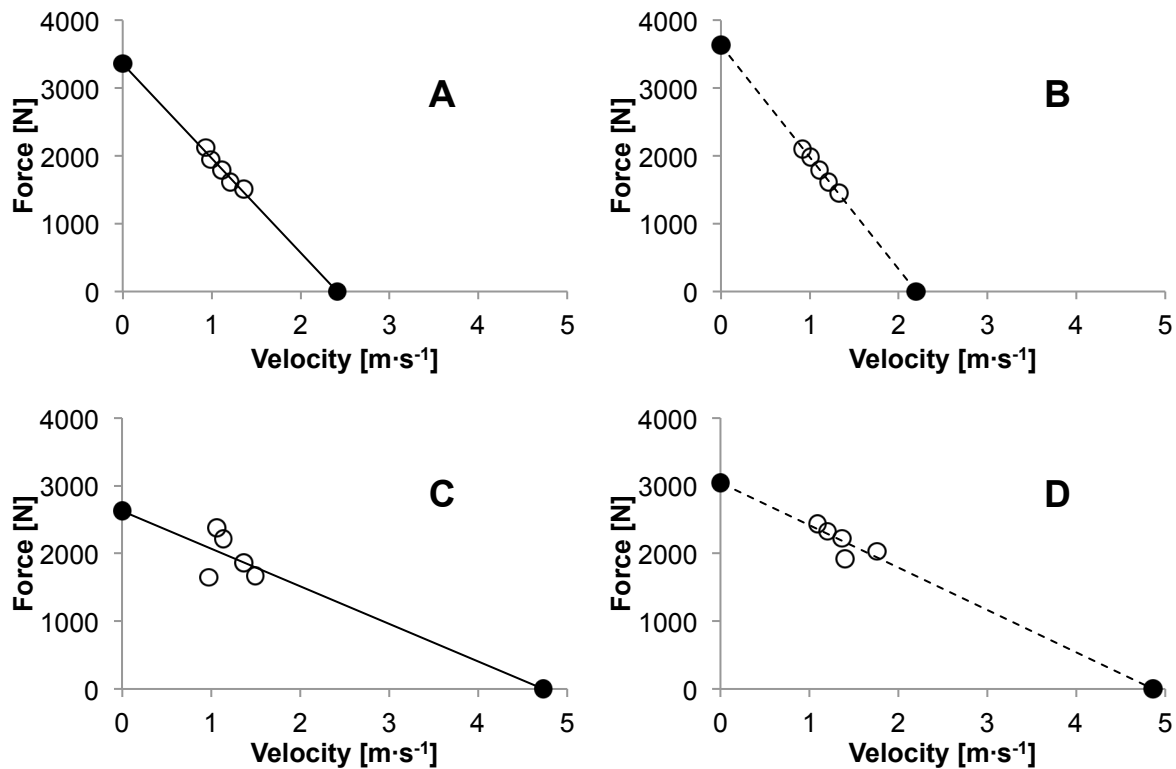


Fig. 6 : F-v profiles of a typical subject for the same sessions implemented from the LPT (panel A and B) and the FP (panel C and D). Open circles represent the results at different loading conditions and filled circles the extrapolated  $F_0$  and  $v_0$ . Continuous lines show the results of session 1 and the dashed lines for session 2.

### **3.4. Discussion**

The objective of this study was to test the reliability of the T-Force system, a linear position transducer, and the Quattro Jump system, a portable force plate. The main finding of this study was that the FP was not consistent in its results, whereas the linear position transducer showed low variability and moderate to good reliability.

Jump heights from both devices were extracted and used to construct the individual force-velocity profile with Samozino's computation method. Each parameter of the F-v relationships were compared with the retest and the analysis showed moderate to good repeatability for the T-Force device with ICC values between 0.74 to 0.90. Other authors reported similar ICCs for jump height, mean and peak power and power velocity measured by a LPT (Hansen et al., 2011; Hori et al., 2007). In addition to the ICC, the most common method of analysing reliability is the coefficient of variance. For the LTP measures, the CVs of all parameters ranged between 6.2 and 15.4%. This is higher than the range of 2.0 – 8.0% reported by the aforementioned authors (Hansen et al., 2011; Hori et al., 2007). It is, however, important to mention that our analysed parameters were not directly measured by the device like it is usually done in reliability studies. This could also be the explanation as to why our CV values differed slightly from those of Hansen et al. (2011) and Hori et al. (2007).

The Quattro Jump device did not deliver acceptable results. During the testing, subjects were often requested to repeat their jump, because of invalid jump height measurements. In addition, the analysis of the four parameters showed poor reliability. ICC values ranged between 0.28 and 0.59. The variability expressed in the CV ranged between 16.2 and 39.6%. This is much higher than what has been reported by other authors [CV: 3.1 – 6.6% (Hansen et al., 2011; Mauch et al., 2014)]. These inconsistent SJ results don't support the use of jump height measurements from the Quattro Jump device in determining F-v profiles.

Another objective of this study was to test the protocol and to become familiar with the procedures and the test devices. By planning, organising and carrying out the study, valuable experience was gained. Moreover, testing the protocol made it possible to detect some weakness and modify them for the BMX force-velocity study. For example, the maximal loading condition was reduced to 80% BM instead of 100% BM.

In conclusion, this study suggests that the T-Force device is a reliable measuring system to assess loaded squat jump height in order to construct the individual force-velocity profiles. Therefore it should be preferred over the Quattro Jump device for the further BMX force-velocity study.

## 4. BMX study

### 4.1. Goals and research questions

The aim of this work is to investigate the transfer of muscle power and force-velocity properties from a simple, linear movement onto a complex, sport-specific, cyclic movement in trained BMX-athletes. In order to identify a transfer mechanism, the correlation between vertical jumps, BMX sprints and BMX starts on a ramp will be analysed based on the power-force-velocity relationships of the three actions.

#### *Research questions*

Is there a correlation between the maximal power output of the BMX sprints, BMX starts and the derived maximal power output of the vertical jump tests?

- $cP_{\max \text{ sprint}}$  with  $jP_{\max}$
- $cP_{\max \text{ start}}$  with  $jP_{\max}$

Do the various parameters of the F-v profiles from the BMX sprints, BMX starts and the vertical jump test correlate?

- $T_0 \text{ sprint}, T_0 \text{ start}$  with  $F_0$
- $Cad_0 \text{ sprint}, Cad_0 \text{ start}$  with  $v_0$
- $S_{T-Cad \text{ sprint}}, S_{T-Cad \text{ start}}$  with  $S_{F-v}$

Are there specific parameters of the F-v profile, which favour the mean power ( $P_{\text{mean } 30}, P_{\text{mean start}}$ ) or the end time ( $v_{\text{mean } 30}, v_{\text{mean start}}$ ) of a 30-meter BMX sprint or a BMX start?

- $F_0, v_0, S_{F-v}$  with  $P_{\text{mean } 30}, P_{\text{mean start}}$
- $F_0, v_0, S_{F-v}$  with  $v_{\text{mean } 30}, v_{\text{mean start}}$

Does vertical jump power ( $P_{\max \text{ jump}}$ ) favour sprint or start performance?

- $jP_{\max}$  with  $P_{\text{mean } 30}, P_{\text{mean start}}$
- $jP_{\max}$  with  $v_{\text{mean } 30}, v_{\text{mean start}}$

## **4.2. Methods**

### **4.2.1. Subjects**

Ten male and three female BMX athletes from the Swiss national team selection pool volunteered and gave their informed consent to take part in this study. They all compete at the national and/or international level in either the junior or elite category. Their mean ( $\pm$  SD) age, height, body mass and body mass index (BMI) were  $24.6 \pm 2.6$  years,  $174.4 \pm 8.0$  cm,  $72.2 \pm 10.5$  kg and  $23.8 \pm 1.9$  kg·m<sup>-2</sup> respectively. Squat training being part of their training routine, they were all familiar with dynamic squat exercises with additional load. All participants were healthy and no injuries were reported.

### **4.2.2. Study design**

For each subject, three tests were conducted on the same day in the facilities of the Velodrome Suisse in Grenchen. Upon arriving at the performance lab, they were given instructions about the testing day and underwent anthropometric measurements. After an individual warm-up on a stationary bike, they first performed the jump test, followed by the BMX gate starts on the supercross ramp and finishing with the 30 m sprints on the flat. The testing of each subject lasted approximately 2.5 hours.

#### *Vertical jump test*

Before starting the testing, the subjects were free to perform some submaximal squat jumps with additional load and instructions about the test were given. Before beginning the test, push-off distance, body mass (BM) and jump position were measured. The push-off distance was necessary to calculate force, velocity and power with Samozino's field method (Samozino et al., 2008). The subjects BM was used to calculate the additional loads used later in the test as well as for calculations using Samozino's field method. Finally, the jump position at the start had to be prescribed, in order that every squat jump has the same push-off distance. This was done by placing a special apparatus underneath the subject's hips in the individually chosen starting position. This apparatus stayed in position throughout the testing.

To obtain the force-velocity profile, each subject performed three squat jumps each at five individual loads. The loading conditions ranged from 0-80% BM with an increment of 20%. The additional weight was placed on a 10 kg barbell; for the 0% loading condition a wooden stick (0.3 kg) was used. The order of the load conditions was randomly assigned. Participants took the loaded barbell from the barbell rack and placed it on their shoulders. Upon an auditory command they went into the previously determined start position. After about two seconds of immobility, they jumped as fast and as high as possible. Three squat jumps were performed for each load condition, plus a fourth or fifth in case of a 10% height difference between the first three jumps. After each jump, the barbell was taken off their shoulder for a 30 second break. Between each set they had a 3-minute break. The overview of the experimental setup is displayed in Figure 7.

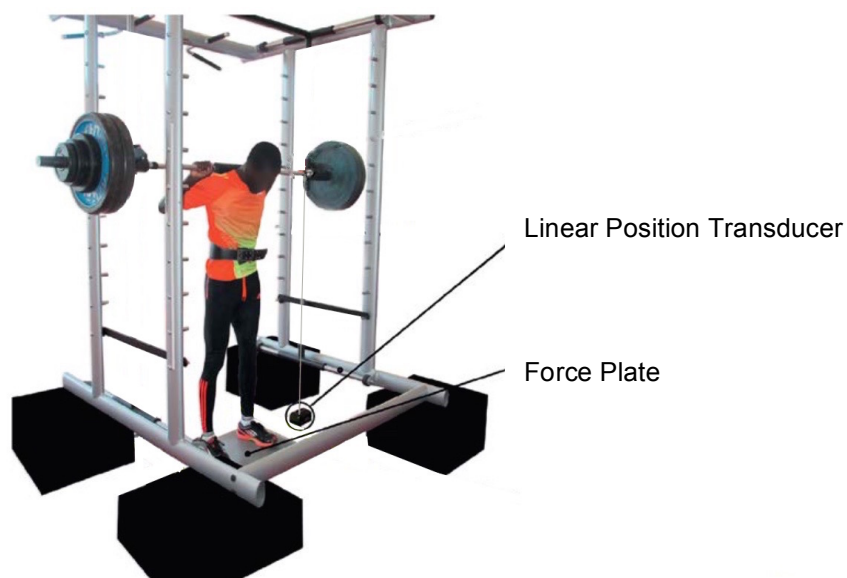


Fig. 7 : Overview of the experimental setup. Adapted from Giroux et al. (2015b)

The data was collected with two measurement systems. A double force plate (MLD-Station Evo2, SP Sport, Austria) recorded the ground reaction force data. Each half of the FP possessed 4 one-dimensional force transducers. The sampling rate was 1000 Hz. The transducer signal was amplified to reduce interference and treated in the software (MLD 2.0, SP Sport, Austria). The software used the recorded ground reaction force to calculate mean force, concentric displacement and concentric time, which were used to calculate concentric velocity and power, as well as jump height. The second measurement system was the linear position transducer (T-Force

System, Ergotech, Spain). The LPT is composed of a two-meter wire attached to the barbell or the wooden stick and wound into a sensor unit placed on the floor. Inside the sensor unit, a tachogenerator measures how fast the wire extends and retracts. The sampling rate was 1000 Hz. The sensor was connected to an electronic data acquisition board, which allows the data transfer to the software (T-Force System Software, Ergotech, Spain). The software calculates jump height, propulsive force, propulsive displacement and velocity from the measured displacement time of the wire and the specified total mass.

The Excel spreadsheet (see Appendix C) based on Samozino's field method was used during the testing. By entering the subject's bodyweight, push-off distance and the jump height obtained from the FP during the test, F-v and P-v profiles for each individual were instantly created. This would help to identify any questionable jumps, allowing these to be repeated. In addition, the spreadsheet calculated the participants' individual F-v parameters ( $F_0$ ,  $v_0$ ,  $S_{F-v}$ , and  $jP_{max}$ ).

### *BMX gate starts*

After an approximately 20 minute break, participants changed clothes and proceeded with their own bike to the BMX track. They completed a 15-minute warm-up to prepare for the gate start test on the supercross ramp. On the ramp they were then given specific instructions. Most importantly, they were instructed to start as fast as possible until the first obstacle.

In order to obtain the force-velocity profile of the gate start, participants performed several starts on the ramp with the same gate, standardized start command and randomized gate used in international competitions. Each rider performed the starts alone. After their run, they went back to the start gate for further starts. Each rider performed a total of five gate starts with 5-6 minutes recovery in between.

Four electronic timing gates (TC Timing System, Brower, Salt Lake City, USA) were installed between the gate and the first obstacle. The first gate was placed at the start and was initiated by the dropping of the starting gate itself. The second timing gate was placed at 5.42 meters from the start, where the ramp becomes steeper. The third timing gate was placed at the end of the ramp (13.26 m beyond the first timing gate). And the last timing gate was placed after a 5-meter section of flat right

before the first obstacle (Figure 8). The last three timing gates were triggered by the front wheel of the rider's bike while riding through. The TC-Timing System allows a highly accurate (to a thousandth of a second) measurement of the different split times.

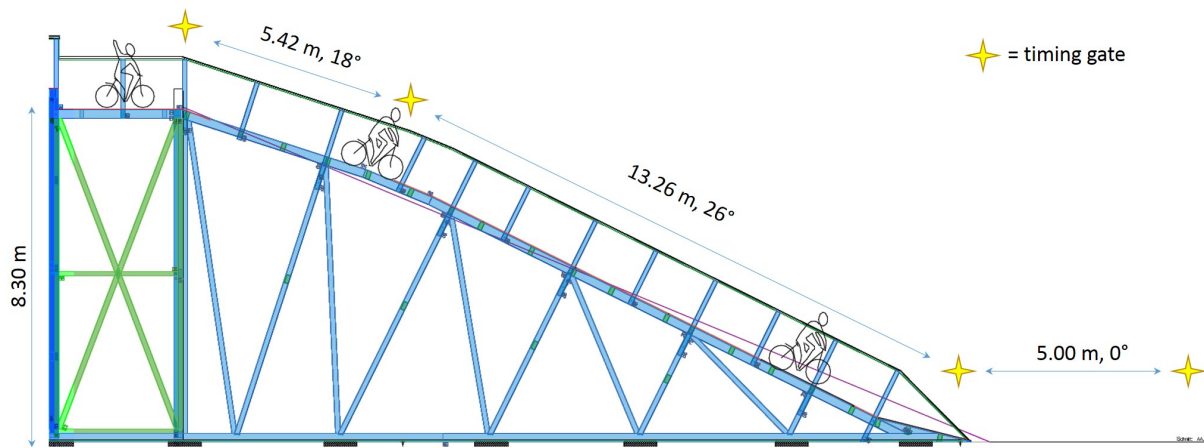


Fig. 8 : Cross section of the BMX Supercross start ramp.

### *BMX Sprints*

Between the last start on the supercross ramp and the final test, participants had 10-15 minutes recovery, during which they proceeded to the last test station with their bikes. There, they were given final instructions before the sprint test.

Once again, the objective of the sprint test was to obtain the F-v curve as well as the time for 30 m. Participant performed three maximal sprints on level ground, similar to the test protocol of Debraux & Bertucci (2011a). The instructions were to accelerate maximally to maximum speed. This distance would be achieved in approximately 50 m and five to six seconds, which corresponds to the time of the force-velocity test on an ergometer described in literature. However, performance time was taken after 30 m. The riders assumed a standing start position with their rear pedal placed on a block to keep their balance and started on their own initiative. Between each effort, participant had 5 minutes recovery.

Two timing gates (Witty, Microgate, Bolzano, Italy) were placed at 0 and 30 m. The front wheel of the bike triggered the time measurement. The time splits were recorded and used in further analysis.



The rider's bikes were equipped with a modified SRM powermeter (SRM Shimano DXR, Schoberer Rad Messtechnik, Jülich, Germany) prior to the tests. The powermeter contains 8 strain gauges installed in the crank for measuring the torque applied on the crank. It was modified to record at a sampling rate of 100 Hz. The collected data were recorded to a local data logger (Axiomo GmbH, Biel), which also contained a gyroscope used to provide synchronized angular crank velocity data.

#### 4.2.3. Data analysis

Although there was some variance in the F-v parameters (CV: 8 – 28%) due to the heterogeneous group, it was decided that the absolute and not relative data of the tests would be used for the analysis. Although athletes do have to surmount mass dependent inertia on the first part of the start, the overall effect of greater body mass on downward sloping ramp starts is not assumed to be detrimental. Furthermore every computation of data increases the bias within itself. Thus, in order to keep this bias to a minimum absolute values were used for data analysis..

#### *Jump test*

From the two devices used during the testing, several measurement points came into consideration when analysing the collected data. In order to decide which ones would be used in the further analysis, a reliability test was performed using Hopkins' spreadsheet (Hopkins, 2011) and the CV of each one was calculated (Table 3). The lowest average CV values over the five loading conditions were found for  $F_{\text{pos\_abs}}$  (mean concentric force) and  $v_{\text{pos}}$  (mean concentric velocity), two measuring points measured by the FP. These two measurement points were used for further analysis and construction of F-v profiles.

Tab. 3 : Coefficient of variance as percentage for various variables from the FP and the LPT for the 5 loading conditions. ( $F_{pos\_abs}$ : mean concentric force,  $v_{pos}$ : mean concentric velocity,  $D_{t_{pos}}$ : mean velocity from concentric distance measured by hand and concentric time, MPF: mean concentric force, MPV: mean concentric velocity, CD\_JH: mean velocity from concentric distance and concentric time,  $D_{PPD}$ : mean velocity from concentric distance measured by hand and concentric time)

|            |                | Loading conditions |      |      |      |      | Mean        |
|------------|----------------|--------------------|------|------|------|------|-------------|
|            |                | 100%               | 120% | 140% | 160% | 180% |             |
| <b>FP</b>  | $F_{pos\_abs}$ | 2.6%               | 2.4% | 1.6% | 1.8% | 1.5% | <b>2.0%</b> |
|            | $v_{pos}$      | 3.2%               | 3.9% | 2.3% | 2.6% | 5.4% | <b>3.5%</b> |
|            | $D_{t_{pos}}$  | 6.0%               | 6.1% | 4.9% | 4.5% | 4.6% | <b>5.2%</b> |
| <b>LPT</b> | MPF            | 5.1%               | 6.6% | 3.9% | 2.0% | 3.2% | <b>4.2%</b> |
|            | MPV            | 6.9%               | 9.9% | 6.6% | 4.7% | 8.2% | <b>7.2%</b> |
|            | CD_JH          | 9.4%               | 6.1% | 6.3% | 4.7% | 8.0% | <b>6.9%</b> |
|            | $D_{PPD}$      | 6.9%               | 7.3% | 6.6% | 6.5% | 7.4% | <b>6.9%</b> |

In order to exclude any outliers from the analysis, the medians of  $F_{pos\_abs}$  and  $v_{pos}$  were calculated for each condition and participant. The F-v relationship were then determined by the least square linear regressions (Figure 9). Each F-v profile was examined separately and any remaining outliers were removed from the linear regressions. A maximum of two data points were removed. The F-v regression lines were then extrapolated to obtain  $F_0$  and  $v_0$ , which corresponds to the intercepts with the force and velocity axes, respectively.  $S_{F-v}$  was the slope of the regression line. The P-v relationships were determined by a second degree polynomial function, because power is derived from the product of force and velocity.  $jP_{max}$  was computed from  $F_0$  and  $v_0$ . The four parameters ( $F_0$ ,  $v_0$ ,  $S_{F-v}$  and  $jP_{max}$ ) of each subject were used for further analysis.

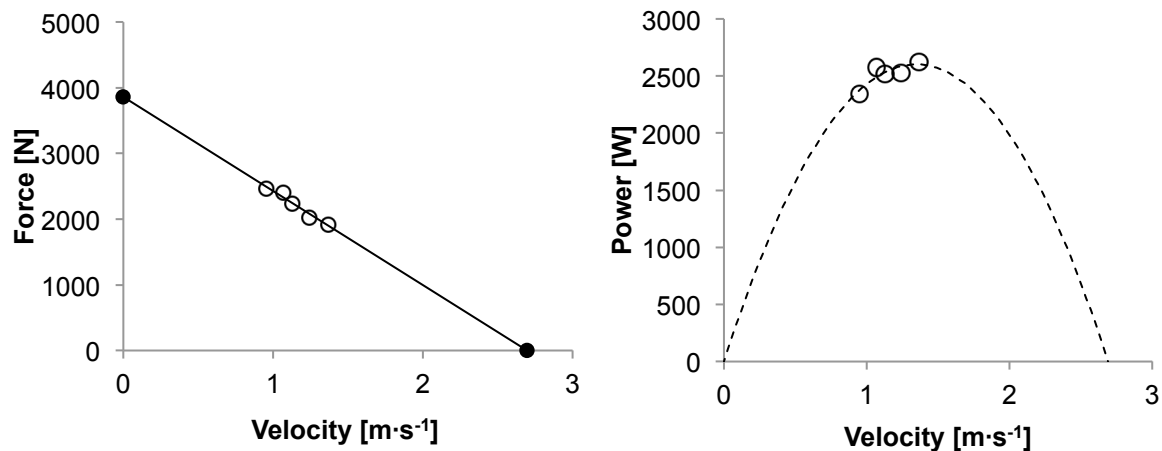


Fig. 9 : F-v (left panel) and P-v (right panel) relationships of a typical subject. Open circles represent the results at different loading conditions and the filled circles represent  $F_0$  and  $v_0$ .

### *BMX start and sprint tests*

The modified SRM powermeter recorded the start and sprint session at a sampling rate of 100 Hz, generating a large amount of data. From the data recordings, start and sprint sequences were detected. Occasional drift of the torque signal over the course of the recording was corrected using a still phase of two to three seconds before each sequence. To generate the T-Cad and P-Cad curve, three parameters were calculated per half pedal revolution; average torque (T), average cadence (Cad) and average power (P). To calculate the average torque, the torque minima had to be identified and all data points in-between averaged. The number of data in-between the torque minima was used to calculate the average cadence (one data point corresponds to 0.01 sec) in revolutions per minute (rpm). To determine the power of each half revolution, Cad was converted into angular velocity (rad/sec) and multiplied by T. This data processing was performed using a MATLAB (The MathWorks Inc., United States) script (see Appendix D).

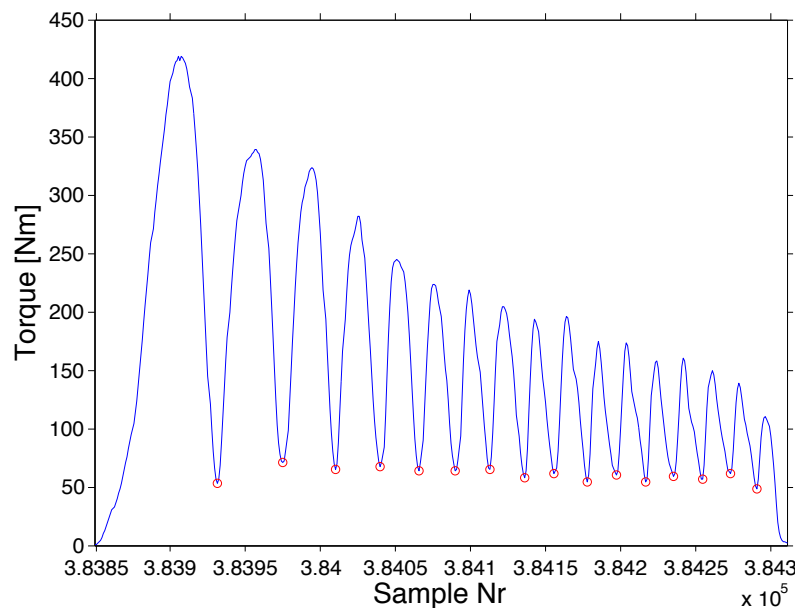


Fig. 10 : Typical torque curve over a level ground BMX sprint. Each red circle represents a torque minimum.

Once the average torque (Figure 10), cadence and power data for each half pedal stroke was determined, the T-cad and P-cad profiles for each trial of each athlete was generated using a linear regression function for T-cad relationship and second

degree polynomial function for P-cad relationship. Figure 11 shows the T-Cad and P-Cad profiles from the sprint test of a typical subject.

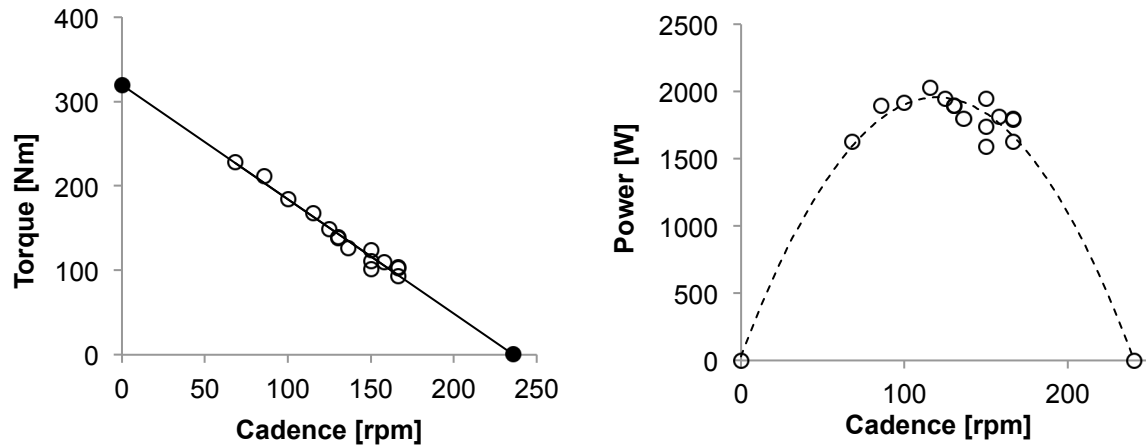


Fig. 11 : T-cad (left panel) and P-cad (right panel) relationships of a typical subject. Open circles represent the results at different loading conditions and the filled circles the  $T_0$  and  $Cad_0$ .

Each T-Cad profile was extrapolated to obtain  $T_0$  and  $Cad_0$ , which correspond to the intercepts of the line with the force and cadence axes, respectively. To obtain only one T-Cad profile per participant,  $T_0$  and  $Cad_0$  of the three sprints and five starts were averaged.  $cP_{max}$  and  $S_{T-Cad}$  were calculated using the average  $T_0$  and  $Cad_0$  of the sprints and starts. The four parameters ( $T_0$ ,  $Cad_0$ ,  $S_{T-Cad}$  and  $cP_{max}$ ) from the sprints and the starts were used for further correlation analysis.

#### 4.2.4. Statistical analysis

The specific profile components from the three tests (jump, sprint and start) as well as the sprint and start performances component mean power ( $P_{mean}$ ) and speed ( $v_{mean}$ ) were compared. Normal distribution of the dataset was confirmed by the Shapiro-Wilk test. The Pearson's product moment correlation coefficient ( $r$ ) was used to determine any significant correlation between the F-v and T-Cad parameters of the three tests. The level of significance was set at  $p \leq 0.05$ . For all statistical analysis, R software (R Foundation for Statistical Computing, Austria) was used (see Appendix E).

### 4.3. Results

Overall, each force-velocity and torque-cadence relationship showed a highly linear fit with average determination coefficients ( $r^2$ ) of  $0.96 \pm 0.03$  for the jump test,  $0.88 \pm 0.15$  for the sprint test and  $0.97 \pm 0.02$  for the start test.

The four calculated parameters of the F-v profiles of each test, as well as the sprint and start performances are represented in Table 5. The mean  $jP_{\max}$  value was 1915 W ( $\pm 490$  W) and  $cP_{\max}$  of the sprint and start test were 1587 W ( $\pm 330$  W) and 1706 W ( $\pm 357$  W), respectively. In general, the ranges of the values were very similar for the two cycling tests.

An analysis of the relationship between the different parameters of the jump profiles and the sprint and start profiles is shown in Table 4. There was a strong correlation between  $jP_{\max}$  and  $cP_{\max}$  of the sprint test ( $r = 0.82$ ,  $p \leq 0.01$ ), as well as of the start test ( $r = 0.83$ ,  $p \leq 0.01$ ), which is displayed in Figure 12.

Tab. 4 : Correlation matrix between the various power parameters of the jump test and the sprint and start test. \*\*  $p \leq 0.01$ ; \*  $p \leq 0.05$

|        |  | Jump      |  |       |                |
|--------|--|-----------|--|-------|----------------|
|        |  | $F_0$ [N] | $V_0$ [ $\text{m}\cdot\text{s}^{-1}$ ] | SFv   | $P_{\max}$ [W] |
| Sprint | $T_0$ [Nm]   | 0.87**    |  |       |                |
|        | $\text{Cad}_0$ [rpm]                                     |           | 0.21                                   |       |                |
|        | $S_{T-\text{Cad}}$                                       |           |  | 0.37  |                |
|        | $P_{\max}$ [W]   |           |  |       | 0.82**         |
|        | $P_{\text{mean } 30}$ [W]                                | 0.83**    | 0.43                                   | -0.31 | 0.81**         |
|        | $v_{\text{mean } 30}$ [ $\text{m}\cdot\text{s}^{-1}$ ]   | 0.70**    | 0.30                                   | -0.30 | 0.65*          |
| Start  | $T_0$ [Nm]   | 0.88**    |  |       |                |
|        | $\text{Cad}_0$ [rpm]                                     |           | 0.47                                   |       |                |
|        | $S_{T-\text{Cad}}$                                       |           |  | 0.53  |                |
|        | $P_{\max}$ [W]   |           |  |       | 0.83**         |
|        | $P_{\text{mean start}}$ [W]                              | 0.83**    | 0.50                                   | -0.23 | 0.86**         |
|        | $v_{\text{mean start}}$ [ $\text{m}\cdot\text{s}^{-1}$ ] | 0.61*     | 0.41                                   | -0.16 | 0.66*          |

Tab. 5: Mean absolute values and standard deviation of the F-v profile parameters for each test and the sprint performance for the whole group, male subjects and female subjects.

|               |  | Combined (n = 13) |       | Male (n = 10) |       | Female (n = 3) |       |
|---------------|--|-------------------|-------|---------------|-------|----------------|-------|
|               |  | Mean              | SD    | Mean          | SD    | Mean           | SD    |
| <b>Jump</b>   | F <sub>0</sub> [N]                           | 3057.1            | 501.7 | 3254.1        | 442.0 | 2527.4         | 341.1 |
|               | V <sub>0</sub> [m·s <sup>-1</sup> ]          | 2.5               | 0.4   | 2.5           | 0.5   | 2.4            | 0.1   |
|               | S <sub>F-v</sub>                             | -1252.0           | 285.0 | -1335.0       | 296.0 | -1054.6        | 188.1 |
|               | P <sub>max</sub> [W]                         | 1914.7            | 489.9 | 2051.0        | 524.0 | 1516.9         | 142.5 |
| <b>Sprint</b> | T <sub>0</sub> [Nm]                          | 275.2             | 48.6  | 295.0         | 38.2  | 215.9          | 10.9  |
|               | Cad <sub>0</sub> [rpm]                       | 219.1             | 11.3  | 224.6         | 6.2   | 202.9          | 4.6   |
|               | S <sub>T-Cad</sub>                           | -1.3              | 0.2   | -1.3          | 0.2   | -1.1           | 0.1   |
|               | P <sub>max</sub> [W]                         | 1586.9            | 329.6 | 1733.5        | 227.5 | 1146.9         | 58.6  |
|               | P <sub>mean 30</sub> [W]                     | 1303.2            | 261.5 | 1426.9        | 0.4   | 932.1          | 17.8  |
|               | V <sub>mean 30</sub> [m·s <sup>-1</sup> ]    | 7.7               | 0.4   | 7.9           | 0.4   | 7.2            | 0.3   |
|               |  |                   |       |               |       |                |       |
|               |  |                   |       |               |       |                |       |
| <b>Start</b>  | T <sub>0</sub> [Nm]                          | 261.3             | 48.1  | 276.8         | 37.2  | 191.3          | 3.4   |
|               | Cad <sub>0</sub> [rpm]                       | 248.9             | 14.9  | 252.9         | 13.2  | 231.0          | 6.3   |
|               | S <sub>T-Cad</sub>                           | -1.1              | 0.2   | -1.1          | 0.2   | -0.8           | 0.0   |
|               | P <sub>max</sub> [W]                         | 1705.9            | 357.3 | 1828.1        | 259.3 | 1156.0         | 10.7  |
|               |  |                   |       |               |       |                |       |
|               | P <sub>mean start</sub> [W]                  | 1306.4            | 298.0 | 1407.8        | 215.9 | 850.3          | 81.8  |
|               | V <sub>mean start</sub> [m·s <sup>-1</sup> ] | 8.2               | 0.3   | 8.3           | 0.2   | 7.6            | 0.2   |

Figure 13 shows a high relationship between sprint and start  $T_0$  with  $F_0$  ( $r = 0.87$ ,  $p \leq 0.01$  and  $r = 0.88$ ,  $p \leq 0.01$ ). The other profile parameters from the sprint and start tests, namely  $Cad_0$  and  $S_{T-Cad}$  did not correlate significantly with the corresponding parameters from the jump test. Interestingly,  $Cad_0$  and  $S_{T-Cad}$  from the start test showed a higher correlation coefficient and coefficient of determination than the sprint test (Figure 14).

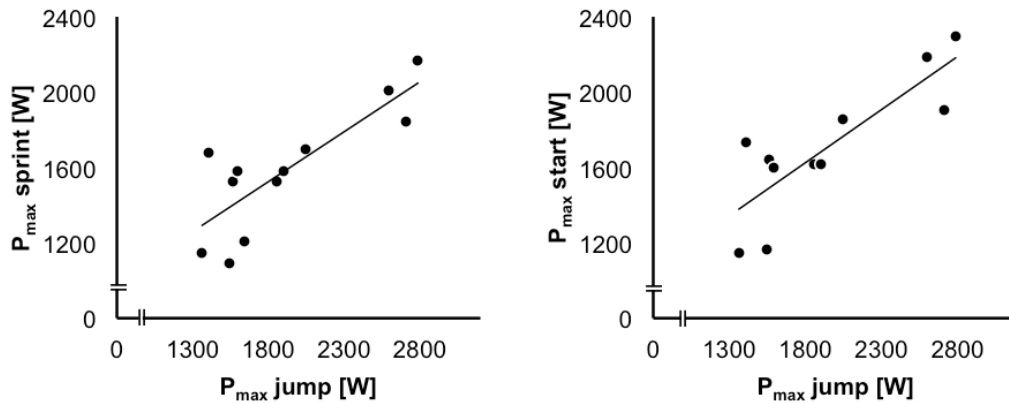


Fig. 12 : Relationship between the theoretical maximal power in the loaded squat jump and the maximal power in BMX sprint on the flat (left panel) and the maximal power in BMX start on a supercross ramp (right panel).

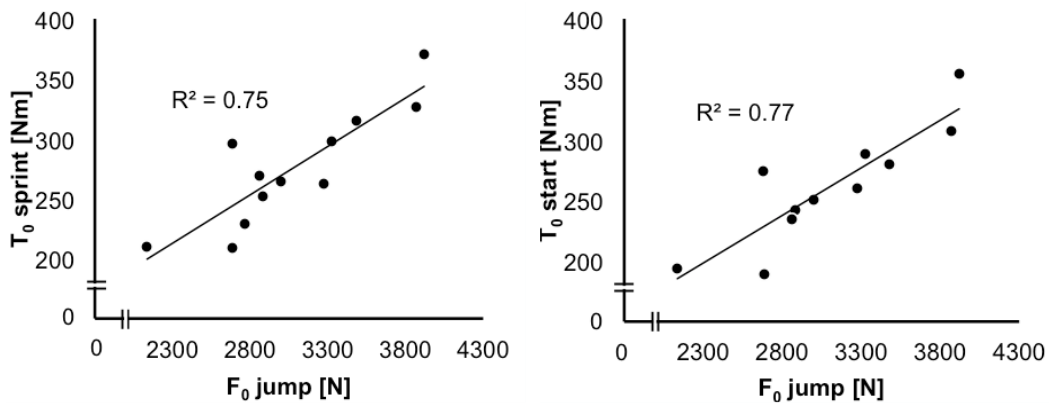


Fig. 13 : Relationship between the theoretical maximal force and torque in loaded squat jump and BMX sprint on the flat (left panel) and BMX start on a supercross ramp (right panel).

When comparing the start performances with the jump profiles, the two profile parameters  $F_0$  and  $jP_{max}$  favoured average power output over a BMX start ( $F_0$ :  $r = 0.83$ ,  $p \leq 0.01$ ;  $jP_{max}$ :  $r = 0.86$ ,  $p \leq 0.01$ ) as well as start end time ( $F_0$ :  $r = 0.61$ ,  $p \leq 0.05$ ;  $jP_{max}$ :  $r = 0.66$ ,  $p \leq 0.05$ ) as shown in Figure 15. However,  $v_0$  and  $S_{F-v}$  both showed no significant relation to  $P_{mean}$ , or  $v_{mean}$ . Very similar results were found for the sprint performances with strong correlations between the  $F_0$  and  $jP_{max}$  and  $P_{mean 30}$  ( $F_0$ :  $r = 0.83$ ,  $p \leq 0.01$ ;  $jP_{max}$ :  $r = 0.81$ ,  $p \leq 0.01$ ) and  $v_{mean 30}$  ( $F_0$ :  $r = 0.70$ ,  $p \leq 0.01$ ;  $jP_{max}$ :  $r = 0.65$ ,  $p \leq 0.05$ ).

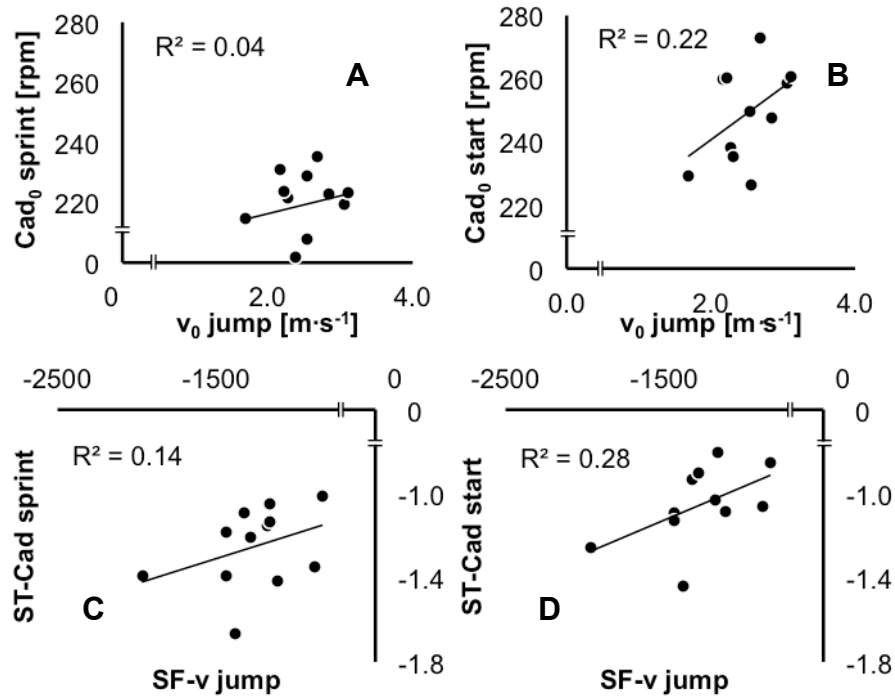


Fig. 14 : Relationships between maximal velocity in the loaded squat jump test and maximal pedalling rate in the sprint test (panel A) and the start test (panel B) and correlations between slopes of the jump test and the sprint test (panel C) and start test (panel D).

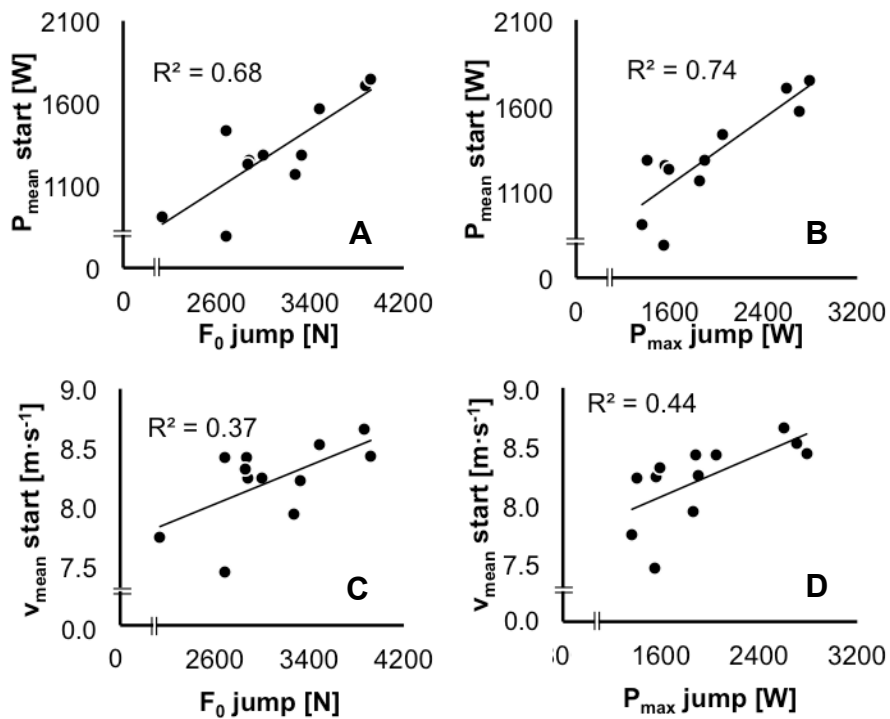


Fig. 15 : Relationship between maximal force (panel A and C) and maximal power (panel B and D) of the jump test and start performance ( $P_{\text{mean}}$  and  $V_{\text{mean}}$ ).



#### 4.4. Discussion

One of the main goals of this study was to explore the transfer of muscular power from simple linear movements into complex, sport-specific cyclic movements based on the power-velocity and force-velocity relationships. The major findings of this study were that squat jump modelled maximal power correlated strongly and significantly with modelled maximal power of the BMX sprint and the BMX start. In addition, theoretical maximal force was related to theoretical maximal torque, both for the BMX sprint and start. These correlations highlight the clear relationship between the power and force-velocity profiles of linear and cyclic movements in BMX racers and suggest a generally good transfer of muscular power from linear to cyclic movement in these subjects.

##### 4.4.1. Correlation of the power parameters $jP_{\max}$ and $cP_{\max}$

The average maximal power of the loaded SJ test ( $1915 \pm 490$  W), the sprint test ( $1587 \pm 330$  W) and the start test ( $1706 \pm 357$  W) were similar to the ones reported in recent studies (Cuk et al., 2014; Dorel et al., 2005; Gardner et al., 2007; Giroux et al., 2015a; Rahmani et al., 2001; Samozino et al., 2014). The  $jP_{\max}$  values of the male (2051 W) and female (1517 W) subjects of this study were almost identical to the value reported by Giroux et al. (2015a) for elite track and BMX riders (male: 2077 W; female: 1377 W). The same was observed for the sprint tests. Gardner et al. (2007) and Dorel et al. (2005) recorded  $cP_{\max}$  average values of 1791 W and 1600 W for male elite track cyclists. The values of our male subjects were almost equal to the ones of Gardner et al. (2007) and higher than the ones of Dorel et al. (2005). The higher  $cP_{\max}$  value is most certainly due to the fact that our subjects were allowed to stand out of the saddle during the sprints, which is known to produce greater power (Reiser et al., 2002). Even greater  $cP_{\max}$  values were shown in the start test. To the best of our knowledge no previous study has measured  $cP_{\max}$  of a BMX start from a supercross ramp, so no comparison can be made. The similarity reported between track sprint and BMX cyclists is due to the similarities of the two disciplines. Both use only one gear and require short bouts of high power.

The reported correlation between maximal power of the SJ test and the sprint and start test ( $r = 0.82$ ,  $p < 0.01$  and  $r = 0.83$ ,  $p < 0.01$ ) compared well with similar studies

where jump height was compared to  $cP_{\max}$  on a cycle ergometer. The correlation coefficients for these studies ranged between  $r = 0.69 - 0.87$  (Bertucci & Hourde, 2011; Driss et al., 1998; Hautier et al., 1996; Vandewalle et al., 1987). Our results show that the jump test as well as the sprint and start test reflect a closely related functional property, which appears to be transferred well in BMX racers. This property is probably linked to the percentage of type II muscle fibres in the legs, since a significant correlation has been reported between this and  $cP_{\max}$  (Hautier et al., 1996).

#### 4.4.2. Correlation of the F-v and T-Cad parameters

Our  $F_0$  value ( $3057 \pm 502$  N) was similar to the one reported by Giroux et al. (2015) for track and BMX cyclists ( $2930 \pm 362$  N). Compared to the active males ( $2613 \pm 539$  N) tested by Cuk et al. (2014), our data showed greater  $F_0$  for male subjects ( $3254 \pm 442$  N). This is explained by the specific BMX training history of our subjects. On the other hand, higher  $F_0$  was measured in elite male ski racers [ $3325 \pm 268$  N (Rahmani et al., 2001)], which is probably due to the specific nature of alpine ski racing. Indeed, ski racing has been characterized by an isometric and low contraction velocity (Tesch, 1995). Our  $V_0$  ( $2.5 \pm 0.4$  m·s<sup>-1</sup>) was similar to active males [ $2.51 \pm 0.51$  m·s<sup>-1</sup> (Cuk et al., 2014)] but lower than for elite athletes [sprinters:  $3.18 \pm 0.42$  m·s<sup>-1</sup>; track and BMX cyclists:  $2.86 \pm 0.34$  m·s<sup>-1</sup> (Giroux et al., 2015a); ski racers:  $3.31 \pm 0.75$  m·s<sup>-1</sup> (Rahmani et al., 2001)].  $S_{F-v}$  is the ratio between theoretical maximal force and velocity. Our data ( $-1252 \pm 285$  N·s·m<sup>-1</sup>) exhibited a steeper slope compared to the ones reported by Samozino et al. (2014) for sprinters, soccer and rugby players ( $-879 \pm 558$  N·s·m<sup>-1</sup>) but is in agreement with cyclists'  $S_{F-v}$  ( $-1120 \pm 220$  N·s·m<sup>-1</sup>) measured by Giroux et al. (2016). In general, the balance between force and velocity capabilities of our subjects is comparable to cyclists in other studies but more force oriented than athletes from the other aforementioned sports.

The T-Cad parameters of the sprint and the start tests were partially in agreement with other studies.  $Cad_0$  of the start test ( $249 \pm 15$  rpm) was found to be higher than in the sprint test ( $219 \pm 11$  rpm), but both values were lower than the ones reported by elite track cyclists [ $260 \pm 9$  rpm (Dorel et al., 2005); 258 rpm (Gardner et al., 2007);  $249 \pm 12$  rpm (Vandewalle et al., 1987)]. In contrast,  $T_0$  values (sprint:  $275 \pm$

48 Nm; start:  $261 \pm 48$  Nm) were found to be higher than the ones of the elite track cyclists [236 – 266 N (Dorel et al., 2005; Gardner et al., 2007)]. Regrettably, no  $S_{T-Cad}$  values were reported by the aforementioned studies. But when using the reported  $T_0$  and  $Cad_0$  from Gardner et al. (2007) and Dorel et al. (2005) to calculate  $S_{T-Cad}$  as follow:

$$S_{T-Cad} = -\frac{T_0}{Cad_0}$$

it appeared that our subjects (sprint:  $-1.3 \pm 0.2$ ; start:  $-1.1 \pm 0.2$ ) once more exhibited steeper slopes than elite track cyclists [ $-1.03$  for Gardner et al. (2007) and  $-0.91$  for Dorel et al. (2005)]. This could indicate that BMX is more force oriented than track sprint cycling.

The correlation of the F-v parameters ( $F_0 - T_0$ ,  $v_0 - Cad_0$  and  $S_{F-v} - S_{T-Cad}$ ) between the jumping and cycling showed inconsistent results. For the sprint test, a weak non-significant correlation was found between the parameters  $v_0$  and  $Cad_0$  ( $r = 0.21$ ) as well as between  $S_{F-v}$  and  $S_{T-Cad}$  ( $r = 0.37$ ). Similar results have been reported in the unpublished work of Gross & Gross (2015) for sports students. This lack of correlation indicates that the capacity for generating velocity in linear and cyclic movements is not always related. This may be due to the nature of the movements. Indeed, in contrast to linear movements, cyclic motions are characterised by a rise and decline of muscle active state. Therefore, the capacity to generate maximal cadence succumbs to muscle coordination. This has also been shown by Samozino et al. (2007). This may explain why no correlation exists between  $S_{F-v}$  and  $S_{T-Cad}$  since these two parameters depend on  $v_0$  and  $Cad_0$ , respectively. Maximal force was significantly related to maximal torque in sprint on levelled ground ( $r = 0.87$ ;  $p < 0.01$ ) and also to maximal torque in starts on a supercross ramp ( $r = 0.88$ ;  $p < 0.01$ ). These results show that  $F_0$ , which is an indicator of maximal strength can be transferred from a linear onto a cyclic movement.

Interestingly, reported correlations ( $F_0 - T_0$ ,  $v_0 - Cad_0$ ,  $S_{F-v} - S_{T-Cad}$  and  $jP_{max} - cP_{max}$ ) between the jump and sprint tests were lower than between the jump and start tests. Despite the fact that correlations of the velocity and slope parameters were not

significant, it shows a tendency, which suggests that our BMX athletes were better adapted to transfer F-v characteristics to the more competition-specific situation.

Intriguingly, the  $cP_{\max}$  value of the start test ( $1706 \pm 357$  W) was higher than the  $cP_{\max}$  value of the sprint test ( $1587 \pm 330$  W). To our knowledge no scientific literature has measured  $cP_{\max}$  of a BMX start from a supercross ramp, so there is no comparison to be made.  $cP_{\max}$  is determined by  $T_0$  and  $Cad_0$ . When these two parameters of the start test and the sprint test were compared, higher  $Cad_0$  and lower  $T_0$  values were observed in the start test. A plausible explanation is the reduced inertial load on an inclined structure such as the supercross ramp. The assistance of the gravitational acceleration force leads to an increase of pedalling rate and hence a decrease in torque. This fast increase in pedalling rate may explain the higher maximal power output in the start test. Rylands et al. (2016) found the same decrease in torque and increase in pedalling rate when reducing inertial load by changing gear to a lower ratio, but their results showed a decrease in peak power.

#### 4.4.3. Correlation of the F-v parameters and start and sprint performances

Another goal of this study was to identify specific parameters of the power profiles from the linear movement, which favours BMX performance. These favourable parameters were found in  $F_0$  and  $jP_{\max}$ . Indeed a significant relationship was described between theoretical maximal jumping power and BMX performance as well as between theoretical maximal force and BMX performance.

Average power performance of the BMX starts was  $1306 \pm 298$  W and mean velocity was  $8.2 \pm 0.3$  m·s<sup>-1</sup>. Unfortunately no performance values were reported in other studies. A strong correlation was found between  $jP_{\max}$  and  $P_{\text{mean start}}$  ( $r = 0.86$ ;  $p < 0.01$ ) and  $jP_{\max}$  and  $v_{\text{mean start}}$  ( $r = 0.66$ ;  $p < 0.05$ ). No such correlation to start power performance has to our knowledge been reported previously. However, the latter is in agreement with the results of Bertucci & Hourde (2011) and Bertucci et al. (2007) who reported similar correlations between countermovement jump height and time performance ( $r = 0.65$ ;  $p < 0.05$ ) and between SJ height and time performance on the initial 29 meters of a BMX track ( $r = 0.58$ ;  $p < 0.01$ ). When comparing squat jump power to time performance, Bertucci et al. (2007) found an even stronger correlation ( $r = 0.83$ ;  $p < 0.01$ ). Our results indicate that there is a strong relationship between

maximal jumping power and the capacity of the riders to accelerate out of the start gate in the first portion of a race. Furthermore, this suggests that performance of the initial straight of a race can partially be explained by maximal SJ power. Debraux et al. (2011) showed that  $F_0$  of non-ballistic half squat correlated with  $cP_{\max}$  of a force-velocity test performed on a cycle ergometer ( $r = 0.65$ ;  $p < 0.05$ ).  $cP_{\max}$  of a force-velocity test is known to correlate with BMX performance over the first portion of a race (Bertucci & Hourde, 2011). Therefore, our strong correlations between  $F_0$  and  $P_{\text{mean start}}$  ( $r = 0.83$ ;  $p < 0.01$ ) and  $F_0$  and  $v_{\text{mean}}$  ( $r = 0.61$ ;  $p < 0.05$ ) confirm the statement of Debraux et al. (2011): “The maximal theoretical force is a determinant factor of the performance in short all-out sprint in cycling”. Indeed, in the first pedal strokes BMX riders must overcome inertia and therefore need to develop a larger amount of force. No significant correlations were found between  $v_0$  and BMX start performance as well as between  $S_{F-v}$  and BMX start performance. In the sprint test on level ground very similar results were found for the performance ( $P_{\text{mean } 30}: 1303 \pm 261 \text{ W}$ ,  $v_{\text{mean } 30}: 7.7 \pm 0.4 \text{ m}\cdot\text{s}^{-1}$ ) as well as for the correlations to the jump parameters.

These discoveries are significant for BMX racing since the start and first straightaway are the most crucial parts of the race. After that, it is very difficult to overtake the opponents. The results suggest that the greater maximal power developed in a squat jump, the greater the mean power produced and the faster the start. Moreover, it gives a clear indication of how the components of the F-v relationship contribute most to power to favour start and sprint performance.

#### 4.4.4. Limitations

Although some significant relationships were found between the force-velocity profiles of linear and cyclic movements, not all power parameters correlated. Higher correlation with higher significance level could have possibly been found if we would have been able to recruit a larger number of participants. On the other hand, our subject cohort was rather heterogeneous, which would have increased the chance of finding significant correlations. This was shown by the relatively high variability of all measured parameters ( $CV\% = 6.0 - 25.6$ ). While all riders participated in the jump test, one subject's data was missing for the sprint test and two for the start test.

Therefore, we may have attained higher significance level for some correlations with a higher number of participants.

## 5. Conclusion

Many researchers have investigated the relationship between force and velocity in both ballistic leg extensions and cycling, but these F-v profiles were never compared. Therefore, the aim of this work was to clarify the relation between the force-velocity profiles of linear and cyclic movements. Prior to the actual BMX study, the reliability study served as pilot project to test the measuring system and the protocol. The results showed non-reliable data from the Quattro Jump force plate and thus was excluded from the BMX study. The main study showed that the force-velocity properties from squat jump test are somewhat related to the torque-cadence properties of BMX sprints or starts and BMX performance. It was shown that maximal force ( $F_0$  and  $T_0$ ) and power ( $jP_{\max}$  and  $cP_{\max}$ ) parameters of these profiles correlate strongly, which supports a good transfer mechanism of leg muscle force at low velocity from linear to cyclic movement patterns. Furthermore, maximal force ( $F_0$ ) and power ( $jP_{\max}$ ) correlated strongly with BMX performance, suggesting that the loaded SJ test is a good performance indicator.

These findings have several implications for coaches and athletes. The assessment of the F-v profile helps identify an athlete's strengths and weaknesses and aid in designing effective and individualised training programs. During a rehabilitation process of an athlete, the F-v profile can help identify deficiencies, which have then to be remedied. It could also act as a decision-making criteria for returning to competition after an injury. Furthermore, it is a simple and cheap method to monitor the athlete's development over the years and can also be used to scout new talents. These findings could also be exploited in other cycling disciplines where maximal power plays an essential role such as track cycling or road cycling.

Future work should be focusing on training-induced changes to F-v characteristic and its consequences on starting performance.

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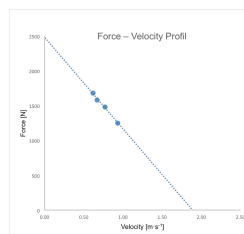
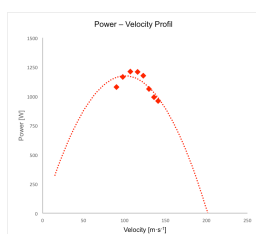
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## APPENDICES

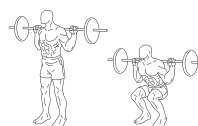
### Appendix A: Recherche de volontaires

#### RECHERCHE VOLONTAIRES POUR PARTICIPATION À UNE ÉTUDE SUR LA RELATION FORCE-VITESSE



**Découvre ta courbe de force-vitesse et reçois des recommandations d'entraînement personnalisées.**

Afin de réaliser mon travail de Master en Science du Sport, option santé/recherche, je cherche 10 sujets masculins intéressés à participer à une étude portant sur la relation force-vitesse des mouvements linéaires explosifs.



**Tâche:** 5 Séries de Squat Jumps  
**Durée de l'étude:** 2 sessions de 30min  
**Dates:** 7. au 20. Septembre 2015 selon votre convenance

Les profils force-vitesse obtenus seront remis à chaque participant en plus de recommandations d'entraînement personnalisées.

Si vous êtes intéressé, veuillez me contacter pour la date et l'heure de la 1<sup>ère</sup> session. Nous fixerons, ensuite le rendez vous pour la 2<sup>ème</sup> session.

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## Appendix B: Questionnaire reliability study



Contrôle de qualité Swiss Olympic

SWISS OLYMPIC MEDICAL CENTERS

### Check-list

Type de test: ☐ nouveau (standard de qualité) ☐ ancien (ne pas cocher)

Nom: \_\_\_\_\_ Prénom: \_\_\_\_\_ Date de naissance: \_\_\_\_\_  
 Poids: \_\_\_\_\_ Taille: \_\_\_\_\_ Type de carte AOS: ☐ aucune  
 Date/heure du test: \_\_\_\_\_ / \_\_\_\_\_ h. Cadre: ☐ pas de cadre

1. **Phase d'entraînement** ☐ Préparation ☐ Pré-compétition ☐ Compétition  
☐ Réhabilitation

2. **Dernière compétition**

Quand: \_\_\_\_\_ Quoi: \_\_\_\_\_

3. **Entraînement** **Type** **Durée totale** **Intensité globale**  
 <60' 60-120' >120' >300' légère mod. dure/interv.  
 2 jours avant test: \_\_\_\_\_ ☐ ☐ ☐ ☐ ☐ ☐ ☐  
 1 jour avant test: \_\_\_\_\_ ☐ ☐ ☐ ☐ ☐ ☐ ☐

4. **Alimentation** (au cours des 2 derniers jours)

Normale ☐  
 Régime enrichi en hydr. de carb. ☐ Régime amaigrissant ☐  
 Régime dissocié ☐ Diète lipidique (début < 4 jours) ☐  
 Alcool (la veille) ☐ non ☐ oui Combien/quoi: \_\_\_\_\_  
 Dernier repas avant (h): \_\_\_\_\_ quoi: \_\_\_\_\_

5. **Maladie** (15 derniers jours)

☐ aucune ☐ : \_\_\_\_\_

6. **Accident(s)** (depuis le dernier test)

☐ aucun ☐ : \_\_\_\_\_

7. **Problèmes le jour du test**

☐ aucun ☐ : \_\_\_\_\_

8. **Etat de forme** (comment je me sens aujourd'hui)

Cocher: 1 2 3 4 5 6 7 8 9 10 (1=catastrophique, 10=super)

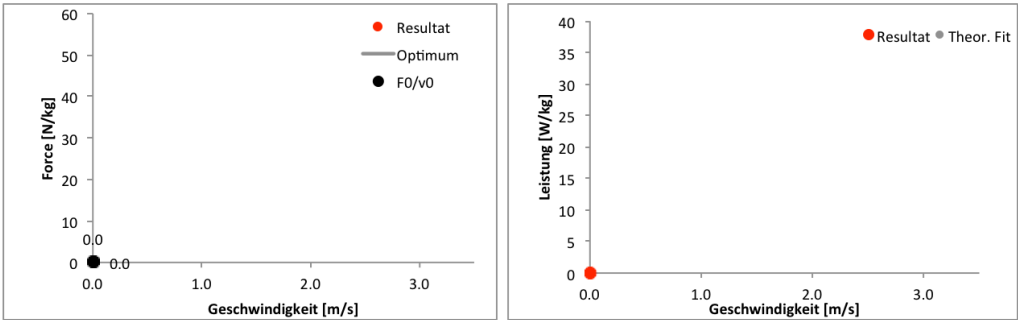
9. **Remarques:**

\_\_\_\_\_  
 \_\_\_\_\_

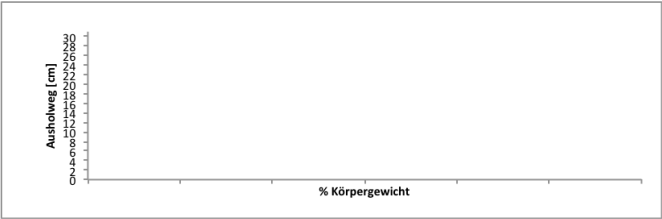


Appendix C: Spreadsheet of Samozino’s computation method

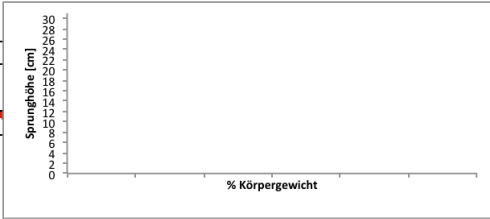
| Körpermasse<br>[kg] | Stufe<br>[%KG] | Zusatzlast<br>[kg] | Sprunghöhe<br>[cm] | Weg<br>[cm] | F<br>[N] | F <sub>rel</sub><br>[N/kg] | V<br>[m/s] | P <sub>abs</sub><br>[W] | P <sub>rel</sub><br>[W/kg] | m <sub>gesamt</sub><br>[kg] |  |  |  |  |
|---------------------|----------------|--------------------|--------------------|-------------|----------|----------------------------|------------|-------------------------|----------------------------|-----------------------------|--|--|--|--|
|                     | 0              |                    |                    |             | #DIV/0!  | #DIV/0!                    | 0.00       | #DIV/0!                 | #DIV/0!                    | 0.0                         |  |  |  |  |
|                     | 20             |                    |                    |             | #DIV/0!  | #DIV/0!                    | 0.00       | #DIV/0!                 | #DIV/0!                    | 0.0                         |  |  |  |  |
|                     | 40             |                    |                    |             | #DIV/0!  | #DIV/0!                    | 0.00       | #DIV/0!                 | #DIV/0!                    | 0.0                         |  |  |  |  |
|                     | 60             |                    |                    |             | #DIV/0!  | #DIV/0!                    | 0.00       | #DIV/0!                 | #DIV/0!                    | 0.0                         |  |  |  |  |
|                     | 80             |                    |                    |             | #DIV/0!  | #DIV/0!                    | 0.00       | #DIV/0!                 | #DIV/0!                    | 0.0                         |  |  |  |  |



|                  | Resultat | Optimum                   |
|------------------|----------|---------------------------|
| S <sub>Fv</sub>  | #DIV/0!  | S <sub>FvOpt</sub> #NV    |
| P <sub>max</sub> | #DIV/0!  |                           |
| v <sub>0</sub>   | #DIV/0!  | v <sub>0Opt</sub> #DIV/0! |
| F <sub>0</sub>   | #DIV/0!  | F <sub>0Opt</sub> #DIV/0! |
| Empfehlung       |          |                           |



alpha (°)  
90  
h<sub>PO</sub>  
#DIV/0!



## Appendix D: MATLAB script

```
%%% Sprint_subject1

clearload BMX_data.mat

% used to extract the sprints

min=subject1_data(:,1)*0.01/60; figure,plot(min,subject1_data(:,3))
figure,plot(subject1_data(:,3)) grid on

% extract sprints

S1=subject1_data([342609:343096],:); S2=subject1_data([373950:374371],:);
S3=subject1_data([405362:405856],:);

%% correct S1, S2, S3

%% S1

corr1=subject1_data([339500:340000],:); mean1=mean(corr1);

% separat in

indiv. matrix

S1c=S1(:,2);S1t=S1(:,3);S1s=S1(:,4);S1p=S1(:,5);S1ap=S1(:,6);% correct indiv. matrix S1c1=S1c-
mean1(:,2); S1t1=S1t-mean1(:,3); S1s1=S1s-mean1(:,4); S1p1=S1p-mean1(:,5); S1ap1=S1ap-
mean1(:,6);% merge indiv. matrixS1a=[S1(:,1) S1c1 S1t1 S1s1 S1p1 S1ap1];

%% S2

corr2=subject1_data([362500:363000],:); mean2=mean(corr2);

% separat in

indiv. matrix

S2c=S2(:,2);S2t=S2(:,3);S2s=S2(:,4);S2p=S2(:,5);S2ap=S2(:,6);% correct indiv. matrix S2c1=S2c-
mean2(:,2); S2t1=S2t-mean2(:,3); S2s1=S2s-mean2(:,4); S2p1=S2p-mean2(:,5); S2ap1=S2ap-
mean2(:,6);% merge indiv. matrixS2a=[S2(:,1) S2c1 S2t1 S2s1 S2p1 S2ap1];

%% S3

corr3=subject1_data([402000:402500],:); mean3=mean(corr3);% separat in indiv.
matrixS3c=S3(:,2);

S3t=S3(:,3);S3s=S3(:,4);S3p=S3(:,5);S3ap=S3(:,6);% correct indiv. matrix S3c1=S3c-mean1(:,2);
S3t1=S3t-mean1(:,3); S3s1=S3s-mean1(:,4); S3p1=S3p-mean1(:,5); S3ap1=S3ap-mean1(:,6);% merge
indiv. matrixS3a=[S3(:,1) S3c1 S3t1 S3s1 S3p1 S3ap1];

% overwrite with corrected data

S1=S1a;
S2=S2a;
S3=S3a;
%% End of correction

% extract torque data

t1=S1(:,3); t2=S2(:,3); t3=S3(:,3);

% extract sample data

sample1=S1(:,1); sample2=S2(:,1); sample3=S3(:,1);

% plot all 3 sprints
```

```

subplot(1,3,1)plot(t1)title('S1')grid online(xlim,[0 0], 'Color','r')

subplot(1,3,2)plot(t2)title('S2')grid online(xlim,[0 0], 'Color','r')

subplot(1,3,3)plot(t3)title('S3')grid online(xlim,[0 0], 'Color','r')

%% Find the local minima

t1inv = -t1;
t2inv = -t2;
t3inv = -t3;
[pks1 loc1] = findpeaks(t1inv,'MinPeakHeight',-100,'MinPeakDistance',8); %find peaks&location
in inversed dataset[pks2 loc2] = findpeaks(t2inv,'MinPeakHeight',-100,'MinPeakDistance',8);

[pks3 loc3] = findpeaks(t3inv,'MinPeakHeight',-100,'MinPeakDistance',8);

%% correcting the peaks

loc2(1) = []; pks2(1) = []; loc3(1) = []; pks3(1) = [];

%% figure with minima

pks1 = -pks1; pks2 = -pks2; pks3 = -pks3;

figure, plot(sample1,t1,sample1(loc1),pks1,'or') xlabel('sample Nr')ylabel('torque')axis tight
figure, plot(sample2,t2,sample2(loc2),pks2,'ob') xlabel('sample Nr')ylabel('torque')axis tight
figure, plot(sample3,t3,sample3(loc3),pks3,'og') xlabel('sample Nr')ylabel('torque')axis tight

%% average torque/cycle

T1(1) = mean(t1(1:loc1(1))); for ka = 1:length(loc1)-1
T1(ka+1) = mean(t1(loc1(ka):loc1(ka+1)));
end

T1(length(loc1)+1) = mean(t1(loc1(end):end)); T1=T1'; %transforme row -> column

T2(1) = mean(t2(1:loc2(1))); for kb = 1:length(loc2)-1
T2(kb+1) = mean(t2(loc2(kb):loc2(kb+1)));
end

T2(length(loc2)+1) = mean(t2(loc2(end):end)); T2=T2'; %transforme row -> column

T3(1) = mean(t3(1:loc3(1))); for kc = 1:length(loc3)-1
T3(kc+1) = mean(t3(loc3(kc):loc3(kc+1)));
end

T3(length(loc3)+1) = mean(t3(loc3(end):end)); T3=T3'; %transforme row -> column

%% nbr position/cycle => time

s1(1) = loc1(1); s1(2:length(loc1)) = diff(loc1); s1(end+1) = length(t1)-loc1(end);

s1 = s1';

s2(1) = loc2(1); s2(2:length(loc2)) = diff(loc2); s2(end+1) = length(t2)-loc2(end);

s2 = s2';

s3(1) = loc3(1); s3(2:length(loc3)) = diff(loc3); s3(end+1) = length(t3)-loc3(end);

```

```

s3 = s3';

% cadence/cycle

rpm1 = 60./(s1*0.01*2); rpm2 = 60./(s2*0.01*2); rpm3 = 60./(s3*0.01*2);

%% angular velocity [rad/sec]

w1 = pi/180*360*rpm1/60; w2 = pi/180*360*rpm2/60; w3 = pi/180*360*rpm3/60;

%% power

p1 = T1.*w1;
p2 = T2.*w2;
p3 = T3.*w3;
%% export data in xlsx% creat a matrix with toruqe, cadence and power Sprint1 =
cat(2,T1,rpm1,p1);Sprint2 = cat(2,T2,rpm2,p2);Sprint3 = cat(2,T3,rpm3,p3);

csvwrite('Subject1_sprint1_corr.csv',Sprint1,1,0)
csvwrite('Subject1_sprint2_corr.csv',Sprint2,1,0)
csvwrite('Subject1_sprint3_corr.csv',Sprint3,1,0)

```

## Appendix E: R script & statistical results

```
### R script

setwd("~/Documents/Universität/MSc Fribourg/Macolin/Methodes Quantitatives/Méthodes
quantitatives de recherche et analyse de données/Fichier de travail R/BMX_stat")

rm(list=ls())

if(T){library(psych) library(reshape2)

library(ggplot2) library(plyr) library(pastecs) library(car)}

# Load files Start=read.table("Start.txt", header=T) Jump=read.table("Jump.txt", header=T)
Sprint=read.table("Sprint.txt", header=T)

# # tests de corrélation (r < 0.5: faible relation // 0.5 < r < 0.7: relation modérée //r >
0.7: forte relation)#si paramétriques#Jump, Sprint, Start

print(stat.desc(cbind(Jump$F0, Jump$v0, Jump$SFv, Jump$Pmax),basic = F,
norm=T))print(stat.desc(cbind(Sprint$T0, Sprint$C0, Sprint$STc, Sprint$Pmax, Sprint$Pmean30,
Sprint$vmean30),basic = F, norm=T)) print(stat.desc(cbind(Start$T0, Start$C0, Start$STc,
Start$Pmax, Start$Pmean_start, Start$vmean_start),basic = F, norm=T))

# ok paramétrique, pearson = r

#Is there a correlation between the maximal power output of the BMX sprints,#BMX starts and
the derived maximal power output of the vertical jump tests?

##Sprint Pmax & Start Pmax vs. Jump Pmax print(cor.test(Sprint$Pmax, Jump$Pmax, method
="pearson")) print(cor.test(Start$Pmax, Jump$Pmax, method ="pearson"))

#Do the various components of the power profiles from the BMX sprints, #BMX starts and the
vertical jump test correlate?##Sprint T0 & Start T0 vs Jump F0print(cor.test(Sprint$T0,
Jump$F0, method ="pearson")) print(cor.test(Start$T0, Jump$F0, method ="pearson"))

##Sprint C0 & Start C0 vs Jump v0 print(cor.test(Sprint$C0, Jump$v0, method ="pearson"))
print(cor.test(Start$C0, Jump$v0, method ="pearson"))

##Sprint STc & Start STc vs Jump SFv print(cor.test(Sprint$STc, Jump$SFv, method ="pearson"))

print(cor.test(Start$STc, Jump$SFv, method ="pearson"))

#Are there specific characteristics of the power profile, which favour the #mean power (Pmean
30, Pmean_start) or the end time (vmean 30, vmean_start) of#a 30 meter BMX sprint or a BMX
start?

##Jump parameter vs Sprint Pmean30 print(cor.test(Sprint$Pmean30, Jump$F0, method ="pearson"))
print(cor.test(Sprint$Pmean30, Jump$v0, method ="pearson")) print(cor.test(Sprint$Pmean30,
Jump$SFv, method ="pearson"))

##Jump parameter vs Start Pmean_ print(cor.test(Start$Pmean_start, Jump$F0, method
="pearson")) print(cor.test(Start$Pmean_start, Jump$v0, method ="pearson"))
print(cor.test(Start$Pmean_start, Jump$SFv, method ="pearson"))

##Jump parameter vs Sprint vmean30 print(cor.test(Sprint$vmean30, Jump$F0, method ="pearson"))
print(cor.test(Sprint$vmean30, Jump$v0, method ="pearson")) print(cor.test(Sprint$vmean30,
Jump$SFv, method ="pearson"))

##Jump parameter vs Start vmean_start print(cor.test(Start$vmean_start, Jump$F0, method
="pearson")) print(cor.test(Start$vmean_start, Jump$v0, method ="pearson"))
print(cor.test(Start$vmean_start, Jump$SFv, method ="pearson"))

#Does vertical jump power (Pmax jump) favour sprint or start performance? ##Jump Pmax vs
Sprint Pmean30print(cor.test(Sprint$Pmean30, Jump$Pmax, method ="pearson"))##Jump Pmax vs
Sprint vmean30

print(cor.test(Sprint$vmean30, Jump$Pmax, method ="pearson"))

##Jump Pmax vs Start Pmean_start print(cor.test(Start$Pmean_start, Jump$Pmax, method
```

```
="pearson")) ##Jump Pmax vs Start vmean_start print(cor.test(Start$vmean_start, Jump$Pmax,
method ="pearson"))
```

```
### statistical results
```

|              | V1            | V2         | V3            | V4            |
|--------------|---------------|------------|---------------|---------------|
| median       | 2.882000e+03  | 2.5000000  | -1181.0000000 | 1.857000e+03  |
| mean         | 3.057154e+03  | 2.4923077  | -1252.0769231 | 1.914615e+03  |
| SE.mean      | 1.391821e+02  | 0.1034418  | 79.0249443    | 1.359198e+02  |
| CI.mean.0.95 | 3.032518e+02  | 0.2253802  | 172.1805624   | 2.961438e+02  |
| var          | 2.518316e+05  | 0.1391026  | 81184.2435897 | 2.401644e+05  |
| std.dev      | 5.018283e+02  | 0.3729646  | 284.9284886   | 4.900657e+02  |
| coef.var     | 1.641489e-01  | 0.1496463  | -0.2275647    | 2.559604e-01  |
| skewness     | 2.137366e-01  | -0.2468304 | -0.8173210    | 6.791658e-01  |
| skew.2SE     | 1.733929e-01  | -0.2002401 | -0.6630482    | 5.509704e-01  |
| kurtosis     | -8.190387e-01 | -0.5138125 | 0.6132674     | -1.125234e+00 |
| kurt.2SE     | -3.438812e-01 | -0.2157291 | 0.2574862     | -4.724402e-01 |
| normtest.W   | 9.453669e-01  | 0.9707521  | 0.9117062     | 8.657327e-01  |
| normtest.p   | 5.300219e-01  | 0.9030895  | 0.1935070     | 4.588092e-02  |

|              | V1           | V2           | V3          | V4            | V5            | V6          |
|--------------|--------------|--------------|-------------|---------------|---------------|-------------|
| median       | 266.6991772  | 222.35493055 | -1.19484227 | 1.579559e+03  | 1317.9154870  | 7.82676755  |
| mean         | 275.1938832  | 219.14921799 | -1.25216789 | 1.586861e+03  | 1303.1936900  | 7.74050394  |
| SE.mean      | 14.0338494   | 3.26000682   | 0.05488374  | 9.514292e+01  | 75.4917774    | 0.12310992  |
| CI.mean.0.95 | 30.8882943   | 7.17522663   | 0.12079831  | 2.094082e+02  | 166.1562818   | 0.26823347  |
| var          | 2363.3871508 | 127.53173334 | 0.03614670  | 1.086261e+05  | 68388.1015152 | 0.19702868  |
| std.dev      | 48.6146804   | 11.29299488  | 0.19012287  | 3.295847e+02  | 261.5111881   | 0.44387913  |
| coef.var     | 0.1766561    | 0.05153108   | -0.15183496 | 2.076960e-01  | 0.2006695     | 0.05734499  |
| skewness     | 0.2999250    | -0.45674175  | -0.60180096 | 5.346743e-02  | -0.1948158    | -0.03404563 |
| skew.2SE     | 0.2353084    | -0.35834012  | -0.47214739 | 4.194827e-02  | -0.1528442    | -0.02761937 |
| kurtosis     | -0.9729321   | -1.12210884  | -0.69889634 | -1.102664e+00 | -1.2698312    | -0.37525296 |
| kurt.2SE     | -0.3947798   | -0.45531023  | -0.28358626 | -4.474201e-01 | -0.5152505    | -0.15755354 |
| normtest.W   | 0.9631369    | 0.93618213   | 0.92752293  | 9.542699e-01  | 0.9174482     | 0.93012127  |
| normtest.p   | 0.8274965    | 0.45025000   | 0.35459502  | 6.999797e-01  | 0.2654790     | 0.34206916  |

|              | V1           | V2           | V3          | V4            | V5            | V6          |
|--------------|--------------|--------------|-------------|---------------|---------------|-------------|
| median       | 259.7579000  | 249.67680000 | -1.06150000 | 1.643519e+03  | 1.281472e+03  | 8.28315000  |
| mean         | 261.2658273  | 248.93639091 | -1.05281818 | 1.705869e+03  | 1.306418e+03  | 8.22080000  |
| SE.mean      | 14.4882044   | 4.49408826   | 0.05537827  | 1.077436e+02  | 8.984912e+01  | 0.09963312  |
| CI.mean.0.95 | 32.2817310   | 10.01345267  | 0.12339047  | 2.400677e+02  | 2.001963e+02  | 0.21929102  |
| var          | 2308.9887235 | 222.16512259 | 0.03373428  | 1.276955e+05  | 8.880151e+04  | 0.11912110  |
| std.dev      | 48.0519378   | 14.90520455  | 0.18366894  | 3.573451e+02  | 2.979958e+02  | 0.34513925  |
| coef.var     | 0.1839197    | 0.05987555   | -0.17445457 | 2.094798e-01  | 2.281015e-01  | 0.04198366  |
| skewness     | 0.1837316    | -0.10637527  | -0.54652350 | -1.606686e-02 | -1.156304e-01 | -0.88181374 |
| skew.2SE     | 0.1390458    | -0.08050347  | -0.41360214 | -1.215920e-02 | -8.750765e-02 | -0.69183349 |
| kurtosis     | -0.7781581   | -1.48381670  | -0.62164392 | -9.953358e-01 | -1.118533e+00 | -0.35581002 |
| kurt.2SE     | -0.3041068   | -0.57988056  | -0.24294054 | -3.889806e-01 | -4.371265e-01 | -0.14437453 |
| normtest.W   | 0.9705398    | 0.93894954   | 0.95112909  | 9.342941e-01  | 9.532159e-01  | 0.89514758  |
| normtest.p   | 0.8919240    | 0.50822861   | 0.65841114  | 4.559053e-01  | 6.852313e-01  | 0.13731271  |

Pearson's product-moment correlation

```
data: Sprint$Pmax and Jump$Pmax
t = 4.5791, df = 10, p-value = 0.001012
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
 0.4717089 0.9487295
sample estimates:
cor
0.8228524
```

Pearson's product-moment correlation

```
data: Start$Pmax and Jump$Pmax
t = 4.5496, df = 9, p-value = 0.001387
```

```
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
 0.4706763 0.9559663
sample estimates:
      cor
0.8348375
```

Pearson's product-moment correlation

```
data: Sprint$T0 and Jump$F0
t = 5.4667, df = 10, p-value = 0.0002743
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
 0.5796785 0.9617422
sample estimates:
      cor
0.8656103
```

Pearson's product-moment correlation

```
data: Start$T0 and Jump$F0
t = 5.497, df = 9, p-value = 0.0003817
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
 0.5870075 0.9679668
sample estimates:
      cor
0.8777866
```

Pearson's product-moment correlation

```
data: Sprint$C0 and Jump$V0
t = 0.6456, df = 10, p-value = 0.5331
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
-0.4223566 0.6942355
sample estimates:
      cor
0.2000307
```

Pearson's product-moment correlation

```
data: Start$C0 and Jump$V0
t = 1.5449, df = 9, p-value = 0.1568
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
-0.1958302 0.8298053
sample estimates:
      cor
0.4578274
```

Pearson's product-moment correlation

```
data: Sprint$STc and Jump$SFv
t = 1.2501, df = 10, p-value = 0.2397
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
-0.2614165 0.7774986
sample estimates:
      cor
0.3676414
```

Pearson's product-moment correlation

```
data: Start$STc and Jump$SFv
t = 1.8881, df = 9, p-value = 0.09162
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
 -0.09879045  0.85828354
sample estimates:
cor
0.5326505
```

Pearson's product-moment correlation

```
data: Sprint$Pmean30 and Jump$F0
t = 4.6538, df = 10, p-value = 0.0009028
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
 0.4820213 0.9500464
sample estimates:
cor
0.8271156
```

Pearson's product-moment correlation

```
data: Sprint$Pmean30 and Jump$v0
t = 1.3706, df = 10, p-value = 0.2005
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
 -0.2283335  0.7910428
sample estimates:
cor
0.3976805
```

Pearson's product-moment correlation

```
data: Sprint$Pmean30 and Jump$SFv
t = -1.0336, df = 10, p-value = 0.3257
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
 -0.7507262  0.3203398
sample estimates:
cor
-0.310678
```

Pearson's product-moment correlation

```
data: Start$Pmean_start and Jump$F0
t = 4.3295, df = 9, p-value = 0.001907
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
 0.4380905 0.9522863
sample estimates:
cor
0.8219559
```

Pearson's product-moment correlation

```
data: Start$Pmean_start and Jump$v0
t = 1.635, df = 9, p-value = 0.1365
```



```
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
 -0.1701886  0.8378881
sample estimates:
      cor
0.4785416
```

Pearson's product-moment correlation

```
data: Start$Pmean_start and Jump$SFv
t = -0.7087, df = 9, p-value = 0.4965
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
 -0.7292101  0.4291591
sample estimates:
      cor
-0.2299024
```

Pearson's product-moment correlation

```
data: Sprint$vmmean30 and Jump$F0
t = 3.2648, df = 11, p-value = 0.007535
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
 0.2453679 0.9033373
sample estimates:
      cor
0.7015128
```

Pearson's product-moment correlation

```
data: Sprint$vmmean30 and Jump$V0
t = 0.9485, df = 11, p-value = 0.3633
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
 -0.3253132 0.7172763
sample estimates:
      cor
0.274956
```

Pearson's product-moment correlation

```
data: Sprint$vmmean30 and Jump$SFv
t = -1.0341, df = 11, p-value = 0.3233
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
 -0.7290671 0.3030340
sample estimates:
      cor
-0.297649
```

Pearson's product-moment correlation

```
data: Start$vmmean_start and Jump$F0
t = 2.4334, df = 10, p-value = 0.03524
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
 0.05530694 0.87685753
sample estimates:
      cor
0.6098514
```

Pearson's product-moment correlation

```
data: Start$vmmean_start and Jump$sv0
t = 1.3452, df = 10, p-value = 0.2083
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
 -0.2353359  0.7882571
sample estimates:
      cor
0.3914324
```

Pearson's product-moment correlation

```
data: Start$vmmean_start and Jump$SFv
t = -0.5088, df = 10, p-value = 0.6219
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
 -0.6715400  0.4566734
sample estimates:
      cor
-0.1588643
```

Pearson's product-moment correlation

```
data: Sprint$Pmean30 and Jump$Pmax
t = 4.3846, df = 10, p-value = 0.001367
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
 0.4436889 0.9450658
sample estimates:
      cor
0.8110658
```

Pearson's product-moment correlation

```
data: Sprint$vmmean30 and Jump$Pmax
t = 2.8622, df = 11, p-value = 0.01546
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
 0.1599153 0.8855438
sample estimates:
      cor
0.6533346
```

Pearson's product-moment correlation

```
data: Start$Pmean_start and Jump$Pmax
t = 5.0239, df = 9, p-value = 0.0007153
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
 0.5334313 0.9626481
sample estimates:
      cor
0.8585705
```

Pearson's product-moment correlation

```
data: Start$vmmean_start and Jump$Pmax
t = 2.7819, df = 10, p-value = 0.01939
```

```
alternative hypothesis: true correlation is not equal to 0
95 percent confidence interval:
 0.1394689 0.8951034
sample estimates:
      cor
0.6605029
```