Chapter 4
A Simple Method for Measuring Lower Limb Force, Velocity and Power Capabilities During Jumping

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Abstract Lower limb ballistic movement performance (jump, sprint start, change of direction) is considered to be a key factor in many sport activities and depends directly on the mechanical capabilities of the neuromuscular system. This chapter presents the force-velocity (F-v) and power-velocity (P-v) relationships, and their associated variables of interest, as an interesting tool to evaluate the different lower limb muscle mechanical capabilities during ballistic push-off: maximal power and F-v profile. In this chapter, we will present the different laboratory and field methods to directly or indirectly assess these muscle properties, as well as their respective limits. We will also present an accurate and reliable simple field method to determine these muscle capabilities with a precision similar to that obtained with specific laboratory ergometers, while being convenient for field use because the computations only require loaded jumps (accurately standardized and performed) and three parameters rather easily measurable out of laboratory: body mass, jump height and push-off distance. The use of this simple method as routine test gives interesting information to coaches or physiotherapists: individual maximal power output and F-v profile. Validation studies, practical testing considerations and limits of this simple method will be presented. This method makes possible the follow-up of athlete muscle capabilities during a season or over several years, but also the comparison between athletes, which can help to optimize training and individualize loads and exercise modalities in strength training.

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J.-B. Morin and P. Samozino (eds.), *Biomechanics of Training and Testing*,
https://doi.org/10.1007/978-3-319-05633-3_4

4.1 Introduction

Accelerating its own body mass is involved in most of animal locomotor behaviors, notably in survival movements, whether to escape from predators or to capture preys. Natural selection acts within populations to further the phenotypic traits that improve such kind of abilities. Examining the factors that determine performance in these ballistic movements could allow to better understand the morphological and physiological adaptations characterizing a large variety of animals. In contrast, for humans (who no longer require ballistic movements to survive), ballistic performances are key factor in numerous sport activities (e.g., jumping, starting phase in sprint running, changing of direction, throwing). The understanding and determination of the physical characteristics underlying ballistic movement optimization is highly valued by performance professionals, such as strength and conditioning coaches. Beyond sport situations, some of movements occurred during daily-life activities can be considered as "ballistic" movements, such as standing up from a sitting position for the elderly or individuals with diseases (Corcos et al. 1996; Mak et al. 2003; Janssen et al. 2002). For these individuals, a sit-to-stand task represents a dynamic maximum effort for which reduced strength or inability to perform rapid muscle contractions can lead to impaired mobility and eventually to institutionalization (Mak et al. 2003; Corcos et al. 1996). So, one of the main questions interesting sport practitioners and physiotherapists is to know which muscle qualities to train or rehabilitate in order to increase (or to get back to a given level of) ballistic performances.

Ballistic performances can be defined as the ability to accelerate a mass as much as possible to reach the highest velocity in the shortest time, be it its one's own mass (e.g., sprints or jumps) or an external mass (e.g., throws or shots). Accelerating a mass can be performed during one unique movement (acyclic movements), often a ballistic push-off when it consists in a lower or upper limb extension (e.g. jumps, first steps of a sprint, throws), or during an acceleration phase over many consecutive movements or steps (cyclic movements, as sprint running acceleration, Chaps. 10–13). Ballistic movements, notably jumping or sprint running, have often been investigated to better understand the mechanical limits of skeletal muscle function in vivo, be it in animals (James et al. 2007; Lutz and Rome 1994) or in humans (Cormie et al. 2007d, 2011a; Jaric and Markovic 2009; Rabita et al. 2015; Samozino et al. 2012).

From Newton's law of motion, accelerating a mass require to apply external force and to produce mechanical work on its center of mass. Being very schematic, this requires "physical" capabilities, to produce the mechanical energy, and "technical" abilities to effectively transfer this mechanical energy from active muscles to center of mass of the body or of other moving system. These "technical" abilities have to respect the specific constraints and demands of the targeted sport activity via optimal motor behavior, segmental configuration or coordination. The present chapter, as well as the next ones, will only focus on "physical" capabilities to produce the maximum mechanical work possible during one or more (see Chap. 6) ballistic movement(s). This can give new insights for strength and conditioning training, while keeping in mind that producing high mechanical work is interesting only when associated to good technical skills specific to the task.

The ability to quickly accelerate the body from a resting position is considered to be particularly important for successful performance in many sport activities, be it in track and field events or in most of team, racket or combat sports. This ability in ballistic movements is directly related to mechanical properties of the neuromuscular system, and notably to power capabilities. Jumping movements have often been investigated to better understand and evaluate the lower limb mechanical properties. Vertical jump is the most widely used movement to assess "explosive" or "ballistic" qualities of lower limbs due to its simplicity, its very short duration ($<$0.5 s) and so very high intensity (it is considered as one of the most "explosive" movements) and its high correlation with peak power output (Davies and Young 1984).

Even if jumping tests will be briefly presented in this chapter, lower limb mechanical capabilities during dynamic extension cannot be only sum-up by maximal power output, and even less by a single performance. Since power is the product of force and velocity, muscle mechanical properties also include force and velocity capabilities which represent two different properties: the ability to develop very high levels of force and the ability to contract muscles—or extend limbs—at very high velocities. Even if both affect maximal power, these two muscle capabilities are independent. A good way to well understand this independency between force and velocity qualities is the analogy between muscle mechanical properties and vehicle engine capabilities. The latter are well described by the relationship between the torque the engine can produce and the velocity at which it turns. And when we compare this relationship between different vehicles (tractors and city or sport cars), we can observe big differences resulting in different properties (Fig. 4.1, Gülch 1994). The city or sport cars engine can go at high velocities, but cannot keep moving when they have to tow a big and heavy trailer. At the opposite, the tractor can move forward towing a trailer weighting several tons. And when the trailer is removed, it does not go very faster, while we can expect that it intensively accelerates once the heavy load is off, since it was able to tow very high loads. This is quite the same thing when the force generator is our neuromuscular system. The athlete's ability to move against very high loads is not associated to the capability to move fast when the mechanical constraints are low. Force and velocity capabilities are independent.

In this way, these different muscle capabilities cannot be distinguished from mechanical outputs obtained from only one single test (Jaric 2016b). The maximum vertical jump height is one of the best example since it has been indiscriminately interpreted as either an index of force (Kawamori et al. 2006), velocity (Yamauchi and Ishii 2007) or power (Cormie et al. 2011b) capabilities. During lower limb dynamic extension, the muscle mechanical capabilities are well and entirely described only by the force-velocity and power-velocity relationships (as presented and detailed for pedaling movement in Chap. 2).

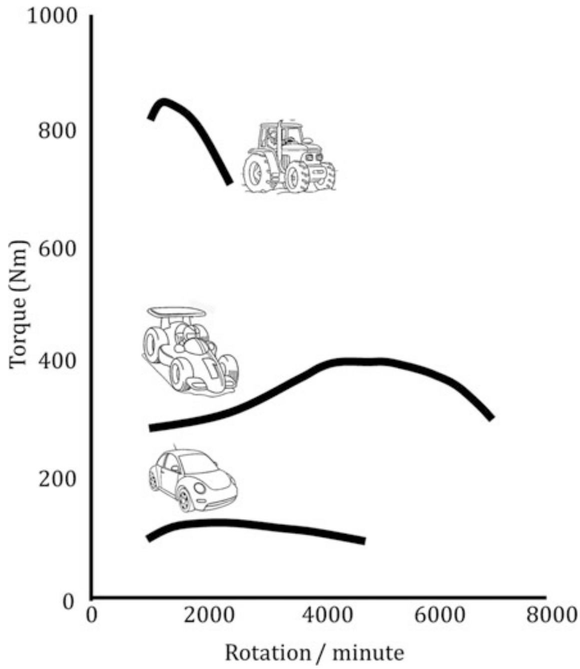

Fig. 4.1 Mechanical properties of the engine of three typical vehicles: a tractor, a sport car and a city car (from Gülch 1994).

In this chapter, we will define the force- and power-velocity relationships during ballistic lower limb push-off, the typical methods commonly used to determine these muscle capabilities, and a simple method we developed to compute them accurately out of labs. Practical applications will then be presented and discussed as well as different technologies that can be used to measure the mechanical inputs of this simple method.

4.2 Force, Velocity, Power Mechanical Profile

4.2.1 Force-Velocity and Power-Velocity Relationships in Jumping

When we focus on all-out or ballistic performances, i.e. movements performed with the highest intensity (force, velocity or power) possible, the performance is mainly limited by the mechanical capabilities of the neuromuscular system during concentric contractions. The overall lower limb dynamic mechanical capabilities have been well described by inverse force-velocity (F-v) and parabolic power-velocity (P-v) relationships (Fig. 4.2). While the F-v relationships obtained on isolated

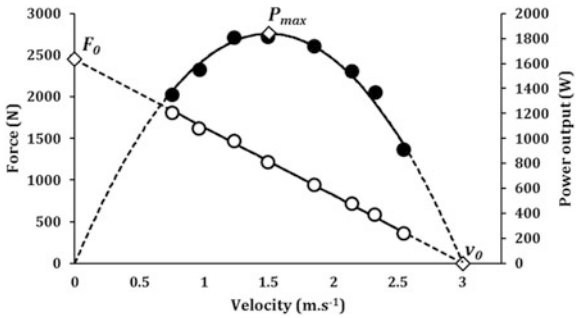

Fig. 4.2 Schematic force-velocity (open circles) and power-velocity (black filled circles) relationships for lower limb extensions during a typical leg press movement. Each point represent a lower limb extension performed against a given load. Black lines represent linear and polynomial regressions for force- and power-velocity relationships, respectively, dashed lines being their respective extrapolations. The mechanical outputs F_0, v_0, P_{max} are represented by the open diamonds, S_{fv} being the slope of the force-velocity relationship

muscles or mono-articular movements are described by a hyperbolic equation (Hill 1938; Thorstensson et al. 1976), linear relationships were consistently obtained for multi-joint functional tasks such as pedaling, squat, leg press or sprint running movements (e.g. Rahmani et al. 2001; Vandewalle et al. 1987a; Yamauchi and Ishii 2007; Bosco et al. 1995; Samozino et al. 2007; Bobbert 2012; Dorel et al. 2010; Morin et al. 2010; Rabita et al. 2015; Jaric 2015).

During ballistic push-offs (e.g. leg press, squat, Samozino et al. 2012; Yamauchi and Ishii 2007; Rahmani et al. 2001; Samozino et al. 2014), these relationships describe the changes in the maximal capability of lower limbs to produce external force and power output with increasing movement velocity over one extension. They characterize the external mechanical limits of the entire neuromuscular system. All the area under the F-v curve (Fig. 4.2) represents combinations of force and velocity outputs than can be produced during submaximal movements, and the F-v curve corresponds to outputs that can be produced during all-out push-offs. The other force and velocity combinations beyond the F-v line are not possible for muscles. These relationships put forward different typical parameters representing the different muscle mechanical capabilities (for details, see Morin and Samozino 2016). The force-axis intercept of the F-v relationships (F_0) represents the maximal external force lower limbs could produce during a theoretical extension movement at null velocity. The velocity-axis intercept (v_0) corresponds to the maximal velocity at which lower limbs could extend during a theoretical extension under zero load. It should be interpreted as the maximal extension velocity until which lower limb muscles can produce force. In other words, this is the athlete's ability to produce force at very high extension velocities. F_0 and v_0 are two purely theoretical values which cannot be measured experimentally, but they have to be considered as targeted values towards which maximal muscle capabilities tend when velocity decreases or increases, respectively. Hence, F_0 and v_0 have to be understood as the "force" and "velocity" maximal capabilities of the entire lower limbs. The apex of the P-v relationships (P_{max}) is the maximal power output lower limbs can produce over one extension and refers to the power capabilities. Under these conditions, the relationship among these three parameters can be described by the following mathematical equation: $P_{max} = F_0 \cdot v_0/4$ (details in Chap. 2, Vandewalle et al. 1987b; Samozino et al. 2012).

These mechanical properties obtained from multi-joint F-v and P-v relationships characterize the mechanical limits of the entire neuromuscular function and so are a complex integration of the different mechanisms involved in the total external force produced during one limb extension. They encompass individual muscle mechanical properties (e.g. intrinsic F-v and length-tension relationships, rate of force development), some morphological factors (e.g. cross sectional area, fascicle length, pennation angle, tendon properties), neural mechanisms (e.g. motor unit recruitment, firing frequency, motor unit synchronization, inter-muscular coordination) and segmental dynamics (Cormie et al. 2011a; Bobbert 2012; Cormie et al. 2010a, b).

The inverse F-v relationship is often misunderstood since we have in mind that if we increase the force applied to an object (or to the ground), we increase the velocity of the object (or of our center of mass). And the F-v relationship says the opposite: force and velocity change in opposite ways. In fact, there is no opposition between these two observations. They just do not refer to the same mechanical constraints. The first one (velocity increases when force applied increases or when resistance decreases) is the expression of the fundamental principles of dynamics well known through the Newton's laws of motion. They are the mechanical constraints imposed by Earth physical laws on human (or all other objects) movements. The second one (force decreases when velocity increases) corresponds to the mechanical properties of the neuromuscular system, and so to the mechanical constraints imposed by the biology on human movements performed with maximal effort (all-out). When physics says that velocity depends on force (2nd Newton's law of motion), physiology says that force depends on velocity (F-v relationship). During sport activities, physical laws are the same for everybody, muscle mechanical properties are not. And ballistic push-off performance is the best solution of both mechanical constraints (this will be detailed in Chap. 5).

4.2.2 Force-Velocity Mechanical Profile in Jumping

Beyond maximal force, velocity and power capabilities, the F-v relationships bring out another interesting information for scientists and coaches: the lower limb force-velocity mechanical profile. It is the slope of the F-v relationship (S_{FV}) and represents the individual ratio between force and velocity qualities ($S_{FV} = -F_0/v_0$). When the F-v relationship is graphically represented with a vertical force-axis, the steeper the slope, the more negative its value, the more "force-oriented" the F-V profile, and vice versa. The F-v profile is very interesting for the following reasons.

Independent from P_{max}. The athlete's F-v profile put forward insights about muscle mechanical qualities independently from power capabilities. Two athletes

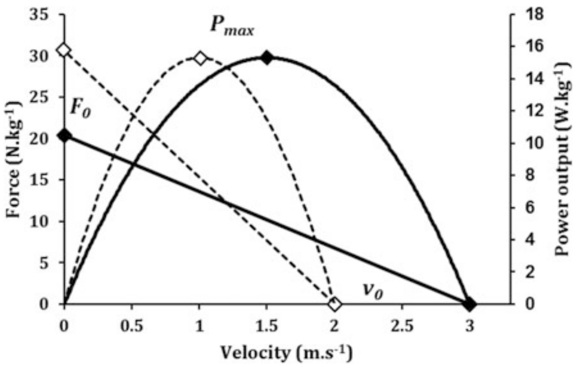

Fig. 4.3 Schematic force-velocity and power-velocity relationships for two hypothetical athletes presenting the same maximal power output (P_{MAX}) and two opposite force-velocity profiles: an athlete with a "force" profile characterized by a high maximal force (F_0) and low maximal velocity (v_0) (white diamonds and dashed lines), an athlete with a "velocity" profile characterized by a low F_0 and a high v_0 (black filled circles and continuous lines)

can present the same P_{max} values with different F-v profiles (Fig. 4.3). The athlete with a "force profile" (i.e. a F-v profile more oriented toward force capabilities) develops his P_{max} at a higher force and a lower velocity than an athlete with a "velocity profile", while both produce the same P_{max}. Since there is no direct relationship with P_{max}, the F-v profile brings another valuable information about the individual mechanical muscle properties.

Sensible to strength training. The F-v profile is sensible to training intervention, which is of great interest for strength and conditioning coaches. Changes in the F-v relationship, notably in its slope, can be achieved by specific strength training (Cormie et al. 2007c, 2010a, b, 2011b; Kaneko et al. 1983; McBride et al. 2002). The maximal force capabilities can be improved through strength training with heavy loads (>75–80% of one repetition maximum) while velocity capabilities can be increased by training with maximal efforts and light (e.g. <30% of one repetition maximum) or negative loading, which is often referred to as "ballistic" or "power" training (McBride et al. 2002; Cormie et al. 2010a, b; Cronin et al. 2001; Markovic et al. 2011; Argus et al. 2011). Note that when training focus on maximal force improvements, the velocity capabilities does not change, and vice versa (Cormie et al. 2010a). This underlined the independency between force and velocity capabilities, both ballistic and heavy strength training being associated to different physiological and neural adaptations (Cormie et al. 2010a, 2011a). This is quite the same history as for vehicle engines presented in the introduction section of this chapter.

Large inter-individual differences. Besides to be sensible to strength training, the other important point which confers great interest in F-v profile for training purposes is the fact that it presents very big differences between individuals. The initial works on F-v relationships obtained during pedaling exercises of Vandewalle and colleagues at the end of eighties well showed that force, velocity and power capabilities were very different across individuals of different ages, expertise levels or sport activities (Vandewalle et al. 1987a, b). During lower limb push-off, same large inter-individual differences can be observed between men and women or between different sport activities (Bosco et al. 1995; Giroux et al. 2016). Giroux et al. (2016) recently reported F- and P-v relationships of world class men and women athletes across different sport activities (Giroux et al. 2016). Between track cyclists, sprinters, taekwondo and fencing athletes, P_{max}, F_0 and v_0 values lots of differed even if all these sports can be considered as explosive activities (Fig. 4.4). These differences can be due to the specific mechanical demands of each activities and/or to their respective strength training habits. Even if this was not the aim of these study, data of Giroux et al. (2016) and Bosco et al. (1995) showed that differences in P_{max} between men and women were mainly explained by differences in velocity capabilities (Fig. 4.4). We can see that for some world class athletes in some sports (e.g. track cyclist, sprinters or taekwondo athletes), muscle mechanical capabilities differed only in v_0 between men and women, resulting in higher P_{max}, for men. Finally, within a same team sport activity, important differences can be observed between players according to their position, their training history and/or their intrinsic properties. And sometimes, F-v profiles do not follow what we can expect. The typical example presented in Fig. 4.5 shows the F-v relationships of two professional rugby players: a forward (body mass: 102 kg, stature: 1.76 m) and a back (body mass: 86 kg, stature: 1.84 m) player. We could expect (notably from his morphology) that the forward player would present a more "force-oriented"

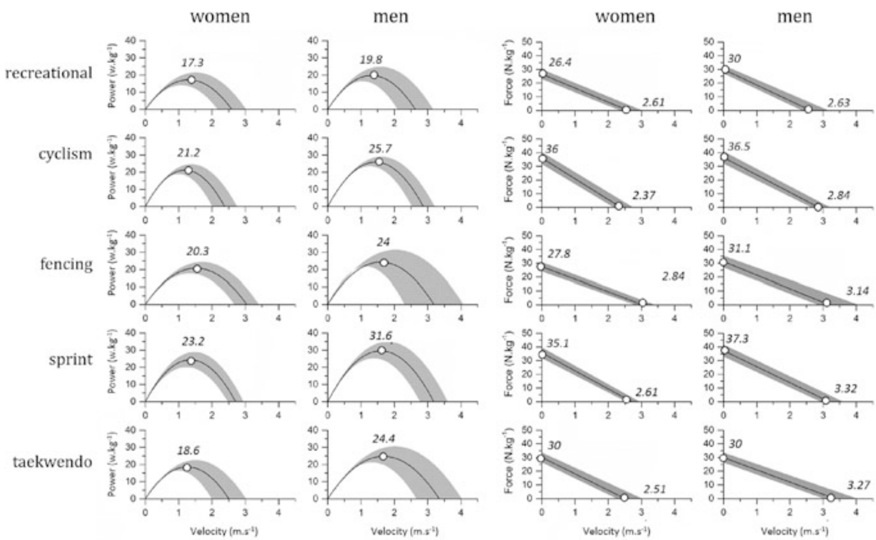

Fig. 4.4 Power- and Force-velocity relationships of men and women recreational individuals and world class sprinting, cycling, fencing and taekwondo athletes. Maximal power and maximal theoretical force and velocity values are presented (filled circles) (Modified from Giroux et al. 2016)

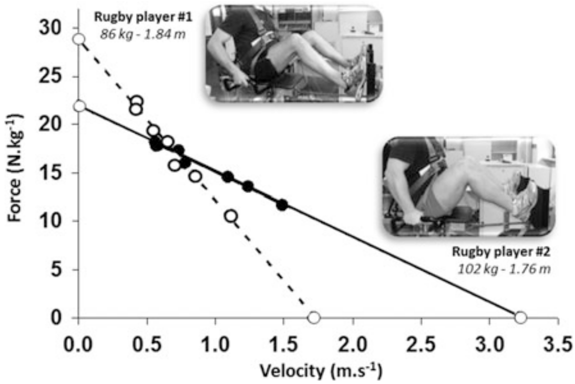

Fig. 4.5 Force-velocity relationships of two 1st-Italian league rugby players: a back (player #1, filled circles, dash line) and a forward player (player #2, black points and continuous line). Each point represents a lower limb extension performed against a given load during leg press exercises

profile (as a tractor) than the back player. This is not actually the case, mainly due to the very large and impressive velocity capabilities of the forward player. His absolute maximal force is also very high, but when expressed relatively to his body mass (which is important for ballistic performances), force capabilities are even lower than backward player's ones. During the leg press movement experimentation, the forward player's ability to fast extend his legs against low resistance was more impressive than his capacity to move against heavy loads.

The complementarity of these different variables to well characterize muscle mechanical capabilities (F_0 and v_0, or P_{max} and F-v profile), their large inter-individual differences, their sensibility to strength training and their high importance in ballistic performances (see Chap. 5 for more details) support the great interest to accurately evaluate them for sport scientists and sport practitioners.

4.3 Reference Testing Methods

4.3.1 Methodological Considerations

Muscle contraction modalities. The determination of lower limb F-v and P-v relationships require several all-out limb extensions performed in different mechanical conditions, each one corresponding to different force, velocity and power values. The different experimental methods require:

- either to control the force developed in order to maintain it constant all over the movement and to measure the movement velocity: isotonic condition. Tests are performed at different force values (e.g. Yamauchi and Ishii 2007; Yamauchi et al. 2005).
- either to control movement velocity to maintain it constant all over the movement and to measure the force produced: isokinetic condition. Tests are performed at different velocity values (e.g. Sargeant et al. 1981; Wilson et al. 1997).

- either to control and maintain constant the resistance acting against the movement and to measure both force produced and movement velocity: isoinertial or isoload condition. The resistance can be inertia (e.g. additional mass) and/or resistive force (e.g. weight of additional loads, elastic band or pneumatic force). Tests are performed at a given resistance, resulting in different force and velocity values which are both measured (e.g. Rahmani et al. 2004; Bosco et al. 1995; Samozino et al. 2014; Cuk et al. 2014; Markovic et al. 2011).

Isokinetic or isotonic testing conditions present many advantages, notably a best control of the mechanical modalities in which the task is realized and a higher safety for subjects. These two methodological concerns, very important in medical, scientific or sport fields, explain the widely use of isokinetic movements in muscle capacity testing, isotonic modality being less commonly used due to the technical difficulty to maintain constant the force produced. However, isokinetic conditions have often been challenged in sport field because some methodological requirements are not always respected (Gülch 1994), and especially because the movement is not "natural" due to constant velocities which are very rare, if not inexistent, in daily life and sport activities (Gülch 1994; Kannus 1994). Indeed, human movements are characterized by acceleration and deceleration of its whole body mass, the mass of a body segment or an external mass. Most of time in actual human performances, the mass of the moving system is constant all over the movement, but the force produced and the movement velocity change. Consequently, lower limb mechanical capabilities testing is well advised to be performed in isoload or isoinertial conditions, notably as part of exploring or training ballistic performances. That is why we will focus on isoinertial conditions in the following sections.

Peak *versus* averaged variables. Testing muscle properties, as for all kind of physical tests, requires to identify the variable(s) which better characterize(s) the muscular effort expended. When we explore the muscle maximal capabilities, the measured parameters are commonly the force produced, the movement velocity and the resulting power output. These three mechanical output can be quantified and presented in two different forms: instantaneous (often peak) values (e.g. Yamauchi et al. 2007; McCartney et al. 1983) or averaged values over one leg extension (e.g. Arsac et al. 1996; Rahmani et al. 2001; Bosco et al. 1995; Zamparo et al. 1997). The choice between instantaneous and averaged values depends on what we have to assess. In 1983, Andrews (Andrews 1983) suggested that:

- **Instantaneous values** are adapted to describe the value of a variable at a specific time of the movement (e.g. take-off during jumping or heel-ground contact during running) or to characterize extreme values of a parameter over a movement (e.g. extreme joint angles to compute range of motion, maximal running speed, minimum heart rate).
- **Averaged values** (or more generally values representing a time interval) are adapted to characterize an effort or a movement in its entirety, notably when the parameter significantly changes over the effort or the movement.

It is worth noting that the two types of values are strongly related during ballistic movements, with for instance averaged values of power output between 40 and 60% of maximal instantaneous values (Marsh 1994; Martin et al. 1997; Driss et al. 2001). So, the general shape of Force- and Power-velocity relationships are quasi the same, only value magnitudes change (Martin et al. 1997).

When we aim to evaluate muscle mechanical capabilities, we want to characterize the lower limb maximal capabilities to produce force or power over one extension. However, force production capabilities change all over lower limb extension: besides to depend on movement velocity, they are affected by the torque-angle (force-length) relationship of muscle groups involved at each joint (e.g. Thorstensson et al. 1976), by the time required for muscles to reach their maximum active state (e.g. van Soest and Casius 2000), or by muscle coordination patterns (e.g. Suzuki et al. 1982; Van Soest et al. 1994). So, only focusing on the instantaneous peak values measured during a functional movement does not make lots of sense since this values would correspond to a very specific anatomical and neuromuscular configuration and does not represent the whole dynamic lower limb capabilities. Consequently, even it is still source of debate (Dugan et al. 2004; Vandewalle et al. 1987b), we think that using force, velocity and power values averaged over the entire extension movement seems to be adapted to characterize these mechanical capabilities (e.g. Arsac et al. 1996; Bassey and Short 1990; Samozino et al. 2007, 2012; Rahmani et al. 2001). Moreover, from a purely mechanical point of view, dynamic principles show that the change in momentum of a system depend directly to the net mechanical impulse applied on it over the entire movement. So, ballistic performances do not depend on the maximum force or power output lower limb muscles are able to produce at a given (very short) time during their extension, but depend especially to force or power output muscles are able to produce over the entire extension phase allowing maximisation of the net mechanical impulse. And this is better described by averaged than by peak instantaneous values.

4.3.2 Laboratory Methods

As presented in Chaps. 2 and 3, lower limb mechanical capabilities were first described through F-v and P-v relationships during pedaling movement in eighties (Seck et al. 1995; Arsac et al. 1996; Martin et al. 1997; Hintzy et al. 1999; McCartney et al. 1983, 1985; Sargeant et al. 1981). Even if pedaling is very pertinent and convenient to assess lower limb extensor muscle capabilities, mechanical outputs produced during this cyclic movement depend directly to very specific muscle coordination (Samozino et al. 2007; van Soest and Casius 2000; Dorel et al. 2012, more details in Chap. 3) and so are quite different from what lower limbs can produce during one ballistic push-off as a jump or a sprint start.

The primary acyclic movement used to determine F-v and P-v relationships are squat or squat jump (when a take-off occurs) movements during which the body mass (and external mass) is moved up in the vertical direction. Even if the vertical jump is widely used to assess lower limb ballistic capabilities, the first studies (and the only one until the last few years) exploring F-v and P-v relationships during this kind of lower limb movements are the works of both Bosco's and Rahmani's teams (Bosco et al. 1995; Rahmani et al. 2001; Bosco and Komi 1979; Rahmani et al. 2004). They described, during squats and squat jumps, these two relationships as linear and parabolic, respectively. In contrast to pedaling, these relationships describe here the mechanical capabilities of both lower limbs acting together (bilateral movement) and require several distinct movements performed against several loads or external resistances: each load/resistance is associated to a movement velocity, a force and a power produced, and so correspond to one point of the F-v and P-v relationships (Fig. 4.2).

Different devices exist to measure the force and power output produced by lower limbs, as well as their extension velocity, during a vertical push-off phase. In the late XIXth century, Etienne-Jules Marey and George Demeny studied vertical jumps combining kinematic and dynamic analyses, notably using chronophotography and dynamograph, ancestors of optoelectronic and force plate systems, respectively (Marey and Demeny 1885). Since these first experimentations, force plates have remained the lab device the most used to measure forces applied onto the ground, but also to determine continuously the body center of mass acceleration, velocity and displacement during the push-off phase of a vertical jump (Fig. 4.6, Bosco and Komi 1979; Harman et al. 1991; Driss et al. 2001; Ferretti et al. 1987; Rahmani et al. 2001; Davies and Rennie 1968) or a contact phase during walking or running (Cavagna 1975). Note that the center of mass velocity during vertical jump has been often used to estimate lower limb extension velocity since feet do not move during push-off. The product of force and velocity data at each instant gives lower limb power output. Since a value of force, power and velocity can be obtained at each push-off phase, and so at each jump, F-v and P-v relationships can be determined from several jumps with different loads. In contrast to pedaling or sprint running movements, the force (vertical component) measured by force plate during vertical jumping corresponds to the quasi-total external force developed by lower limbs (horizontal force components are very low and negligible).

Other devices, less expensive than force plates and easier to use with strength training systems in weights room, were then developed to measure force, velocity and power during squat or jumps. In 1995, Bosco proposed to measure these parameters from only the displacement of the moving mass (body mass and additional mass) obtained from an optical sensor. This kinematic method, validated few years later by Rahmani in comparison to force plate measurements (Rahmani et al. 1998, 2000) consists in deriving twice over time the displacement signal to obtain center of mass velocity and acceleration, and then net external force developed. Based on this methodology, several systems have then been proposed using linear position transducers or accelerometers to measure directly the acceleration (Cormie et al. 2007a, b; Harris et al. 2007; Giroux et al. 2015; McMaster et al. 2014; Comstock et al. 2011; Cronin et al. 2004). Other lower limb extension movements have been also used to evaluate mechanical muscle capabilities during

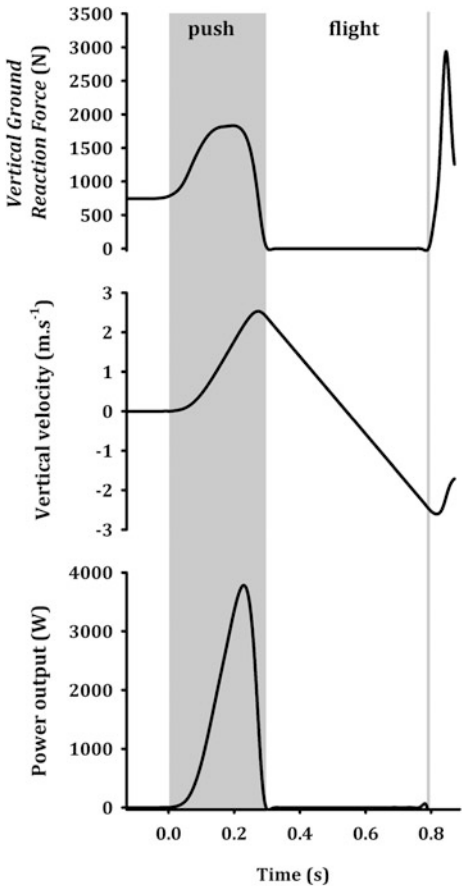

Fig. 4.6 Vertical force, velocity and power output signals obtained from force plate measurements during a squat jump (push-off and flight phases)

inclined or horizontal push-offs with different kind of ergometers measuring force, velocity and power output during push-off phase (Zamparo et al. 1997; Yamauchi et al. 2007; Avis et al. 1985; Pearson et al. 2004; Bassey and Short 1990; Macaluso and De Vito 2003; Zamparo et al. 2000; Samozino et al. 2012). The non-vertical orientation makes possible to change the gravity magnitude against which the movement is performed and to vary the body configuration (notably hip angle and range of motion (Padulo et al. 2017). Many of these devices have led to F-v and P-v relationship determination (e.g. Yamauchi and Ishii 2007; Samozino et al. 2012).

The different methodologies used in laboratory to determine force, velocity and power muscles capabilities present very high accuracy and high reliability. The standard error of measurement ranges from ~ 3 to $\sim 10\%$ and intraclass correlation coefficient from ~ 0.85 to ~ 0.99 according to the device, the protocol or the movement tested (Cuk et al. 2014; Giroux et al. 2015; Rahmani et al. 2001). Be it during vertical or horizontal movements, P_{max}, v_0 and F_0 values are very different according to subject levels and vary between 700 and 3500 W (from ~ 15 to

45 W kg^{-1}), between 1000 and 3000 N (from $\sim$20 to 50 N kg^{-1}) et between 2 and 8 m s^{-1}, respectively. However, the main limit of such lab methodologies is that they are not compatible with the daily constraints of the main users. Indeed, evaluating muscle mechanical capabilities is in the center of the training process of many sport activities. So this is of great interest for coaches and strength and conditioning coaches who look for simple, cheap and quick methods which can be easily set up in field conditions. This is not the case for such lab methods requiring very specific and expensive tools, as well as advanced skills in data acquisition and analysis. So, the above-mentioned laboratory methods on jumping movements have existed for more than 20 years, but very little used by sport practitioners. The later prefer performed tests convenient in field conditions, even if less accurate.

4.3.3 Field Methods

Before the few last years, no method have made possible the determination of P_{max} and F-v relationship out of laboratory and without skilled persons. However, maximal power, force and velocity capabilities have been assessed directly or indirectly by coaches using different simple methodologies.

Maximal strength. Out of laboratory, the maximum force the lower limb extensor muscles are able to produce is usually evaluated through the maximum load the athlete can move one time over an entire extension movement (one repetition maximum, 1RM). Different protocols exist to determine it on lower limbs during squat or a leg press exercises, all of them using increasing loads. Considering the inverse F-v relationship, the maximum muscle force can be produced at null velocity, which corresponds to isometric contraction. Even if the movement is realized at a non-negligible velocity, the one maximum repetition load is a good index of maximal dynamic strength. This test is convenient for field using and present a high reliability (McMaster et al. 2014; Seo et al. 2012; Verdijk et al. 2009). Moreover, the maximum isometric force depends directly on the joint (hip, knee and ankle for lower limb) angles at which the effort is performed and requires dynamometers to be measured. Very recently, the 1RM strength index was compared to F_0 by situating the 1RM point along the F-v relationship (Riviere et al. 2017). On the velocity axis, the 1RM point was shown to be situated at $\sim$30% from F_0 and $\sim$70% from the point corresponding to the SJ performed with the highest load. On the force axis, the 1RM point was $\sim$11% below F_0 and $\sim$16% above the highest force obtained during loaded SJs. This suggests that 1RM performance is affected partly (even slightly) by velocity qualities, and so does not represent only pure force capacities, even if it still represents a good practical index of dynamic maximal strength (Riviere et al. 2017).

Maximal extension velocity. When sport practitioners want to assess lower limb velocity capabilities of their athletes, they often measure a performance associated to high movement velocities, such a vertical jump, a sprint time or an agility test performance. However, beside to depend on muscular velocity qualities, each of these movements also require force production, and the velocity reached is far to be maximal. So, assessing the maximal extension velocity of lower limb cannot be performed measuring the performance of a movement depending on both force and velocity, and so on power output.

Maximal power output. Different field tests have been proposed to simply assess lower limb maximal power output, one of the most famous (but not commonly used) is the Margaria stair test (Margaria et al. 1966). Vertical jumps have remained the most widely used tests to assess power capabilities due to its simplicity, its very short duration and very high intensity. In 1921, Dudley Allen Sargent proposed the first field method to estimate the vertical displacement of the center of mass during a vertical jump by the difference between the maximal height reached by the hand during the jump and in standing position, both with the upper limb extended to the top. Some years later, in 1924, the jump height associated to this test was proposed as a measure of muscle power by a namesake, Sargent (1924). Other simple methods were then proposed to estimate the center of mass displacement during a jump though the roll-out of a ribbon attached to the athlete's waist (Abalakov's test) or the flight time of the jump (Bosco's test). Flight time measurement was made possible by the use of "timer" mat (e.g. Ergojump™, Bosco 1992) or photocells placed at some millimeters above the ground (e.g. Optojump®), both easy to bring and use in field conditions. Jump height can be then computed using Newton's law of motion, as firstly proposed by Asmussen and Bonde-Petersen (1974). Several jumping modalities exist, each of them being associated to specific muscle mechanical properties: squat jump (starting from a crouching position), countermovement jump (starting from a standing upright position followed by a downward countermovement before jumping), drop jump (starting upright from an elevated place) and rebound jumps (hopping during a given time, see Chap. 6). Although maximal jump height was shown to be highly correlated to P_{max}, this does not give a power values, nor force or velocity ones. Consequently, the jump height as an index of power capabilities can be biased by the subject body mass and the lower limb range of motion. Two athletes of different mass and jumping at the same height do not develop the same power output, the heavier one being more powerful. In the same way, two athletes with the same body mass but different vertical push-off distances (lower limb range of motion over which the push-off is performed) and jumping at the same height do not produce the same power, the athlete using the shorter push-off distance being more powerful. So, jump height alone cannot be an accurate index of maximal power output.

For these reasons, different formulae have been proposed (still recently, see review McMaster et al. 2014) to estimate the power produced during a vertical jump from jump height and body mass (Table 4.1). Some of them were developed from fundamental principles of dynamics (Gray et al. 1962; Lewis formulae cited in Fox and Mathews 1974), but the biomechanical models from which they are based have been challenged (Harman et al. 1991). All the other formulae were statistically determined from regression equations obtained from experimental measurements (Table 4.1, Johnson and Bahamonde 1996; Canavan and Vescovi 2004; Harman et al. 1991; Sayers et al. 1999; Lara et al. 2006a, b; Shetty 2002; Bahamonde 2005;

Table 4.1 Equations previously proposed to indirectly estimate lower limb power output (from Lara et al 2006a)

Authors	Equations
Lewis	Power = $\sqrt{4.9} \times 9.8 \times$ body mass (kg) $\times \sqrt{}$(jump height (m))
Harman et al. (1991)	Power = 61.9 $\times$ jump height (cm) + 36 $\times$ body mass (kg) − 1822
Bahamonde (2005)	Power = 78.5 $\times$ jump height (cm) + 60.6 $\times$ body mass (kg) − 15.3 $\times$ height (cm) − 1308
Sayers et al. (1999)	Power = 60.7 $\times$ jump height (cm) + 45.3 $\times$ body mass (kg) − 2055
Shetty (2002)	Power = 1925.7 $\times$ jump height (cm) + 14.7 $\times$ body mass (kg) − 66.3
Canavan and Vescovi (2004)	Power = 65.1 $\times$ jump height (cm) + 25.8 $\times$ body mass (kg) − 1413.1
Lara et al. (2006a)	Power = 62.5 $\times$ jump height (cm) + 50.3 $\times$ body mass (kg) − 2184.7

Wright et al. 2012). Besides the lack of theoretical background, the main limit of this kind of formulae is their dependence to the population from which they were obtained, which can lead to important error in the power estimation (from 3 to 40%, Lara et al. 2006a, b; McMaster et al. 2014).

In 1983, Carmelo Bosco proposed a simple test to measure lower limb power output during series of rebound jumps over 15–60 s (Bosco et al. 1983). The mathematical formulae based on Newton laws of motion give validated power values. However, this power is the mean power developed over series of jumps, and does not correspond to the maximal power output lower limbs can produce over one extension.

4.3.4 *Limitations of the Reference Methods*

On one side, laboratory methodologies present very accurate and reliable measurement of the different muscle mechanical qualities (force, velocity and power capabilities) but are not widely used by sport practitioners due to the need of expensive tools and very specific skills in data analysis. On the other side, simple tests used in routine in field conditions are not very accurate and valid and do not allow coaches to evaluate the entire spectrum of muscle capabilities, notably the athlete's F-v profile. It is worth noting that the different tests and formulae frequently proposed, notably to estimate maximal power output, well show the great interest, past or present (from 1962 to nowadays), to evaluate muscle mechanical capabilities with simple methodologies easily usable out of laboratories.

In order to answer to this need while considering the limitations of previous tests, we proposed a simple field method to compute accurately force, velocity and power lower limb capabilities from few data inputs that are easy to obtain in typical training practice.

4.4 A Simple Method for Measuring Force, Velocity and Power During Jumping

4.4.1 Theoretical Bases and Equations

The simple method is based on the fundamental principles of dynamics applied to the body center of mass during a vertical jump and on the analyses of its mechanical energy (kinetic and potential) at different specific instants of the movement (Fig. 4.7). This gives the following equations (for detailed computations, see Samozino et al. 2008) to compute the mean force (F) and power output (P) produced by lower limbs during one vertical jump and their mean extension velocity (v):

$$F = m.g.\left(\frac{h}{h_{PO}} + 1\right) \tag{4.1}$$

$$v = \sqrt{\frac{g.h}{2}} \tag{4.2}$$

$$P = m.g.\left(\frac{h}{h_{PO}} + 1\right) \cdot \sqrt{\frac{g.h}{2}} \tag{4.3}$$

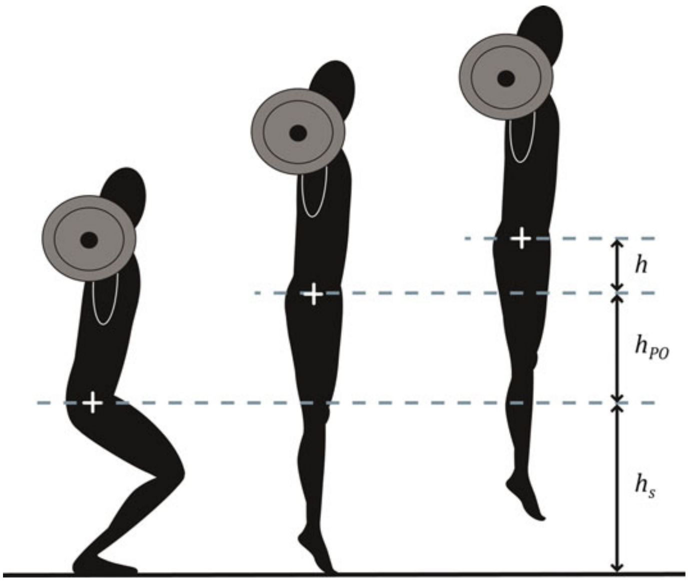

Fig. 4.7 The three key positions during a loaded vertical squat jump and the three distances used in the computations of the simple method

These 3 equations required only three input variables to estimate force, velocity and power during one jump: m the athlete body mass + additional mass (if any, in kg), h the jump height (in m) and h_{PO} the push-off distance which is the vertical distance over which the force is produced and thus corresponds to the lower limb length change between the starting position (h_s) and the moment of takeoff (Fig. 4.7). These three input variables are easy to obtain out of laboratory (see "technologies and inputs measurements" section).

Using these three equations for vertical jumps performed with different additional loads gives different points of the F-v relationship: the higher the moving mass (body mass + additional mass), the higher the force and the lower the velocity. Plotting F versus v and modeling this relationship by a linear equation gives the F-v relationship which can be extrapolated to obtain the maximal force (F_0) and velocity (v_0) values as the intercept with the force- and velocity-axis, respectively (Fig. 4.2). The maximal power output (P_{max}) can be computed as the apex of the 2nd order polynomial P-v relationship (if the number and range of the computed F-v points are sufficient), or easier by the following validated equation (Samozino et al. 2012; Vandewalle et al. 1987a):

$$P_{max} = \frac{F_0 \cdot v_0}{4} \tag{4.4}$$

4.4.2 Limits of the Method

The theoretical computations on which were developed the above-mentioned equations are based on fundamental principles of dynamics. However, some mathematical and physical simplifying assumptions have been required to express F, v and P from only three simple parameters.

- The Newton's laws were applied to a whole body considered as a system and represented by its center of mass (e.g. Bosco and Komi 1979; Harman et al. 1990). So, only the mechanical energy applied to the center of mass was considered.
- The air resistance was neglected since it was shown to only affect very small animals jump height (body mass below 0.5 g, Scholz et al. 2006).
- It was supposed that the center of mass vertical displacement during push-off corresponds to the lower limb length change (i.e. h_{PO}), whereas the actual relative position of the center of mass within the body shifts slightly downwards due to the lower limb extension. This simplification was necessary to make h_{PO} measurement possible during field testing (see "technologies and inputs measurements" section).
- The mean power output over the push-off phase was computed as the product of the averaged values of force and velocity, which was mathematically wrong per se. Mean power is the average of instantaneous power values computed as the product of instantaneous force and velocity values. However, during an explosive movement during which the movement is only accelerated in one direction, the induced error is minor.

Knowing these different simplifying assumptions, it was important to quantify the errors they induced on mechanical variables, as well as the errors induced by the measurements of the three input variables with devices usable out of laboratories. So, the three equations and the simple method were validated in comparison to the gold standard force plate measurements.

4.4.3 Validation of the Method

The simple method has been the object of different validation protocols done by our research group, but also by others.

The first protocol aimed at validating the three equations to compute F, v and P during unloaded and loaded vertical jumps (Samozino et al. 2008). Eleven male physically active men performed two maximal squat jumps without and with 3 different additional loads (25, 50 and 75% of body weight). During each trial, F, v and P were calculated during push-off from both force plate measurements (Kistler type 9861A, Winterthur, Switzerland, 2000 Hz) and the proposed computations. For the latter, jump height was obtained from flight time and h_{PO} measured a priori as the difference between the great trochanter height in the crouch starting position (h_s, Fig. 4.7) and the extended lower limb length with maximal foot plantar flexion (great trochanter to tiptoe distance, see “technologies and inputs measurements”). The systematic bias between the two methods were not significant and lower than 2% for force, and lower than 8% for velocity and power whatever the load. The random errors ranged between 1 and 9% (Table 4.2). The concurrent validity of the computation method was also highlighted by high correlation and linear regressions close to the identity line (for full details and statistics, see Samozino et al. 2008). The low changes in the mean, low standard error of measurements and high intraclass coefficient between the two trials demonstrated the good reliability of the simple method whatever the additional load (Table 4.3). This reliability is in line with (and even better than) the reliability obtained with the reference method, which shows that the difference between both trials is due to the intra-individual variability in a jumping task (biological error, Hopkins et al. 2001). These results supported that the errors induced by the simplifying assumptions on which equations were developed are very low. The proposed method, solely based on three simple parameters easily obtained in field conditions (body mass, jump height and push-off distance), is valid and reliable to compute force, velocity and power developed by lower limb extensor muscles during loaded and unloaded squat jumps.

In 2014, an Italian research group tested the validity of the simple method to quantify power output during jumping comparing it to a method based on a multibody model that simulates the jumps processing the data obtained by a three-dimensional (3D) motion capture system and the dynamometric measurements obtained by the force platforms (Palmieri et al. 2015). The comparison gave

Table 4.2 Mean ± SD of force, velocity and power output obtained with force plate and simple methods, systematic bias and random error between the two methods and characteristics of correlations between the two methods

	Load (% body mass)	Force plate	Simple method	Systematic Bias (%)	Random error (%)	Pearson correlation coefficient (r)	
Force (N)	0	1294 ± 132	1282 ± 133	−0.88	1.94	0.98	***
	25	1451 ± 143	1433 ± 141	−1.20	1.70	0.99	***
	50	1554 ± 151	1557 ± 153	0.21	2.21	0.97	***
	75	1675 ± 175	1654 ± 170	1.20	1.43	0.99	***
	All conditions			−0.77	1.90	0.99	***
Velocity (m s^{-1})	0	1.08 ± 0.12	1.10 ± 0.12	1.62	3.15	0.96	***
	25	0.96 ± 0.11	0.95 ± 0.10	−1.30	4.63	0.92	***
	50	0.81 ± 0.11	0.80 ± 0.10	−0.18	6.17	0.87	***
	75	0.72 ± 0.07	0.66 ± 0.09	−7.93	8.84	0.72	***
	All conditions			0.05	4.89	0.96	***
Power output (W)	0	1412 ± 221	1411 ± 224	−0.14	3.04	0.98	***
	25	1389 ± 198	1357 ± 186	−2.13	4.49	0.95	***
	50	1253 ± 198	1246 ± 187	−0.30	6.64	0.88	***
	75	1182 ± 142	1085 ± 152	−8.07	8.41	0.76	***
	All conditions			−0.86	4.96	0.92	***

***$P < 0.001$

Table 4.3 Inter-trial reliability parameters for the simple method

	Load (% body mass)	Change in the mean (%)		Standard error of measurement (%)		Intraclass coefficient	
		Force plate	Simple method	Force plate	Simple method	Force plate	Simple method
Force (N)	0	0.32	0.64	2.52	2.56	0.94	0.94
	25	0.68	−0.30	1.47	1.57	0.98	0.98
	50	−1.37	0.30	2.24	1.46	0.95	0.98
	75	0.18	0.07	1.70	1.82	0.97	0.97
Velocity (m s^{-1})	0	2.22	2.32	6.23	3.84	0.70	0.89
	25	0.06	−0.60	5.70	3.27	0.78	0.91
	50	−3.79	0.21	7.93	3.60	0.66	0.93
	75	−0.15	−1.28	7.47	5.91	0.50	0.82
Power (W)	0	2.55	2.96	7.24	6.35	0.79	0.85
	25	0.79	−0.89	5.72	4.66	0.85	0.89
	50	−4.36	0.51	9.22	5.13	0.67	0.89
	75	−0.19	−1.21	8.55	7.89	0.52	0.70

errors lower than 6% on mean power output and mechanical work over the push-off, that "*can be accepted for the benefit of a very simple procedure which requires very few data as input*". The same year, Caroline Giroux and the research team of the French National Institute of Sport determined the concurrent validity and reliability of force, velocity and power capabilities measurements provided by the simple method (jump height obtained from flight time using an optical measurement system, OptojumpNext®, Mircogate, Bolzano-Bozen, Italy), force plate (Kistler, Wintertur, Switzerland), accelerometer (Myotest Pro®, Myotest SA, Sion, Switzerland) and linear position transducer (GymAware®, Kinetic Performance, Mitchell, Australia) during loaded squats jumps (Giroux et al. 2015). Values obtained by the simple method showed very good agreement with force plate measurements, similar to accelerometer or linear position transducer (low bias between 2.6 and 3.2%, narrow confidence intervals ranging from 6.2 to 12.7%). All methods were shown to be reliable, especially the simple method (ICC = 0.97–0.99; SEM = 2.7–8.6%). The authors concluded from their results and the ease of use of the simple method that "*this method is suitable for monitoring power training sessions under field conditions*".

Very recently, we validated the simple method computations and their validity to determine F-v relationships during countermovement jumps (CMJ) representing more commonly used movements in all sport activities (Jimenez-Reyes et al. 2016). The mechanical capabilities derived from F-v relationships (F_0, v_0, P_{max} and F-v profile) were obtained with both the simple method and force plate measurements (Bertec, Type 4060-15, Bertec Corporation, Columbus, OH, USA). Results showed high agreement between values obtained by both methods (mean absolute bias values between 0.9 and 3.7%) and high reliability of the simple method when applied during CMJ (ICC > 0.98). This supports the accuracy of the simple method, not only to compute F, v and P during one vertical jump, but also to determine F-v relationships from several loaded SJ or CMJ.

4.5 Technologies and Input Measurements

The accuracy and reliability of the simple method depends on both validity of equations (see previous section for details) and accuracy of the devices and technologies used to obtain the mechanical inputs of the models (m, h and h_{PO}), notably jump height and push-off distance.

4.5.1 Jump Height

Jump height (h) can be easily measured out of laboratories using different methodologies and devices (see Sect. 4.3.3). Most of them are based on the flight time and laws of motion to determine the center of mass elevation after take-off

(Bosco and Komi 1979). Even if the flight time method was very accurate and reliable, it requires field equipment detecting contact and no contact with the ground, and forces subjects to land in the same leg position as they take off. Such devices detect ground contact from optical measurement system just above the ground (e.g., OptojumpNext™, Glatthorn et al. 2011), contact pressure on the ground (e.g., Ergojump™), accelerometry (e.g. Myotest™, Casartelli et al. 2010) or video analysis (e.g. MyJump, Balsalobre-Fernandez et al. 2015). The main advantage of flight time methods is that the upper limb are free, which allows them to hold additional loads on shoulders. This is not the case for the well-known Sargent test (or similar) during which the athlete has to touch a wall (or other devices, e.g. Vertec™) the highest as possible with the hand. Video analysis can also be used to measure directly the vertical displacement of one point of the body which does not move relatively to the center of mass after take-off (e.g. a point at the hip or shoulders).

Whatever the methodology, the accuracy and the resolution of the jump height measurement directly affect the accuracy of force, velocity and power computations. For instance, for a device measuring flight time with a resolution of 30 data per second (as a standard video camera at 30 fps), the potential error on power values is between 7 and 19%. Increasing the resolution leads to lower errors: from 4 to 10% for 60 fps, from 2 to 6% for 120 fps, and from 1.3 to 3.5% for 180 fps. Recently, smartphones present cameras that allow for slow motion modes with up to 240 fps (e.g. Apple iPhone 6 and subsequent models). The flight time determination can be made with a resolution of ~4 ms, which gives errors lower than 3% on jump height and power. This is the basis of the app named MyJump which allow users to measure accurately jumping performance in a few seconds by filming the feet on the ground during a jump and then by just clicking on the screen to select the frames corresponding to foot ground contact and take-off (Fig. 4.8). Besides to be validated to measure jump height (validation against force plate measurements, Balsalobre-Fernandez et al. 2015), this app also compute force, velocity and power variables to determine F-v relationship on the basis of the simple method presented here.

4.5.2 Push-off Distance

The distance covered by the center of mass during the push off (h_{PO}) can be easily estimated (with the slight overestimation discussed in the method limit section) in field conditions through the hip vertical elevation corresponding to the leg length change. The later can be determined before testing by the difference between the hip (great trochanter or superior iliac crest) height in the crouch starting position (Fig. 4.9) and the extended lower limb length with maximal foot plantar flexion (great trochanter/superior iliac crest to tiptoe distance, measured lying down on the back, Fig. 4.10) which is the configuration of lower limbs at take-off (Fig. 4.7). This is a very convenient and simple method requiring only a measuring tape. The

Fig. 4.8 The iPhone app “Myjump” uses the high-speed video slow motion mode to measure the aerial time of the jump, and thus compute jump height and all Force-velocity profile variables (some of whom will be presented in the next chapter)

crouch starting position can be set at a given knee angle for all athletes (e.g. 90°, as done during the validation protocol, Samozino et al. 2008) or letting athletes free to choose their preferred starting position in order to maximize jump height. Then, the starting position as to be standardized for all jumps to ensure that h_{PO} corresponds to the values determined a priori (Fig. 4.9). Note that the h_{PO} was measured in this way in the first validation protocol of the simple method, and results showed very low bias. Other techniques may be found to increase the precision of this parameter and/or the easiness of use, as what we proposed for bench press in Chap. 7 which could be adapted for jumping.

4.6 Practical Applications

The interest of such a simple method to determine F-v relationship is to be used directly in typical training practice as a relatively simple routine test of the force, velocity and power generating capacities of lower limb muscles. After a warm-up, a

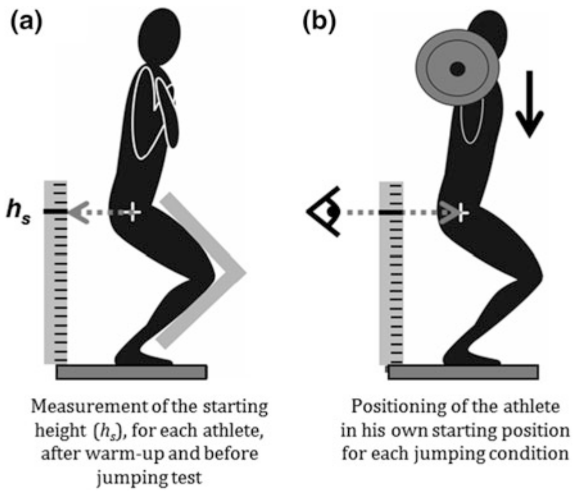

Fig. 4.9 Measurement of the starting height (h_s) after warm-up and before jumping test for each athlete (**a**) and using of this value to position each athlete in his own starting position before each jumping trial (**b**)

good processing of the simple method makes possible to test 3 or 4 athletes in 30–40 min. Here we will detail the different practical points of a typical testing session using the simple method that contributes to the accuracy and the relevance of the obtained data.

Warm-up. After 5–10 min of a typical general warm-up (e.g. running, cycling or rowing), a specific warm-up has to include vertical jumps with a progressive increase in the intensity and loaded jumps. Besides to complete warm-up, the latter also aim at avoiding any apprehension of this kind of exercise and taking advantage of a potential potentiation effect from the beginning of the tests. Note that if athletes are not accustomed to loaded SJ and CMJ and/or to loaded squat exercises, an accustomed session should be done some days before. The specific warm-up should be used to check that athletes (i) perform vertical jumps without countermovement if the tests focus on SJ and (ii) contact the ground at landing with an ankle plantar flexion if jump height is measured from flight time.

Push-off distance measurement. Before, during or after warm-up, a mark has to be put on great trochanter or superior iliac crest. In a practical point of view, a mark on the superior iliac crest is easier to see during the testing session to standardize the starting position. The extended lower limb length with maximal foot plantar flexion can be measured lying down on the back (Fig. 4.10). At the end of the warm-up, the vertical height of the mark is measured when athlete is in the crouch starting position for SJ or the crouch position corresponding to the beginning of the ascendant phase for CMJ (Fig. 4.9). As previously mentioned, this position can be fixed or let free to the athletes (recommended). In the latter case, the choice of the

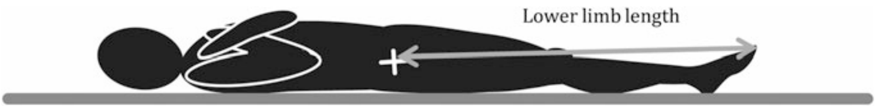

Fig. 4.10 Measurement of the lower limb length with maximal foot plantar flexion, which corresponds to the height of the hip at the instant of take-off during a vertical jump

starting position can be done through different trials with and without loads. Note that this choice is more relevant when performed after the warm-up than before.

Number and choice of loads. To determine a F-v relationship, several jumps with different loads are required. A minimum of two different loads is necessary (the two-load model recently proposed by Jaric 2016a), the maximum of loads depending on fatigue occurrence. The lower the number of loads, the higher the sensibility of the mechanical outputs to the potential measurement errors. So, we recommended, notably during field testing, to test 5 or 6 different loads including the condition without load. The loads can be determined at given values relative to body mass (Samozino et al. 2008), at given values relative to the one maximum repetition in squat (Giroux et al. 2015) or at absolute values (Samozino et al. 2014). Note that if several athletes are tested together in the same session, absolute values of loads are easier to set up. The exact values of the load is not so important, the idea is that the several loads cover the highest range of values as possible, the lowest load being without additional load and the highest load being the highest load with which the athlete can jump. For security and quality of movement execution, we advise to not test loads with which the athlete cannot jump higher than ~8 to 10 cm. In practice, the highest load is from ~75% of body mass for athlete non-accustomed to heavy strength training to ~100% of body mass for others. The number and choice of loads can be changed during testing considering the actual jumping performance realized, for instance by adding a supplementary loading condition if the athlete jump largely higher than 10 cm with the highest load or slightly decreasing the highest load if an athlete does not feel to jump with it. The different loads can be randomized.

Jumping tests. Each athlete has to perform at least two trials at each load, only the best performance being considered for analysis. If performances are too much different between the two trials, athlete should do another one to confirm or infirm the best jump previously performed. An overestimation of the performance can be due to a non-respect of the instructions: incorrect countermovement, feet too much dorsiflexed at landing (if using flight time) or important trunk extension during push-off. All these criteria have to be carefully checked at each jump to be validated. The different trials at each load can be performed successively with 20–30 s of rest between them. The different loading conditions can be separated by a 5-min rest, period during which other athletes can be tested. For each trial, athlete set up for the squat jump in a standing position while holding a barbell across their shoulders for additional loads conditions or with arms crossed on torso for the no-load jump. For SJ, athlete are asked to bend their legs and reach the a priori defined starting height carefully checked thanks to a ruler and the mark on athlete hip (Fig. 4.9). After having maintained this crouch position for about 2 s, they were asked to apply force as fast as possible and to jump for maximum height. For CMJ, athletes initiate a downward movement until the a priori defined squatting position followed immediately by a jump to maximum height. To control if the degree of crouching squatting achieved is good, an elastic band can be extended just under the athlete buttock at the height corresponding to the a priori defined position. If the athlete is too far from the elastic or if he/she touches too much it, the trial cannot be validated.

Live feedback and adjustment quality of the F-v relationship. The accuracy and reliability of the mechanical outputs (F_0, v_0, P_{max} and F-v profile) depend directly on the adjustment quality of the F-v linear regression. If the different points corresponding to the different loading conditions (best trials) are not well aligned as expected, the obtained outputs make less sense. A good objective index of the adjustment quality of the F-v relationship is the determination coefficient (r^2) which should be higher than ~ 0.95 when 5 or 6 loads (i.e. points on the F-v curve) are used. In practice, it is interesting to have a feedback of the F-v relationship and its adjustment quality in live during testing in order to ask athlete to do again a condition in case of doubts (a point strangely above or below the linear F-v curve) (Fig. 4.2). A simple spreadsheet including the different computations and F-v relationship diagram allows athletes or coaches, after entering the individual inputs data (h_{PO}, and h and m for each condition), to have this kind of feedback and to know the individual muscle capabilities directly at the end of the test.[1] The MyJump App makes also possible this kind of direct feedback.

4.7 Conclusion

This chapter present the F-v relationship as an interesting tool to evaluate the different lower limb muscle mechanical capabilities during ballistic push-off: maximal power and F-v profile. This chapter also present an accurate and reliable simple field method to determine these muscle capabilities with a precision similar to that obtained with specific laboratory ergometers, while being convenient for field use because the computations only require loaded jumps (accurately standardized and performed) and three parameters rather easily measurable out of laboratory: body mass, jump height and push-off distance.

The use of this simple method as routine test gives interesting information to coaches or physiotherapists: individual maximal power output and F-v profile. This

[1]A typical spreadsheet and a tutorial to use it (home-made by Morin and Samozino) can be downloaded/viewed here: https://www.researchgate.net/publication/320146284_JUMP_FVP_profile_spreadsheet

makes possible the follow-up of athlete muscle capabilities during a season or over several years, but also the comparison between athletes, which can help to optimize training and individualize loads and exercise modalities in strength training.

As for all kind of tests, determining the strengths and the weaknesses of an athlete based on the comparison with other athletes or with indexes thresholds computed from other athlete data is limited, yet interesting if no other way to interpret them. In order to optimize and individualize strength training, the idea would be rather to compare each athlete data to the data he/she should present to reach the best ballistic performance as possible. This will be addressed in the next chapter.

References

Andrews GC (1983) Biomechanical measures of muscular effort. Med Sci Sports Exerc 15(3): 199–207

Argus CK, Gill ND, Keogh JW, Blazevich AJ, Hopkins WG (2011) Kinetic and training comparisons between assisted, resisted, and free countermovement jumps. J Strength Conditioning Res 25(8):2219–2227. https://doi.org/10.1519/JSC.0b013e3181f6b0f4

Arsac LM, Belli A, Lacour JR (1996) Muscle function during brief maximal exercise: accurate measurements on a friction-loaded cycle ergometer. Eur J Appl Physiol 74(1–2):100–106

Asmussen E, Bonde-Petersen F (1974) Storage of elastic energy in skeletal muscles in man. Acta Physiol Scand 91(3):385–392

Avis FJ, Hoving A, Toussaint HM (1985) A dynamometer for the measurement of force, velocity, work and power during an explosive leg extension. Eur J Appl Physiol Occup Physiol 54(2): 210–215

Bahamonde RE (2005) Power prediction equations. Med Sci Sports Exerc 37(3):521; discussion 521-522

Balsalobre-Fernandez C, Glaister M, Lockey RA (2015) The validity and reliability of an iPhone app for measuring vertical jump performance. J Sports Sci 33(15):1574–1579. https://doi.org/10.1080/02640414.2014.996184

Bassey EJ, Short AH (1990) A new method for measuring power output in a single leg extension: feasibility, reliability and validity. Eur J Appl Physiol Occup Physiol 60(5):385–390

Bobbert MF (2012) Why is the force-velocity relationship in leg press tasks quasi-linear rather than hyperbolic? J Appl Physiol 112(12):1975–1983. https://doi.org/10.1152/japplphysiol.00787.2011

Bosco C (1992) La valutazione della forza con il test di Bosco [Strength assessment with the Bosco's Test]. In: Societa Sampa Sportiva, Roma, pp 56–57

Bosco C, Belli A, Astrua M, Tihanyi J, Pozzo R, Kellis S, Tsarpela O, Foti C, Manno R, Tranquilli C (1995) A dynamometer for evaluation of dynamic muscle work. Eur J Appl Physiol Occup Physiol 70(5):379–386

Bosco C, Komi PV (1979) Potentiation of the mechanical behavior of the human skeletal muscle through prestretching. Acta Physiol Scand 106(4):467–472

Bosco C, Luhtanen P, Komi PV (1983) A simple method for measurement of mechanical power in jumping. Eur J Appl Physiol Occup Physiol 50(2):273–282

Canavan PK, Vescovi JD (2004) Evaluation of power prediction equations: peak vertical jumping power in women. Med Sci Sports Exerc 36(9):1589–1593

Casartelli N, Muller R, Maffiuletti NA (2010) Validity and reliability of the Myotest accelerometric system for the assessment of vertical jump height. J Strength Conditioning Res 24(11):3186–3193. https://doi.org/10.1519/JSC.0b013e3181d8595c

Cavagna GA (1975) Force platforms as ergometers. J Appl Physiol 39(1):174–179
Comstock BA, Solomon-Hill G, Flanagan SD, Earp JE, Luk HY, Dobbins KA, Dunn-Lewis C, Fragala MS, Ho JY, Hatfield DL, Vingren JL, Denegar CR, Volek JS, Kupchak BR, Maresh CM, Kraemer WJ (2011) Validity of the Myotest® in measuring force and power production in the squat and bench press. J Strength Conditioning Res 25(8):2293–2297. https://doi.org/10.1519/JSC.0b013e318200b78c
Corcos DM, Chen CM, Quinn NP, McAuley J, Rothwell JC (1996) Strength in Parkinson's disease: relationship to rate of force generation and clinical status. Ann Neurol 39(1):79–88. https://doi.org/10.1002/ana.410390112
Cormie P, Deane R, McBride JM (2007a) Methodological concerns for determining power output in the jump squat. J Strength Conditioning Res 21(2):424–430
Cormie P, McBride JM, McCaulley GO (2007b) Validation of power measurement techniques in dynamic lower body resistance exercises. J Appl Biomech 23(2):103–118
Cormie P, McCaulley GO, McBride JM (2007c) Power versus strength-power jump squat training: influence on the load-power relationship. Med Sci Sports Exerc 39(6):996–1003
Cormie P, McCaulley GO, Triplett NT, McBride JM (2007d) Optimal loading for maximal power output during lower-body resistance exercises. Med Sci Sports Exerc 39(2):340–349
Cormie P, McGuigan MR, Newton RU (2010a) Adaptations in athletic performance after ballistic power versus strength training. Med Sci Sports Exerc 42(8):1582–1598
Cormie P, McGuigan MR, Newton RU (2010b) Influence of strength on magnitude and mechanisms of adaptation to power training. Med Sci Sports Exerc 42(8):1566–1581
Cormie P, McGuigan MR, Newton RU (2011a) Developing maximal neuromuscular power: part 1—biological basis of maximal power production. Sports Med 41(1):17–38
Cormie P, McGuigan MR, Newton RU (2011b) Developing maximal neuromuscular power: part 2—training considerations for improving maximal power production. Sports Med 41(2):125–146
Cronin J, McNair PJ, Marshall RN (2001) Velocity specificity, combination training and sport specific tasks. J Sci Med Sport 4(2):168–178
Cronin JB, Hing RD, McNair PJ (2004) Reliability and validity of a linear position transducer for measuring jump performance. J Strength Conditioning Res 18(3):590–593. https://doi.org/10.1519/1533-4287(2004)18<590:RAVOAL>2.0.CO;2
Cuk I, Markovic M, Nedeljkovic A, Ugarkovic D, Kukolj M, Jaric S (2014) Force-velocity relationship of leg extensors obtained from loaded and unloaded vertical jumps. Eur J Appl Physiol 114(8):1703–1714. https://doi.org/10.1007/s00421-014-2901-2
Davies CT, Rennie R (1968) Human power output. Nature 217(5130):770–771
Davies CT, Young K (1984) Effects of external loading on short term power output in children and young male adults. Eur J Appl Physiol Occup Physiol 52(3):351–354
Dorel S, Couturier A, Lacour JR, Vandewalle H, Hautier C, Hug F (2010) Force-velocity relationship in cycling revisited: benefit of two-dimensional pedal forces analysis. Med Sci Sports Exerc 42(6):1174–1183. https://doi.org/10.1249/MSS.0b013e3181c91f35
Dorel S, Guilhem G, Couturier A, Hug F (2012) Adjustment of muscle coordination during an all-out sprint cycling task. Med Sci Sports Exerc 44(11):2154–2164. https://doi.org/10.1249/MSS.0b013e3182625423
Driss T, Vandewalle H, Quièvre J, Miller C, Monod H (2001) Effects of external loading on power output in a squat jump on a force platform: a comparison between strength and power athletes and sedentary individuals. J Sports Sci 19(2):99–105
Dugan EL, Doyle TLA, Humphries B, Hasson CJ, Newton RU (2004) Determining the optimal load for jump squats: a review of methods and calculations. J Strength Conditioning Res 18(3):668–674
Ferretti G, Gussoni M, Di Prampero PE, Cerretelli P (1987) Effects of exercise on maximal instantaneous muscular power of humans. J Appl Physiol 62(6):2288–2294
Fox EL, Mathews DK (1974) Interval training: conditioning for sports and general fitness. In: Saunders WB (eds) Philadelphia, pp 257–258

Giroux C, Rabita G, Chollet D, Guilhem G (2015) What is the best method for assessing lower limb force-velocity relationship? Int J Sports Med 36(2):143–149. https://doi.org/10.1055/s-0034-1385886

Giroux C, Rabita G, Chollet D, Guilhem G (2016) Optimal balance between force and velocity differs among world-class athletes. J Appl Biomech 32(1):59–68. https://doi.org/10.1123/jab.2015-0070

Glatthorn JF, Gouge S, Nussbaumer S, Stauffacher S, Impellizzeri FM, Maffiuletti NA (2011) Validity and reliability of Optojump photoelectric cells for estimating vertical jump height. J Strength Conditioning Res 25(2):556–560. https://doi.org/10.1519/JSC.0b013e3181ccb18d

Gray R, Start K, Glenross D (1962) A test of leg power. Res Q 33:44–50

Gülch RW (1994) Force-velocity relations in human skeletal muscle. Int J Sports Med 15(Suppl 1):S2–S10

Harman EA, Rosenstein MT, Frykman PN, Rosenstein RM (1990) The effects of arms and countermovement on vertical jumping. Med Sci Sports Exerc 22(6):825–833

Harman EA, Rosenstein MT, Frykman PN, Rosenstein RM, Kraemer WJ (1991) Estimation of human power output from vertical jump. J Appl Sport Sci Res 5(3):116–120

Harris NK, Cronin JB, Hopkins WG (2007) Power outputs of a machine squat-jump across a spectrum of loads. J Strength Conditioning Res 21(4):1260–1264

Hill AV (1938) The heat of shortening and the dynamic constants of muscle. Proc R Soc Lond B Biol Sci 126B:136–195

Hintzy F, Belli A, Grappe F, Rouillon JD (1999) Optimal pedalling velocity characteristics during maximal and submaximal cycling in humans. Eur J Appl Physiol Occup Physiol 79(5): 426–432

Hopkins WG, Schabort EJ, Hawley JA (2001) Reliability of power in physical performance tests. Sports Med 31(3):211–234

James RS, Navas CA, Herrel A (2007) How important are skeletal muscle mechanics in setting limits on jumping performance? J Exp Biol 210(Pt 6):923–933

Janssen WG, Bussmann HB, Stam HJ (2002) Determinants of the sit-to-stand movement: a review. Phys Ther 82(9):866–879

Jaric S (2015) Force-velocity relationship of muscles performing multi-joint maximum performance tasks. Int J Sports Med 36(9):699–704. https://doi.org/10.1055/s-0035-1547283

Jaric S (2016a) Two-load method for distinguishing between muscle force, velocity, and power-producing capacities. Sports Med. https://doi.org/10.1007/s40279-016-0531-z

Jaric S (2016b) Two-load method for distinguishing between muscle force, velocity, and power-producing capacities. Sports Med 46(11):1585–1589. https://doi.org/10.1007/s40279-016-0531-z

Jaric S, Markovic G (2009) Leg muscles design: the maximum dynamic output hypothesis. Med Sci Sports Exerc 41(4):780–787

Jimenez-Reyes P, Samozino P, Pareja-Blanco F, Conceicao F, Cuadrado-Penafiel V, Gonzalez-Badillo JJ, Morin JB (2016) Validity of a simple method for measuring force-velocity-power profile in countermovement jump. Int J Sports Physiol Perform. https://doi.org/10.1123/ijspp.2015-0484

Johnson DL, Bahamonde R (1996) Power output estimate in university athletes. J Strength Conditioning Res 10(3):161–166

Kaneko M, Fuchimoto T, Toji H, Suei K (1983) Training effect of different loads on the force-velocity relationship and mechanical power output in human muscle. Scand J Sports Sci 5(2):50–55

Kannus P (1994) Isokinetic evaluation of muscular performance: implications for muscle testing and rehabilitation. Int J Sports Med 15(Suppl 1):S11–S18

Kawamori N, Rossi SJ, Justice BD, Haff EE, Pistilli EE, O'Bryant HS, Stone MH, Haff GG (2006) Peak force and rate of force development during isometric and dynamic mid-thigh clean pulls performed at various intensities. J Strength Conditioning Res 20(3):483–491. https://doi.org/10.1519/18025.1

Lara AJ, Abian J, Alegre LM, Jimenez L, Aguado X (2006a) Assessment of power output in jump tests for applicants to a sports sciences degree. J Sports Med Phys Fitness 46(3):419–424

Lara AJ, Alegre LM, Abian J, Jimenez L, Urena A, Aguado X (2006b) The selection of a method for estimating power output from jump performance. J Hum Mov Stud 50:399–410

Lutz GJ, Rome LC (1994) Built for jumping: the design of the frog muscular system. Science 263(5145):370–372

Macaluso A, De Vito G (2003) Comparison between young and older women in explosive power output and its determinants during a single leg-press action after optimisation of load. Eur J Appl Physiol 90(5–6):458–463

Mak MK, Levin O, Mizrahi J, Hui-Chan CW (2003) Joint torques during sit-to-stand in healthy subjects and people with Parkinson’s disease. Clin Biomech (Bristol, Avon) 18(3):197–206. doi:S0268003302001912 [pii]

Marey JE, Demeny G (1885) Locomotion humaine, mécanisme du saut. Comptes rendus des séances de l’Académies des Sciences; séance du 24 août 1885, vol 101. Institut de France, Académies des Sciences, Paris

Margaria R, Aghemo P, Rovelli E (1966) Measurement of muscular power (anaerobic) in man. J Appl Physiol 21(5):1662–1664

Markovic G, Vuk S, Jaric S (2011) Effects of jump training with negative versus positive loading on jumping mechanics. Int J Sports Med 32:1–8

Marsh RL (1994) Jumping ability of anuran amphibians. Adv Vet Sci Comp Med 38B:51–111

Martin JC, Wagner BM, Coyle EF (1997) Inertial-load method determines maximal cycling power in a single exercise bout. Med Sci Sports Exerc 29(11):1505–1512

McBride JM, Triplett-McBride T, Davie A, Newton RU (2002) The effect of heavy- vs. light-load jump squats on the development of strength, power, and speed. J Strength Conditioning Res 16(1):75–82

McCartney N, Heigenhauser GJ, Sargeant AJ, Jones NL (1983) A constant-velocity cycle ergometer for the study of dynamic muscle function. J Appl Physiol 55(1 Pt 1):212–217

McCartney N, Obminski G, Heigenhauser GJ (1985) Torque-velocity relationship in isokinetic cycling exercise. J Appl Physiol 58(5):1459–1462

McMaster DT, Gill N, Cronin J, McGuigan M (2014) A brief review of strength and ballistic assessment methodologies in sport. Sports Med 44(5):603–623. https://doi.org/10.1007/s40279-014-0145-2

Morin JB, Samozino P, Bonnefoy R, Edouard P, Belli A (2010) Direct measurement of power during one single sprint on treadmill. J Biomech 43(10):1970–1975

Morin JB, Samozino P (2016) Interpreting power-force-velocity profiles for individualized and specific training. Int J Sports Physiol Perform 11(2):267–272

Padulo J, Migliaccio GM, Ardigo LP, Leban B, Cosso M, Samozino P (2017) Lower limb force, velocity, power capabilities during leg press and squat movements. Int J Sports Med. http://doi.org/10.1055/s-0043-118341

Palmieri G, Callegari M, Fioretti S (2015) Analytical and multibody modeling for the power analysis of standing jumps. Comput Methods Biomech Biomed Engin 18(14):1564–1573. https://doi.org/10.1080/10255842.2014.930135

Pearson SJ, Cobbold M, Harridge SD (2004) Power output of the lower limb during variable inertial loading: a comparison between methods using single and repeated contractions. Eur J Appl Physiol 92(1–2):176–181

Rabita G, Dorel S, Slawinski J, Saez de villarreal E, Couturier A, Samozino P, Morin JB (2015) Sprint mechanics in world-class athletes: a new insight into the limits of human locomotion. Scand J Med Sci Sports. doi:https://doi.org/10.1111/sms.12389

Rahmani A, Dalleau G, Viale F, Belli A, Lacour JR (1998) Mesure de la force dynamique par un test ballistique. Science et Sports 13:241–242

Rahmani A, Dalleau G, Viale F, Hautier CA, Lacour JR (2000) Validity and reliability of a kinematic device for measuring the force developed during squatting. J Appl Biomech 16: 26–35

Rahmani A, Locatelli E, Lacour JR (2004) Differences in morphology and force/velocity relationship between Senegalese and Italian sprinters. Eur J Appl Physiol 91(4):399–405

Rahmani A, Viale F, Dalleau G, Lacour JR (2001) Force/velocity and power/velocity relationships in squat exercise. Eur J Appl Physiol 84(3):227–232

Riviere JR, Rossi J, Jimenez-Reyes P, Morin JB, Samozino P (2017) Where does the one-repetition maximum exist on the force-velocity relationship in squat? Int J Sports Med. http://doi.org/10.1055/s-0043-116670

Samozino P, Edouard P, Sangnier S, Brughelli M, Gimenez P, Morin JB (2014) Force-velocity profile: imbalance determination and effect on lower limb ballistic performance. Int J Sports Med 35(6):505–510. https://doi.org/10.1055/s-0033-1354382

Samozino P, Horvais N, Hintzy F (2007) Why does power output decrease at high pedaling rates during sprint cycling? Med Sci Sports Exerc 39(4):680–687

Samozino P, Morin JB, Hintzy F, Belli A (2008) A simple method for measuring force, velocity and power output during squat jump. J Biomech 41(14):2940–2945

Samozino P, Rejc E, Di Prampero PE, Belli A, Morin JB (2012) Optimal force-velocity profile in ballistic movements. Altius: citius or fortius? Med Sci Sports Exerc 44(2):313–322

Sargeant AJ, Hoinville E, Young A (1981) Maximum leg force and power output during short-term dynamic exercise. J Appl Physiol 51(5):1175–1182

Sargent LW (1924) Some observations on the Sargent test of neuromuscular efficiency. Am Phys Educ Rev 29:47–56

Sayers SP, Harackiewicz DV, Harman EA, Frykman PN, Rosenstein MT (1999) Cross-validation of three jump power equations. Med Sci Sports Exerc 31(4):572–577

Scholz MN, Bobbert MF, Knoek van Soest AJ (2006) Scaling and jumping: gravity loses grip on small jumpers. J Theor Biol 240(4):554–561

Seck D, Vandewalle H, Decrops N, Monod H (1995) Maximal power and torque-velocity relationship on a cycle ergometer during the acceleration phase of a single all-out exercise. Eur J Appl Physiol Occup Physiol 70(2):161–168

Seo DI, Kim E, Fahs CA, Rossow L, Young K, Ferguson SL, Thiebaud R, Sherk VD, Loenneke JP, Kim D, Lee MK, Choi KH, Bemben DA, Bemben MG, So WY (2012) Reliability of the one-repetition maximum test based on muscle group and gender. J Sports Sci Med 11(2):221–225

Shetty AB (2002) Estimation of leg power: a two-variable model. Sports Biomech 1(2):147–155

Suzuki S, Watanabe S, Homma S (1982) EMG activity and kinematics of human cycling movements at different constant velocities. Brain Res 240(2):245–258

Thorstensson A, Grimby G, Karlsson J (1976) Force-velocity relations and fiber composition in human knee extensor muscles. J Appl Physiol 40(1):12–16

Van Soest AJ, Bobbert MF, Van Ingen Schenau GJ (1994) A control strategy for the execution of explosive movements from varying starting positions. J Neurophysiol 71(4):1390–1402

van Soest O, Casius LJ (2000) Which factors determine the optimal pedaling rate in sprint cycling? Med Sci Sports Exerc 32(11):1927–1934

Vandewalle H, Peres G, Heller J, Panel J, Monod H (1987a) Force-velocity relationship and maximal power on a cycle ergometer. Correlation with the height of a vertical jump. Eur J Appl Physiol Occup Physiol 56(6):650–656

Vandewalle H, Peres G, Monod H (1987b) Standard anaerobic exercise tests. Sports Med 4(4): 268–289

Verdijk LB, van Loon L, Meijer K, Savelberg HH (2009) One-repetition maximum strength test represents a valid means to assess leg strength in vivo in humans. J Sports Sci 27(1):59–68. https://doi.org/10.1080/02640410802428089

Wilson GJ, Walshe AD, Fisher MR (1997) The development of an isokinetic squat device: reliability and relationship to functional performance. Eur J Appl Physiol Occup Physiol 75(5):455–461

Wright GA, Pustina AA, Mikat RP, Kernozek TW (2012) Predicting lower body power from vertical jump prediction equations for loaded jump squats at different intensities in men and women. J Strength Conditioning Res 26(3):648–655. https://doi.org/10.1519/JSC.0b013e3182443125

Yamauchi J, Ishii N (2007) Relations between force-velocity characteristics of the knee-hip extension movement and vertical jump performance. J Strength Conditioning Res 21(3): 703–709

Yamauchi J, Mishima C, Fujiwara M, Nakayama S, Ishii N (2007) Steady-state force-velocity relation in human multi-joint movement determined with force clamp analysis. J Biomech 40(7):1433–1442

Yamauchi J, Mishima C, Nakayama S, Ishii N (2005) Torque-velocity relation of pedaling movement against stepwise increase in load. Int J Sport Health Sci 3:110–115

Zamparo P, Antonutto G, Capelli C, di Prampero PE (2000) Effects of different after-loads and knee angles on maximal explosive power of the lower limbs in humans. Eur J Appl Physiol 82(5–6):381–390

Zamparo P, Antonutto G, Capelli C, Girardis M, Sepulcri L, di Prampero PE (1997) Effects of elastic recoil on maximal explosive power of the lower limbs. Eur J Appl Physiol Occup Physiol 75(4):289–297