What is the Best Method for Assessing Lower Limb Force-Velocity Relationship?

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Key words
- muscle power
- linear transducer
- accelerometry
- force plate
- ballistic movements

Abstract

This study determined the concurrent validity and reliability of force, velocity and power measurements provided by accelerometry, linear position transducer and Samozino's methods, during loaded squat jumps. 17 subjects performed squat jumps on 2 separate occasions in 7 loading conditions (0–60% of the maximal concentric load). Force, velocity and power patterns were averaged over the push-off phase using accelerometry, linear position transducer and a method based on key positions measurements during squat jump, and compared to force plate measurements. Concurrent validity analyses indicated very good agreement with the reference method (CV = 6.4–14.5%). Force, velocity and power patterns comparison confirmed the agreement with slight differences for high-velocity movements. The validity of measurements was equivalent for all tested methods (r = 0.87–0.98). Bland-Altman plots showed a lower agreement for velocity and power compared to force. Mean force, velocity and power were reliable for all methods (ICC = 0.84–0.99), especially for Samozino's method (CV = 2.7–8.6%). Our findings showed that present methods are valid and reliable in different loading conditions and permit between-session comparisons and characterization of training-induced effects. While linear position transducer and accelerometer allow for examining the whole time-course of kinetic patterns, Samozino's method benefits from a better reliability and ease of processing.

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Bibliography
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Introduction

The ability to generate high velocity at release (e.g., jumping) or direction change (e.g., cutting-manoeuvre) is a determinant of performance in many sport activities [26]. During a vertical jump, the velocity reached at take-off is determined by the mechanical impulse, i.e., the product of the force exerted against the ground and the time during which the force is applied [31]. This capacity is related to the power that a muscle can produce during a shortening contraction, defined as the product of the force it exerts and the speed at which it shortens. Measurement of power production is important for training and rehabilitation purposes but also for improving the understanding of the basic properties and function of the neuromuscular system [8, 32].
According to the hyperbolic function for the force-velocity relationship observed on isolated muscle [19], muscle force-generating capacity decreases as the velocity increases, leading to an optimal balance between both parameters that corresponds to the production of maximal power output [11, 30, 34]. In functional tasks involving a combination of joint rotations, the force-velocity relationship is quasi-linear [2, 5, 28, 35]. Maximal power output is correlated to performance in several sport activities [9, 13]. Likewise, it has been shown that increasing maximal power typically results in improving athletic performance [25, 31]. However, training-induced changes in the force-velocity relationship are subtle in well-trained athletes [4]. Therefore, the assessment of this relationship needs to be really sensitive to any changes in velocity or force output. While many devices and methods have been proposed to evaluate power output during single or multi-joint movements [3, 10, 28, 29], the reference method is based on force plate (FP) data [3, 7]. Recently developed devices (e.g., linear position transducer, accelerometer) or simple methods based on jump height [29] can also be used to assess power output directly at training venue. However, most of these methods have been tested during a single-load (and thus single-

velocity) condition, and no study has investigated their concurrent validity and reliability throughout the whole force-velocity relationship. Therefore, the evaluation of the validity and reliability of the most commonly-used methods would help to accurately monitor training sessions directly on the field and evaluate power output improvement.

The aim of this study was thus to determine the concurrent validity and reliability of the force, velocity and power patterns measured by 3 methods (accelerometer, linear position transducer and Samozino's methods) during isoinertial vertical jumps.

Methods

Ethics statement

Written informed consent was obtained from each subject prior to participation. This study was approved by the local ethics committee and conducted according to the Declaration of Helsinki. This study meets the ethical standards in sports and exercises science research [17].

Participants

17 volunteers (9 female, 8 male; age: 23.7 ± 3.7 years; height: 171.9 ± 8.6 cm; body mass: 70.2 ± 11.5 kg) participated in this study. This number included 11 sedentary or participants with a low physical activity (i.e., less than 3 h per week) and 6 elite athletes used to squat jumps and testing procedures.

Experimental design

The procedure included 3 test sessions (i.e., familiarisation, test, re-test) separated by 1 week. Participants performed squat jumps with progressive increase in the additional external load to determine their lower limb force-velocity relationship. 3 methods based either on accelerometer, linear position transducer or squat jump positions measurements [29] were compared to a reference method (i.e., force plate). Jumps were executed in a squat rack (**Fig. 1a**) comprising an anteroposterior and vertical guided bar of 23.6 kg (Max Rack, Gym80 International, Gelsenkirchen, Germany). This system allowed for the execution of free weight-like squats without oscillations in the frontal plane, thus limiting the potential impact of unintended lateral movements on mechanical measurements. A free bar was used for loads under 23.6 kg, and a 0.5 kg bar was used in body weight condition to simulate the same experimental configuration for all tested loads. Pilot data showed that frictional forces were negligible with the guided bar (1.1 ± 0.1 N, i.e., 0.09 ± 0.02 % of body mass).

During the familiarization session, the starting position was self-selected by the participant. The position was then kept constant for subsequent trials. A marker on the squat cage indicated the bar height (**Fig. 1a**) in this position. Then, participants performed squat jumps with load increasing progressively. Participants were asked to jump with the bar (ballistic movement) so that they use the whole range of motion and produce the greatest possible amount of power output [6]. The load increment depended on the jump height achieved during the body weight condition (with a 0.5 kg bar). Under a 0.2 m jump height, 10 % of the body mass was added at each trial until the load was sufficient to obtain a jump height below 0.05 m. A supplemental load corresponding to 15, 20, or 25 % of body mass was added when jump height in the body weight condition was above 0.2 m, 0.3 m, and 0.4 m, respectively. The maximal additional load the participants were able to lift concentrically once (1RM) was

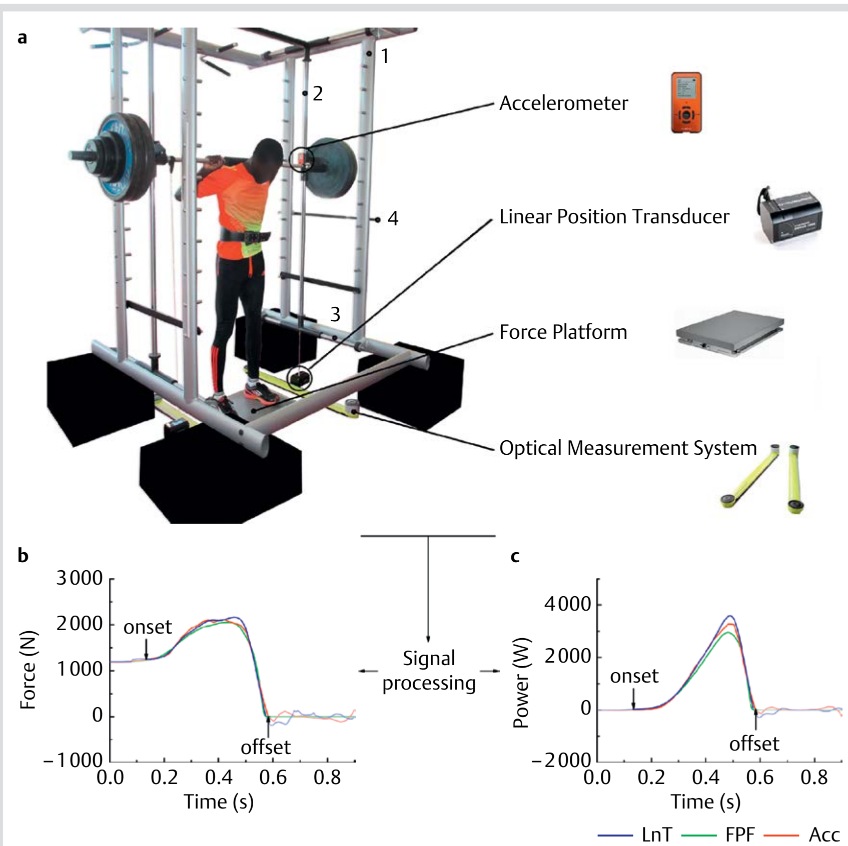

Fig. 1 Overview of the experimental setup **a** and data processing **b–e**. Participants executed isoinertial vertical jumps in a squat cage **1** that included vertical **2** and horizontal **3** guides. Force plate (FP), linear position transducer (LnT), accelerometer (Acc) and optical measurement system allowing for the determination of jump height in Samozino's method (Sam) were used to measure force, velocity and power during the squat jump push-off phase, respectively. The starting position was set by a horizontal marker **4**. Jump push-off phase was defined as the period of time between the point corresponding to a 50 N increase of the vertical force (onset) and the point where vertical power reached zero (offset; **b** and **c**).

determined from the load-velocity relationship obtained during the familiarization session. 1RM was selected as 90% of the load corresponding to zero velocity [23]. During test and re-test sessions, the 7 tested loading conditions were 0, 10, 20, 30, 40, 50 and 60% of 1RM.
At the beginning of each trial, participants were asked to stand still on the force plate to assess the total system load (i.e., participant body mass + external load). After staying in the starting position for 1 s, the participant jumped as fast and high as possible. Participants performed 2 trials at each load, plus a third one in the case of a 10% height difference between the 2 trials. The highest jump trial was considered for further analysis. Movement execution was monitored through the FP signals and trial was repeated if the jump was not executed properly (i.e., if countermovements were observed).

Data collection and processing

For each method, force, velocity and power signals were obtained as follows.

Force plate

A force plate (FP) (Kistler, Wintertur, Switzerland) was used as reference method. Vertical ground reaction force was recorded and sampled at 1 000 Hz. F_z component was used to calculate the vertical instantaneous acceleration (a_z; $m \cdot s^{-2}$) of the centre of mass (COM):

$$a_z = \frac{F_z}{m} - g \tag{1}$$

where m is the total mass (in kg).
a_z was then integrated to provide instantaneous vertical velocity (v_z; in $m \cdot s^{-1}$) of the COM at time t:

$$v_z = \int a\, dt + v_{z0} \tag{2}$$

As the jump begins with a period of immobility, at t_0:

$$v_{z0} = 0 \tag{3}$$

At each instant, power was then calculated as the product of force and velocity ($P_z = F_z \cdot v_z$; in W).

Accelerometer

The 3-dimensional accelerometer (Acc) used in this study was a Myotest Pro (Myotest SA, Sion, Switzerland) that was directly fixed to the bar. Mechanical signals (i.e., force, velocity, power) were recorded at a sampling frequency of 500 Hz. At each instant, acceleration of the bar was used to calculate force:

$$F = a\, m \tag{4}$$

Velocity and power were obtained in the same way as for force plate data analyses.

Linear position transducer

The linear position transducer (LnT) GymAware (Kinetic Performance, Mitchell, Australia) was tested in this experiment. LnT was composed of an encoded wire directly fixed to the bar and winding into a sensor unit fixed to the floor. The sensor time-stamped the displacement data with a 1 ms resolution and then down-sampled to 50 Hz.
Vertical displacement (d_z) of the bar was differentiated once to calculate instantaneous velocity (v_z). Velocity was then differentiated to calculate instantaneous acceleration. Force and power were obtained in the same way as accelerometer and force plate signal analyses.

Samozino's method

Samozino's method (Sam) is a simple method based on Newton's second law, establishing that mean force ($\bar{F}$), velocity ($\bar{v}$), and power ($\bar{P}$) can be calculated during a vertical jump movement from the jump height and squat jump positions measurements [29]. Jump height was obtained using an OptoJump Next optical measurement system (Microgate, Bolzano-Bozen, Italy). Mean force ($\bar{F}$), velocity ($\bar{v}$) and power ($\bar{P}$) were calculated using the following equations.

$$\bar{F} = mg\left(\frac{h}{h_{PO}} + 1\right) \tag{5}$$

$$\bar{v} = \frac{h_{PO}}{t_{PO}} \tag{6}$$

$$\bar{P} = mg\left(\frac{h}{h_{PO}} + 1\right)\sqrt{\frac{gh}{2}} \tag{7}$$

where m is the body mass of the subject (in kg), g is the gravitational acceleration (in $m \cdot s^{-2}$), h_{PO} is the vertical push-off distance (in m), t_{PO} is the push-off phase duration (in s) and h is the jump height (in m).
Anterior iliac crest was selected as anatomical marker to calculate the vertical push-off distance (h_{PO}). The vertical push-off distance corresponded to the displacement of the marker between the starting position and the moment of toe-off. The vertical position of the marker was easily determined with a stadiometer in the starting position. For toe-off moment position, the participant was lying on his back, ankle in maximal extension with tip of toes reaching a wall. The distance between the wall and the iliac crest corresponded to the vertical toe-off position of the marker. These measurements were done and verified at the beginning of each test.
All data were analysed with custom-written scripts (Origin 9.0, OriginLab corporation, USA). The onset of the push-off was set as the point corresponding to a 50 N increase of the vertical force at the end of the stabilization period in the starting position (**Fig. 1b**). The offset of the push-off phase (i.e., take-off) corresponded to the point where vertical power reached zero (**Fig. 1c**). For graphical representation standardization, a linear interpolation technique was used to obtain force, velocity and power values every 5% of the total duration of the jump push-off phase [12]. Therefore, the same amount of points was used to represent all movements. The average force, velocity and power were calculated between those onset and offset time points for each loading condition.

Statistical analyses

Sample size

A non-inferiority sample size calculation was used to determine the sample-size required for the validity analysis. Data for the sample size calculation were collected in a pilot study. Non-inferiority limits were set at 5% of the maximal values obtained in the pilot study (i.e., 135 N for force, 0.06 $m \cdot s^{-1}$ for velocity, 113 W for power), with standard deviations of 371 N for force, 1.18 $m \cdot s^{-1}$

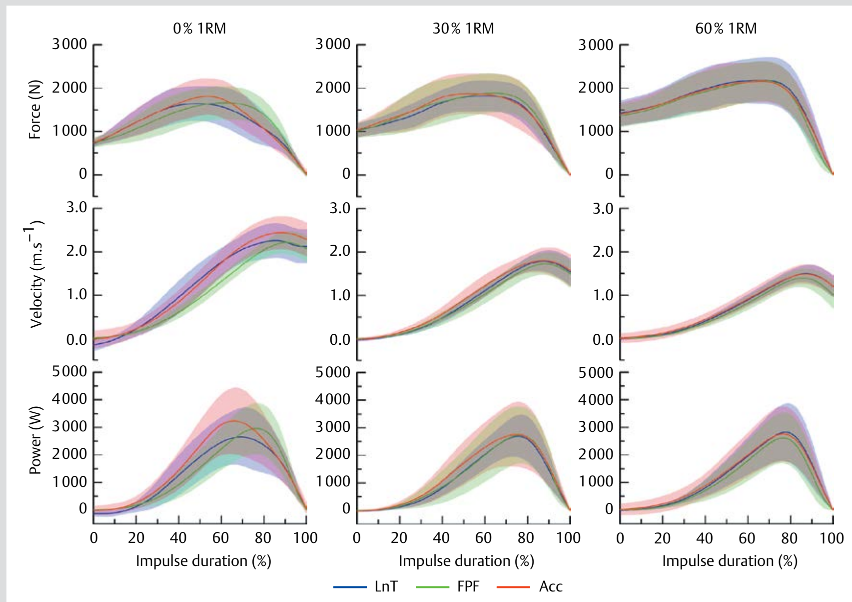

Fig. 2 Force (top panel), velocity (middle horizontal panel) and power (bottom panel) patterns provided by the force plate (FP), linear position transducer (LnT) and accelerometer (Acc) during isoinertial squat jumps, performed at 3 loading conditions: 0% (left panel), 30% (middle vertical panel), and 60% (right panel) of the maximal load that the participant could lift once (1RM). Time is normalized to the push-off duration (in %). Values are presented as mean ± SD.

for velocity, and 317 W for power. Significance and power criteria were set at 5% and 80%, respectively. It was necessary to test 15 participants. We chose to increase the number to 17.

Validity and reliability

To determine the concurrent validity of the different methods, linear regressions were performed and Bravais-Pearson correlation coefficient (r) were determined between FP (i.e., reference measurement) and LnT, Sam and Acc methods for mean force, mean velocity and mean power. Coefficients of variation (CV) were calculated [20]. The level of concordance for measurements between LnT, Sam, Acc and FP method were assessed using Bland-Altman plots, with limits of agreement defined as the mean difference ±1.96 SD of the difference [1]. The reliability between the 2 test sessions was evaluated for the mean force, velocity and power, using the intraclass correlation coefficient (ICC) and CV [20].

Results

Force, velocity and power patterns

Fig. 2 displays the patterns of force, velocity and power provided by FP, LnT and Acc during squat jumps performed at 0, 30, and 60% of 1RM. When considering all methods and testing conditions, participants exerted maximal force, velocity and power values of 1695.0±386.8 N (range: 981.5–2764.3 N), 1.50±0.46 $m \cdot s^{-1}$ (range: 0.75–2.99 $m \cdot s^{-1}$) and 1413.7±465.7 W (range: 526.0–2718.8 W), respectively. Kinetic patterns of LnT and Acc were slightly different from FP for the 0% of 1RM loading condition. The time occurrence of the maximal force changed depending on the method (i.e., between 50% and 60% of the push-off phase), while in the heaviest loads maximal force occurred at the same instant of the push-off (i.e., 65%) for all methods.

Validity of mean parameters

Pearson correlation coefficients were 0.98 for force for all tested methods, were lower for velocity than for force (for FP vs. LnT, r=0.91; FP vs. Acc, r=0.87; FP vs. Sam r=0.88) and lower than 0.90 for power (LnT and Sam, r=0.89; Acc, r=0.87). CV were lower than 5% for force (LnT, CV=3.3%; Acc, CV=4.2%; Sam, CV=3.7%). Velocity CV ranged from 6.4% for LnT to 11.4% for Sam, and reached 8.2% for Acc. CV were lower than 15% for power measurements (LnT, CV=14.5%; Acc, CV=12.5%; Sam CV=13.3%).

Bland-Altman plots are depicted in **Fig. 3**. Graphical analysis showed a noticeable and similar concordance between tested methods and FP for average force measurements, as shown by the low bias values (range: 2.6–3.2%) and narrow confidence interval (range: 6.2–12.7%). For all methods, average velocity and power data exhibited higher bias values (range: 8.4–9.7% for velocity; 9.3–14.2% for power) and larger confidence intervals than for force.

Reliability of mean parameters

Mean ICC and CV for average force, velocity and power recorded with FP, LnT, Acc and Sam methods are shown in **Table 1**. The results demonstrated an excellent reliability for the 3 parameters with ICC ranging from 0.89 to 0.99. Force measurements showed CV values lower than 5% for all methods. CV values were lower than 10% for velocity, except for Acc (CV=10.2%). CV were slightly higher than 10% for power except for Sam (CV=8.6%).

Discussion

The present study aimed to evaluate the concurrent validity and reliability of the methods most commonly used to determine average force, velocity and power during the push-off phase of vertical loaded jumps. Slight differences were observed between the tested methods and force plate measurements for high velocity and power levels. Overall, our results indicate that force, velocity and power measurements can be assessed with the present methods, as they all presented similar validity (**Fig. 3**), while measurements obtained from the Samozino's method showed the most reliable results.

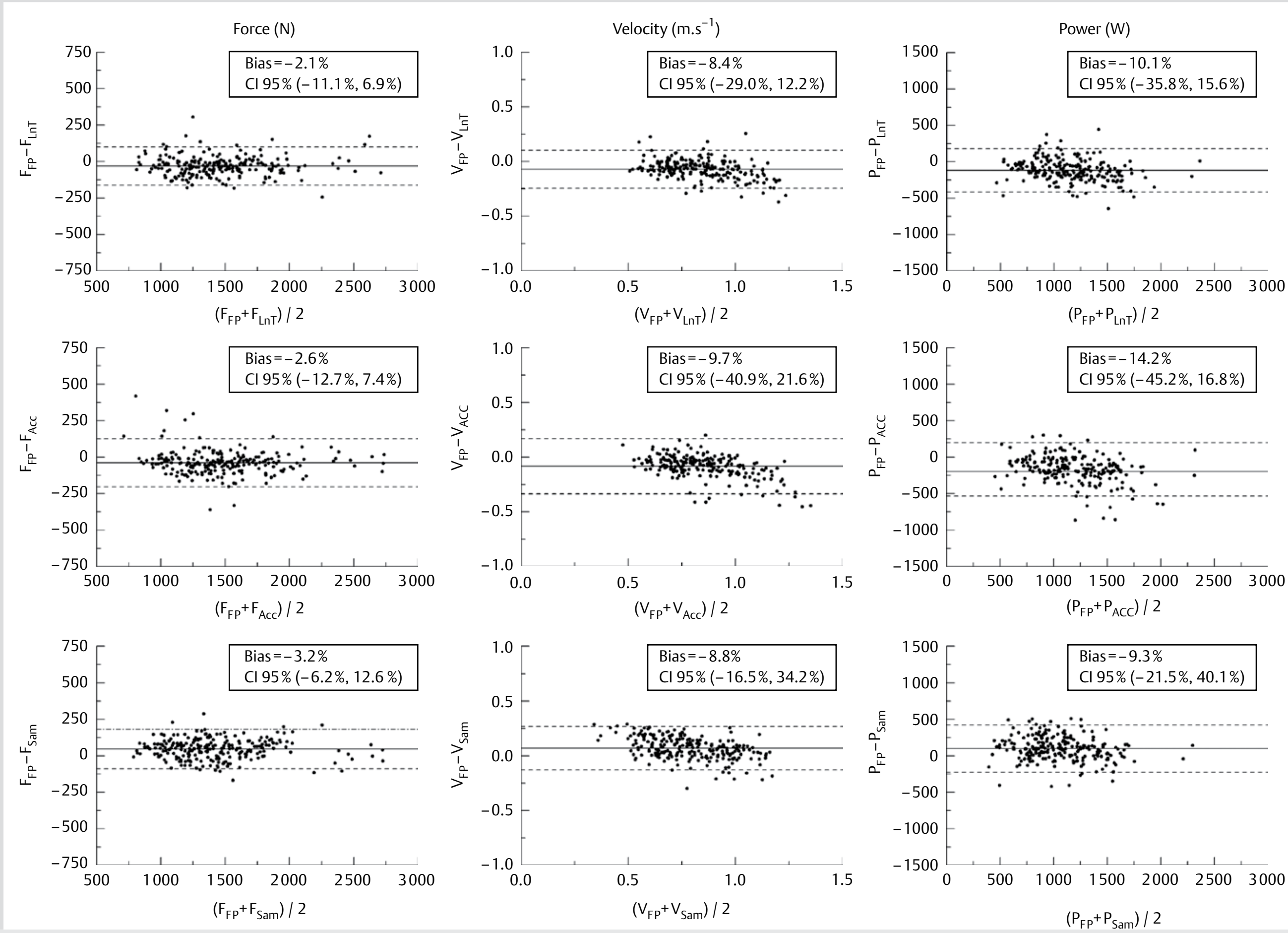

Fig. 3 Bland-Altman plots of force plate (FP) vs. linear position transducer (LnT, top panel) accelerometer (Acc, middle horizontal panel), and Samozino's method (Sam, bottom panel) for force (left panel), velocity (middle vertical panel) and power (right panel) measurements. Bias and 95% confidence interval (CI) are indicated for each plot.

To our knowledge, this study is the first to compare the current available methods used for the assessment of the force-velocity relationship of the lower limb extensor muscles. Linear position transducer and accelerometer allow for the description of the entire time-course of mechanical parameters recorded during the jump push-off phase (**Fig. 2**). The comparison of force, velocity and power patterns obtained with those methods exhibited almost perfectly overlapped curves compared to the reference method (force plate). However, the validity of mechanical measurements decreased as velocity increased (i.e., near body weight condition, **Fig. 2**). The position measurements performed with the transducer consider the movement velocity when the encoded wire is winding into the sensor box. Indeed, as the velocity increases, the sampling frequency increases thus leading to more accurate measurements. Moreover, it has been shown that the measurements obtained with accelerometry are more valid as acceleration is higher (i.e., high velocity movement). Therefore, the variability of measurements performed during high-velocity jumps cannot be attributed to devices limitations [22]. This finding has been observed in previous investigations that used identical linear transducer and accelerometer, which showed a weaker agreement for mechanical measurements obtained during fast movements [7]. These results could originate from the fact that light loading/high-velocity conditions could influence the jump trajectory notably by intensifying non-vertical movements and probably accentuate the differences between methods. A guided bar would possibly have been able to limit this phenomenon in high-velocity conditions. This observation suggests more valid mechanical measurements during slower movements (i.e., heavier loads). Actually, the comparison between the tested methods and the reference revealed slight differences (when considering all load conditions), especially for mean velocity and power data (**Fig. 2**). As previously reported, these differences could be due to the fact that linear transducers and accelerometers evaluate the bar dis-

Table 1 Reliability of force, velocity and power measurements provided by force plate (FP), linear position transducer (LnT), accelerometer (Acc) and Samozino method's (Sam).

		FP	LnT	Acc	Sam
Force (N)	Mean	1453.4	1469.7	1505.9	1407.7
	SD	371.6	354.0	381.5	372.8
	ICC	0.98	0.96	0.97	0.99
	CV%	3.1	5.0	5.3	2.7
Velocity ($m \cdot s^{-1}$)	Mean	0.8	0.9	0.9	0.7
	SD	0.16	0.2	0.2	0.2
	ICC	0.88	0.86	0.84	0.97
	CV%	7.3	9.3	10.2	6.5
Power (W)	Mean	1103.3	1241.7	1302.1	1053.5
	SD	318.0	394.1	431.9	420.3
	ICC	0.91	0.89	0.89	0.97
	CV%	10.6	12.2	12.8	8.6

placement, whereas the force plate measures the centre of mass of the total system displacement [7, 14]. Differences in velocity between the bar centre of gravity and the total system (i.e., participant + bar) centre of gravity have been previously highlighted [21]. Indeed, the individual lifting technique can contribute to the jump impulse and explain the observed differences between force plate and methods measuring the bar displacement. Upper body stability and core strength are also considered as important factors for jump performance [18]. Under heavy loads, lumbar spine muscles could be more activated to deal with an exacerbated trunk flexion resulting from the applied load and preserve an effective lifting technique. In view of these elements, a greater variability of the measurement in heavy than light loads conditions could have been expected. Nevertheless, differences were observed mainly under light loads. This can be explained by the fact that the more the load increases, the more the centre of mass moves toward the upper body, thereby minimizing the gap distance between the centre of mass and the bar. Therefore, the differences observed in average values (for all loads) might be mainly due to light load trials. Samozino's method, which is also based on displacement of the centre of mass, presented the lowest bias levels when compared to force plate. Given that calculations performed with this procedure depend on a unique main variable (jump height), the variations of the kinematic parameters during the jump are not taken into account when using this method. In this context, the slight differences observed with the force plate can also originate from the photoelectric system, which has been shown to slightly underestimate jump height assessment [16]. Despite the small differences described above and in agreement with previous reports [7], the concurrent validity of our findings were acceptable and similar for all methods and for different level of muscular abilities, as shown by the wide range of force and power values measured in this study.

When considering the mean values calculated over the entire push-off phase, we observed an excellent concurrent validity ($r = 0.98$ for all methods) and reliability ($ICC \geq 0.96$) for force values in accordance with previous studies [3, 7, 33]. In comparison with force, mean velocity and power were less valid and reliable (**Table 1**). It has been suggested that the mathematical transformation induced by time derivation (for linear transducer) or integration (for accelerometer) of the recorded signal would lead to a lower reliability for velocity measurements [7, 14]. In this context, the reliability of power measurements was affected to a lesser extent. This result can be explained by the fact that power output does not only depend on velocity but also on force production, which showed reliable measurements for all tested methods [7, 22]. Samozino's method showed excellent reliability ($ICC \geq 0.97$ and $CV < 10\%$ for all parameters). This result could originate from the calculation used in this method, which is based on a few discrete variables. Moreover, the mechanical variations that should be observed through the push-off phase are not taken into account, thus limiting their potential impact on the validity of kinetic measurements [24].

As squat jump is a ballistic and multi-joint movement involving agonist and antagonist muscles, a part of the variability between 2 tests could be due to the different muscle coordination used under the same imposed load. Very few data are available regarding the evolution of neuromuscular strategies with increase of load [15, 27]. However, as the shape of mechanical patterns (i.e., rate of force or power development) changed according to the total imposed load (**Fig. 2**), it would be interesting to explore how the changes in muscle coordination with the additional load imposed upon the lower limbs could influence this variability.

The necessity of recording valid and reliable force and velocity measurements is strengthened by the fact that these data are used to determine maximal theoretical parameters (i.e., maximal force, maximal velocity and maximal power) from the force-velocity relationship. Beyond the fact that such indicators could serve as predictive criteria of particular sport performance [9, 31], they could also be used to calibrate training sessions (i.e., external load, movement velocity) and therefore impose the optimal mechanical stimulus to improve performance without risking any injuries. It is recognized that the loading parameters used to design power training programs influence the type and magnitude of resulting performance improvements as well as the nature of the underlying physiological adaptations [6]. Using the present methods would thus help to reliably determine the neuromuscular adaptations specifically induced by different types of resistance training, or by chronic practice of a considered activity.

In conclusion, the 3 present methods are similarly valid for assessing mean mechanical parameters determined during the push-off phase of a squat jump performed under different loading conditions. Furthermore, while all methods are reliable, the Samozino's procedure provides the greatest reliability. Those methods permit between-session comparison and characterization of the training-induced effects. While mechanical patterns appear to differ from one method to another, especially when light loads are involved (i.e., high velocity), these methods can be used with confidence to assess the force-velocity relationship and provide information on the athletic profiles of trained and untrained subjects. Our findings and the ease of use of the Samozino's procedure suggest that this method is suitable for monitoring power training sessions under field conditions.

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References

1 *Bland JM, Altman DG.* Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986; 1: 307–310
2 *Bobbert MF.* Why is the force-velocity relationship in leg press tasks quasi-linear rather than hyperbolic? J Appl Physiol 2012; 112: 1975–1983
3 *Comstock BA, Solomon-Hill G, Flanagan SD, Earp JE, Luk H-Y, Dobbins KA, Dunn-Lewis C, Fragala MS, Ho J-Y, Hatfield DL, Vingren JL, Denegar CR, Volek JS, Kupchak BR, Maresh CM, Kraemer WJ.* Validity of the Myotest® in Measuring force and power production in the squat and bench press. J Strength Cond Res 2011; 25: 2293–2297
4 *Cormie P, McGuigan MR, Newton RU.* Influence of strength on magnitude and mechanisms of adaptation to power training. Med Sci Sport Exer 2010; 42: 1566–1581
5 *Cormie P, McGuigan MR, Newton RU.* Developing maximal neuromuscular power: Part 1 – Biological basis of maximal power production. Sports Med 2011; 41: 17–38
6 *Cormie P, McGuigan MR, Newton RU.* Developing maximal neuromuscular power: Part 2 – Training considerations for improving maximal power production. Sports Med 2011; 41: 125–146

7 *Crewther BT*, *Kilduff LP*, *Cunningham DJ*, *Cook C*, *Owen N*, *Yang GZ*. Validating two systems for estimating force and power. Int J Sports Med 2011; 32: 254–258
8 *Cronin J*, *Sleivert G*. Challenges in understanding the influence of maximal power training on improving athletic performance. Sports Med 2005; 35: 213–234
9 *Cronin JB*, *Hansen KT*. Strength and power predictors of sports speed. J Strength Cond Res 2005; 19: 349–357
10 *Cronin JB*, *Hing RD*, *Mc Nair PJ*. Reliability and validity of a linear position transducer for measuring jump performance. J Strength Cond Res 2004; 18: 590–593
11 *De Haan A*. The influence of stimulation frequency on force-velocity characteristics of in situ rat medial gastrocnemius muscle. Exp Physiol 1998; 83: 77–84
12 *Dorel S*, *Guilhem G*, *Couturier A*, *Hug F*. Adjustment of muscle coordination during an all-out sprint cycling task. Med Sci Sports Exerc 2012; 44: 2154–2164
13 *Dorel S*, *Hautier CA*, *Rambaud O*, *Rouffet D*, *Van Praagh E*, *Lacour JR*, *Bourdin M*. Torque and power-velocity relationships in cycling: relevance to track sprint performance in world-class cyclists. Int J Sports Med 2005; 26: 739–746
14 *Dugan EL*, *La Doyle T*, *Humphries B*, *Hasson CJ*, *Newton RU*. Determining the optimal load for jump squats: Areview of methods and calculations. J Strength Cond Res 2004; 18: 668–674
15 *Eloranta V*. Effect of postural and load variation on the coordination of the leg muscles in concentric jumping movement. Electromyogr Clin Neurophysiol 1996; 36: 59–64
16 *Glatthorn JF*, *Gouge S*, *Nussbaumer S*, *Stauffacher S*, *Impellizzeri FM*, *Maffiuletti NA*. Validity and reliability of optojump photoelectric cells for estimating vertical jump height. J Strength Cond Res 2011; 25: 556–560
17 *Harriss DJ*, *Atkinson G*. Ethical standards in sport and exercise science research: 2014 update. Int J Sports Med 2013; 34: 1025–1028
18 *Hibbs AE*, *Thompson KG*, *French D*, *Wrigley A*, *Spears I*. Optimizing performance by improving core stability and core strength. Sports Med 2008; 38: 995–1008
19 *Hill AV*. The heat of shortening and the dynamic constants of muscle. P Roy Soc Lond B Bio 1938; 126: 136–195
20 *Hopkins WG*. Measures of reliability in sports medicine and science. Sports Med 2000; 30: 1–15
21 *Hori N*, *Newton RU*, *Nosaka K*, *McGuigan MR*. Comparison of different methods of determining power output in weightlifting exercises. Strength Cond J 2006; 28: 34–40
22 *Jidovtseff B*, *Crielaard J*, *Cauchy S*, *Croisier J*. Validity and reliability of an inertial dynamometer using accelerometry. Sci Sport 2008; 23: 94–97
23 *Jidovtseff B*, *Harris NK*, *Crielaard JM*, *Cronin JB*. Using the load-velocity relationship for 1RM prediction. J Strength Cond Res 2011; 25: 267–270
24 *Knudson DV*. Correcting the use of the term “power” in the strength and conditioning literature. J Strength Cond Res 2009; 23: 1902–1908
25 *Kraemer WJ*, *Newton RU*. Training for muscular power. Phys Med Rehabil Clin N Am 2000; 11: 341–368
26 *Newton RU*, *Kraemer WJ*, *Hakkinen K*. Effects of ballistic training on preseason preparation of elite volleyball players. Med Sci Sports Exerc 1999; 31: 323–330
27 *Nuzzo JL*, *McBride JM*. The effect of loading and unloading on muscle activity during the jump squat. J Strength Cond Res 2013; 27: 1758–1764
28 *Rahmani A*, *Viale F*, *Dalleau G*, *Lacour JR*. Force/velocity and power/velocity relationships in squat exercise. Eur J Appl Physiol 2001; 84: 227–232
29 *Samozino P*, *Morin JB*, *Hintzy F*, *Belli A*. A simple method for measuring force, velocity and power output during squat jump. J Biomech 2008; 41: 2940–2945
30 *Sargeant AJ*, *Hoinville E*, *Young A*. Maximum leg force and power output during short-term dynamic exercise. J Appl Physiol 1981; 51: 1175–1182
31 *Sleivert G*, *Taingahue M*. The relationship between maximal jump-squat power and sprint acceleration in athletes. Eur J Appl Physiol 2004; 91: 46–52
32 *Suzovic D*, *Markovic G*, *Pasic M*, *Jaric S*. Optimum load in various vertical jumps support the maximum dynamic output hypothesis. Int J Sports Med 2013; 34: 1007–1014
33 *Taylor K-L*, *Cronin J*, *Gill N*, *Chapman D*, *Sheppard J*. Sources of variability in iso-inertial jump assessments. Int J Sport Physiol Perform 2010; 5: 546–558
34 *Trappe S*, *Williamson D*, *Godard M*, *Porter D*, *Rowden G*, *Costill D*. Effect of resistance training on single muscle fiber contractile function in older men. J Appl Physiol 2000; 89: 143–152
35 *Vandewalle H*, *Peres G*, *Heller J*, *Panel J*, *Monod H*. Force-velocity relationship and maximal power on a cycle ergometer. Eur J Appl Physiol 1987; 56: 650–656