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A Simple Method for Measurement of Mechanical Power in Jumping

Carmelo Bosco, Pekka Luhtanen, and Paavo V. Komi

Department of Biology of Physical Activity, University of Jyväskylä,
SF-40100 Jyväskylä 10, Finland

Summary. A simple test for the measurement of mechanical power during a vertical rebound jump series has been devised. The test consists of measuring the flight time with a digital timer (± 0.001 s) and counting the number of jumps performed during a certain period of time (e.g., 15–60 s). Formulae for calculation of mechanical power from the measured parameters were derived. The relationship between this mechanical power and a modification of the Wingate test ($r = 0.87$, n = 12 ♂) and 60 m dash ($r = 0.84$, n = 12 ♂) were very close. The mechanical power in a 60 s jumping test demonstrated higher values (20 W × kgBW^{-1}) than the power in a modified (60 s) Wingate test (7 W × kgBW^{-1}) and a Margaria test (14 W × kgBW^{-1}). The estimated powers demonstrated different values because both bicycle riding and the Margaria test reflect primarily chemo-mechanical conversion during muscle contraction, whereas in the jumping test elastic energy is also utilized. Therefore the new jumping test seems suitable to evaluate the power output of leg extensor muscles during natural motion. Because of its high reproducibility ($r = 0.95$) and simplicity, the test is suitable for laboratory and field conditions.

Key words: Jumping test – Mechanical power – Muscle mechanics – Elastic energy

Introduction

Maximal aerobic power, measured by maximal oxygen consumption, has been investigated by various methods (direct or indirect) and is often used as a synonym for "fitness". On the other hand, and in spite of the fact that anaerobic types of work are essential in many activities, less attention has been paid to anaerobic tests. The methods commonly considered to reflect anaerobic

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Offprint requests to: Carmelo Bosco, PhD (address see above)

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characteristic are: oxygen debt, oxygen deficit, concentration of lactic acid (LA) in the blood or in the muscle, the Margaria test (1966), vertical jump (e.g., Davies 1971) and Wingate test (e.g., Bar-Or 1980). Among those the Margaria and Wingate tests are the most used in laboratory routines, because of the simplicity of the methods and easy access to the test equipment. However, the mechanics of muscular behaviour, especially on a bicycle, are not necessarily the most natural ones. On the other hand, a vertical jump represents an activity of ballistic motion, and the maximal explosive power has been recorded from such a movement utilizing a force-platform technique (Davies and Rennie 1968; Davies 1971; Cavagna et al. 1971; Cavagna et al. 1972; Bosco and Komi 1979; Bosco et al. 1981a). However, the force-platform measurements require several instruments both for recording and processing of the data. Therefore there was a need to develop a test to determine the capacity to perform maximal activities of short duration which is simple, reliable, and specific. This paper presents this new method which consists of recording the work-power performed during continuous jumping performance.

Methods

The vertical jumping power and capacity of man can be evaluated according to the approximation of kinematic laws by measuring the flight time of consecutive vertical jumps during a certain time period. The flight time could be measured with a recently developed electronic apparatus (Bosco 1980) called "Ergojump" (Junghans GMBH-Schramberg, BRD). This apparatus consists of a digital timer (± 0.001 s) connected by a cable to a resistive (or capacitative) platform. The timer is triggered by the feet of the subject at the moment of release from the platform, and will be stopped at the moment of touch down. Thus the flight time (t_f) of the subject during the jump is recorded. This method of calculation assumes that the positions of the jumper on the platform were the same in take-off and in landing. The error of measurement, when compared with film analysis has been reported to be in the order of ± 2% (Komi and Bosco 1978). If several jumps are performed, the timer is summing the respective t_f of the single jump. To estimate the maximal mechanical power of the leg extensor muscle, the protocol requires that the subject jumps continuously with maximal effort on the platform for a certain period (e.g., 15–60 s). To standardize the knee angular displacement during the contact phase, the subject is required to bend the knee to about 90 degrees. The effects of fatigue on maintaining the same take-off and landing position for 60 s has been recently studied by Bosco et al. (1981c), who observed a slight variation ($< 6\%$) as measured from a Video Cassette System (Sanyo VTC 7100) and from electrogoniometer analysis. Furthermore, to avoid unmeasurable work output, horizontal and lateral displacements should be minimized, and the hands must be kept on the hips throughout the jump. To calculate the average mechanical power ($\overline{\dot{W}}$) during e.g. 60 s the following formula is used:

$$\overline{\dot{W}} = \frac{\overline{W}}{\overline{t_c}} \qquad (1)$$

where $\overline{W}$ = the total average work performed during 60 s; $\overline{t_c}$ = average total contact time of vertical jumping.

The total work (W) performed during a vertical jump can be calculated utilizing the following formula:

$$W = m \times g \times h \qquad (2)$$

where m = mass of the subject; g = acceleration of gravity (9.81 m/s^2); h = total displacement of C.G.

The total displacement of C.G. (h) of the subject consists of both the displacement of C.G. during the flight (h_f) and the contact period (h_c). The the total displacement of C.G. is

$$h = h_c + h_f . \tag{3}$$

The displacement of C.G. during flight (h_f) is calculated using recorded flight time (t_f) as follows:

$$h_f = \frac{g\,t_f^2}{8}. \tag{4}$$

The displacement of C.G. during contact can be estimated assuming that the vertical velocity from the lowest point of the C.G. to the release is linearly increasing (Asmussen and Bonde-Petersen 1974a). If the release velocity is v_v and contact time t_c, then the rise of C.G. (h_c) during contact is

$$h_c = \frac{v_v}{2} \cdot \frac{t_c}{2}. \tag{5}$$

Because the vertical release velocity and impact velocity are equal in a harmonic jump series, the vertical velocity (v_v) at the impact and release phase can be written

$$v_v = \frac{g\,t_f}{2} \tag{6}$$

where t_f = flight time between jumps.
Applying the formulas (6) and (5) we can rewrite

$$h_c = \frac{g t_f \cdot t_c}{8}. \tag{7}$$

The total displacement of C.G. (h) can then be obtained as follows:

$$h = \frac{g t_f t_c}{8} + \frac{g\,t_f^2}{8} = \frac{g t_f t_t}{8} \tag{8}$$

where t_f = flight time of one jump; t_c = contact time of one jump; t_t = total time of one jump = $t_f + t_c$, and g = gravitational constant (9.81 mxs^{-2}).
The total work performed (formula 2) during a vertical jump can now be written as follows:

$$W = \frac{m g^2 t_f t_t}{8}. \tag{9}$$

Assuming that the time of the positive work phase (t_{pos}) during contact can be half of the total contact time (Asmussen and Bonde-Petersen 1974a), then the average mechanical power of the positive work phase ($\bar{W}$) per body mass is

$$\bar{W} = \frac{W}{m \cdot t_{pos}} = \frac{g^2 t_f \cdot t_t}{4\,t_c}. \tag{10}$$

In the jump series the "Ergojump" is summing the total flight time (T_f) of all (n) jumps, and therefore the average flight time ($\bar{t}_f$) for one jump is

$$\bar{t}_f = \frac{T_f}{n}. \tag{11}$$

If in the jump series (including n jumps) the total performance time (T_f) is e.g. 60 s, then the average total time ($\bar{t}_t$) of one jump is

$$\bar{t}_t = \frac{T_t}{n} = \frac{60\ \mathrm{s}}{n}. \tag{12}$$

The contact time in a jump series of n jumps is the total performance time minus the total flight times. Then the average contact time ($\bar{t}_c$) in one jump is

$$\bar{t}_c = \frac{T_t - T_f}{n} = \frac{T_c}{n}. \tag{13}$$

Now substituting the individual flight times for the average flight times the average mechanical power ($\bar{W}$) in a jump series (formula 10) can be written using the times of the jump series as follows:

$$\bar{W} = \frac{g^2 T_f T_t}{4\,n T_c}. \tag{14}$$

If the total time (T_t) of the jump series is e.g. 60 s, the formula (14) can be written

$$\bar{W} = \frac{g^2 \cdot T_f \cdot 60}{4\,n(60 - T_f)}. \tag{15}$$

The unit of mechanical power per mass unit is then Watts per kg ($W \times kg^{-1}$).

Thus, to apply formula (15), we need only to know the sum of the flight time recorded by the timer for each jumping performance and the number of jumps executed during that work time period.

A modification of the Wingate test (e.g., Bar-Or 1978) was used to estimate average power output during a cycle ergometer ride. The Wingate test consists of all-out pedalling for 30 s, e.g. on a Monark ergometer with a resistance of 75 g × kg body weight. In the present experiments the work period was prolonged to 60 s to compare the Wingate test with the new jumping test. Furthermore, the mechanical power output for each 15-s period was calculated and the following two variables were determined: peak power, which was reached during the first 15 s of work, and the average power generated during the 60 s work. In both jumping and Wingate tests the power measurements (0–15 s) period were extracted from the 60 second test.

Mechanical power was also measured according to the method of Margaria et al. (1966). The subjects ran up the stairs at maximal speed. The running velocity was recorded with photocells and an electronic timer. The recorded speed was converted to vertical velocity ($m \times s^{-1}$) and muscular power ($\mathrm{Watt} \times \mathrm{kgBW}^{-1}$). In both the jumping test and the Wingate test, blood samples for lactate determination (enzymatic method, Biochemica Boehringer) were drawn from a fingertip 5 min after the test. The time to run 30 m and 60 m at maximal speed was also recorded with an electronic timer (± 0.001 s).

Subjects. Thirty-eight male subjects 16–30 years old participated in the study, and were divided into three groups. One group belonged to a regional basketball team (Bp) (n = 12), another to the Italian Volleyball student team (Vp) (n = 12) and fourteen were school boys (Sb) who although active did not practice a single sport specifically. Basketball players and school boys were accustomed to all tests employed, and both Bp and Sb reported twice to the laboratory. On the first visit they performed the Wingate and Margaria tests, and on the following day a jumping test and sprinting. One trial was carried out for bicycle and jumping tests, and for the Margaria test and sprinting the best of three trials was selected. Volleyball players were investigated in field conditions (indoor facilities) and were not familiar with the new jumping test. Table 1 gives the physical characteristics of the subjects.

Table 1. Physical characteristics of the subject groups. The values indicate the mean ± SD

Subjects	Age (years)	Weight (kg)	Height (cm)
Basketball players (n = 12)	23.7 3.7	78.4 8.8	188.7 5.2
Volleyball players (n = 12)	21.7 1.3	84.4 3.9	192.0 4.9
School boys (n = 14)	17.3 0.8	68.5 5.0	180.1 6.5

Table 2. Average power output calculated for every 15 s during 60-s jumping test performed by volleyball players (n = 12). Mean values ± SD are presented for two successive days

	Period				
	(0–15 s)	(15–30 s)	(30–45 s)	(45–60 s)	(0–60 s)
First day ($W \times kgBW^{-1}$)	26.7 3.0	23.4 2.3	21.2 3.2	16.7 2.4	21.5 2.0
Second day ($W \times kgBW^{-1}$)	26.5 4.0	22.7 3.8	21.2 3.8	17.5 2.0	21.7 3.1

Results

A basic requirement of any test is that repeated measurements yield consistent results. The test-retest reliability of the new jumping test was checked using volleyball players as subjects. They performed a 60-s jumping test on each of two successive days. Table 2 presents the average power outputs as estimated for every 15-s work period. The obtained values produced a correlation of 0.95 ($p \leq 0.001$).

Calculations of maximal explosive power performed by basketball players with the different tests are presented in Table 3. Blood lactate reached higher values in the Wingate test (15.4 ± 2.1 $mM \cdot l^{-1}$) than in the jumping test (8.1 ± 0.9 $mM \cdot l^{-1}$). An analysis of the interrelationship between the different variables measured for Bp demonstrated a strong correlation between the power output calculated for the first 15 s of jumping performance and the results of both the 60 m dash ($r = 0.84, p \leq 0.001$) and the 15 s bicycle ergometer test ($r = 0.87, p \leq 0.001$). Similarly, the 15-s bicycle test was closely related to the 60 m dash ($r = 0.73$, $p \leq 0.001$). In contrast, the Margaria test did not show any relationship with the other mechanical parameters studied. Intercorrelation analysis of the various parameters investigated for the Bp is shown in Table 4. Values comparable to those of basketball players were reached by the school boys, as shown in Table 5. Analysis of the interrelationship between the various variables examined in the school boys is shown in Table 6, and demonstrated trends similar to those noted for Bp.

Table 3. Mean values and standard deviations of the various parameters studied in basketball players (n = 12)

	$\bar{x}$	SD
Jumping test		
0–15 s $\bar{W}$ (Watt × kgBW^{-1})	24.7	2.6
0–60 s $\bar{W}$ (Watt × kgBW^{-1})	19.8	2.2
0–60 s Number of jumps	56.8	4.3
0–60 s Blood lactate (mM · l^{-1})	8.1	0.9
Bicycle ergometer test (Wingate)		
0–15 s $\bar{W}$ (Watt × kgBW^{-1})	8.8	1.0
0–60 s $\bar{W}$ (Watt × kgBW^{-1})	6.9	0.6
0–60 s Blood lactate (mM · l^{-1})	15.4	2.1
Margaria test stairs climbing (Watt × kgBW^{-1})	14.3	1.6
Sprinting 60 m dash (time in s)	7.83	0.41

Table 4. Correlation matrix for the various mechanical parameters calculated from the different tests performed by basketball players (n = 12). Mean values ± SD

1 Jumping (0–15 s)	1				
2 Jumping (0–60 s)	0.91	2			
3 Wingate (0–15 s)	0.87	0.54	3		
4 Wingate (0–60 s)	0.67	0.80	0.82	4	
5 Margaria	0.12	0.03	0.18	0.19	5
6 Sprinting (60 m dash)	0.84	0.58	0.73	0.50	0.20

Table 5. Average power calculated for 60-s work period performed with new jumping test and with modified Wingate bycycle ergometer test. Maximal anaerobic power calculated with Margaria test and time to run 30 m dash are also presented. Values are means ± SD for school boys (n = 14)

Jumping test		Bicycle ergometer test (Wingate) (60 s) (Watt × kgBW^{-1})	Margaria test stairs climbing (Watt × kgBW^{-1})	Sprinting 30 m dash (Time in s)
(60 s) (Watt × kgBW^{-1})	Number of the jumps			
22.2	63.2	7.10	15.9	4.5
1.8	5.8	0.4	0.8	0.1

Table 6. Correlation matrix for the various mechanical parameters calculated for different tests performed by school boys (n = 14). Mean ± SD

1 Jumping (60 s)	1		
2 Wingate (60 s)	0.53	2	
3 Margaria	0.23	0.47	3
4 Sprinting (30 m dash)	0.56	0.75	0.29

Discussion

The present results demonstrate a close relationship between the jumping test and the Wingate test. Thus the high correlation observed between both tests indicates that either of them could be used for determination of explosive power. However, in the present study, no relationship was noted between the Margaria test and the other tests performed. These findings are in contrast to previous studies in which a strong relationship has been found between the Margaria test and both the Wingate test (e.g., Ayalon et al. 1974; Bar-Or et al. 1978) and the average power output calculated from a single vertical jump performance (Bosco et al. 1981b). A reasonable explanation for this discrepancy has not yet been found. However, even if the basketball (Bp) and student (Sb) groups were treated statistically separately (see Tables 4 and 6), they showed a similar trend in the various interrelationships performed. However, the main purpose of the present investigation was to study the reliability and validity of the new jumping test. Therefore, first of all, it is interesting to observe how the power output calculated in jumping was much higher than that calculated for both the Wingate and Margaria tests. The power values of the two latter tests are in line with the results reported previously (e.g., Bar-Or 1978; Bar-Or et al. 1980; Jacobs 1980; Bosco et al. 1981b). Therefore, the difference noted between jumping and both the Wingate and Margaria tests can be attributed solely to the large values recorded for the jumping test.

An explanation for these results can be sought from the different mechanical behaviour of the leg muscles involved during a test performance. The power output recorded during the jumping test does not measure only the power of the chemomechanical conversion. In these forms of exercise a substantial recovery of mechanical energy stored in the elastic elements of the body takes place (Cavagna et al. 1971, 1972; Asmussen and Bonde-Petersen 1974a, b; Thys et al. 1972, 1975; Komi and Bosco 1978; Bosco et al. 1981b, c). It should be pointed out that gravitational potential energy affects jumping exercises more than when running uphill, and is negligible in cycling. This means that during a stretch-shortening cycle the muscles store potential energy (from gravitational pull) and re-use it as mechanical work. As a consequence, the measured work and power outputs are higher than the chemomechanical value in conditions where the muscles are contracting primarily concentrically. This can only be assessed in those exercise modes which do not permit, or permit only to a minor extent, the storage and recovery of elastic energy, such as in cycling (e.g., Wingate test) or running up-hill (slope > 25%) (e.g., in Margaria test the slope is > 40–50%). In agreement with the Wingate test (Bar-Or 1978) the concentration of blood lactate reached high values ($\approx$ 15 $\text{mM} \cdot \text{l}^{-1}$). This supports the notion that a maximal effort on a bicycle taxes the anaerobic pathway. Thus, the Wingate and Margaria tests might be used to estimate, respectively, the power of the lactate and phosphagen components. The jumping test may be able to evaluate also the elastic potential of muscle during a stretch-shortening exercise, which is the most common type of human locomotion. In this connection Bosco and Komi (1982) have shown that athletes engaged in various sport activities demonstrate different elastic potentials in their muscles. In addition it has been shown that muscle elasticity can be influenced also by training (Komi 1979; Bosco et al. 1979).

The present study, however, does not support the findings of Davies et al. (1982), who reported a higher peak power output during cycling performance than in a jumping test. Perhaps the reason for this discrepancy might be the fact that in the experiment of Davies et al. the jumping test was performed without a contribution of elastic energy. In addition, those authors compared the peak power in both cycling and jumping in contrast to the present work where only average power was compared.

It should be pointed out that the development of high instantaneous power (peak power) does not necessarily mean a parallel development of average power. In this respect the calculation of instantenous power in jumping exercises has been severely criticized by Adamson and Whitney (1971). Recently, Sargeant et al. (1981), utilizing a bicycle ergometer test set at constant velocity, found an average power output of 9.3 W × kgBW^{-1}, similar to the value recorded for 15 s in the present experiment (8.8 W × kgBW^{-1}) (Table 3). These authors found in the same bicycle experiments rather high values of peak power (39 W × kgBW^{-1}). This was, however, lower than the peak power calculated during jumping by Cavagna et al. (1971) (50 W × kgBW^{-1}).

It is interesting to note that the jumping frequencies during a 60-s period observed in both Bp and Sb were very close (56 Hz vs. 63 Hz, respectively) and in agreement with a previous study (Bosco et al. 1981c). Jumping frequencies between 55–65 Hz are generally obtained when it is necessary to bend the knee by about 90 degrees. This large angular displacement seems to enhance the storage and re-use of elastic energy compared to small angular displacements (Bosco et al. 1981c). However, in 60-s jumping with a small angular displacement ($\approx$ 45 degrees) the frequency increases about twice, and because of a favorable moment arm around the knee joint (Smidt 1973), and a better neuromuscular function, both mechanical efficiency and power output reach very high values (Asmussen and Bonde-Petersen 1974b; Bosco et al. 1981c).

The jumping test naturally also taxes the anaerobic energy conversion system. This can be noted from blood lactate measurements performed on basketball players, which showed values around 8 $\text{mM} \cdot \text{l}^{-1}$. This means that, during 60 s of jumping performance, a great part of the work was performed by anaerobic energy-yielding processes. That the jumping test can be used to evaluate muscular power of short duration is further supported by recent findings (Bosco et al. 1982), who showed that explosive power quality expressed as a percentage of fast twitch fibers in the vastus lateralis demonstrated a high correlation $r = 0.86$ ($n = 10$) with the power calculated from a 15-s jumping test.

There is an apparent disagreement between the high power value estimated in the jumping test for both Bp and Sb and those calculated e.g. in the Wingate test. It is also possible to argue that during the jumping test (60 s) the effective positive work output is not longer than approximately 15 s, because 15 s are spent in the eccentric phase and the rest (30 s) in the airborne phase. However, comparing the power output during a 15-s bicycle ergometer test with a 60-s jumping test, much lower values are observed from the pedalling exercise (Table 3).

In addition it should be kept in mind that the leg extensor muscles are working alternatively in the Wingate test. This means that when one leg is working, the other is resting. On the other hand, in the jumping exercise, both legs are working and resting simultaneously.

In conclusion, based on the above considerations and supported by the high reliability observed ($r = 0.95$), the reported jumping test might offer the possibility of evaluating the mechanical power of the leg extensor muscles during explosive stretch-shortening type exercises, which involve both metabolic and mechanical behaviour of skeletal muscles. In addition, because of its simplicity and low cost, the test is suitable for both laboratory and field conditions.

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