

TAKE-OFF EFFICIENCY: TRANSFORMATION OF MECHANICAL WORK INTO KINETIC ENERGY DURING THE BOSCO TEST

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ABSTRACT

Purpose. The aim of the study is to present a new method for determining the efficiency of take-off during a 60-s Bosco repeated vertical jump test.

Method. The study involved 15 physical education students (age: 21.5 ± 2.4 years; height: 1.81 ± 0.08 m; mass: 76 ± 9 kg). The data were collected with the use of a pedobarographical system (Pedar-x; Novel, Munich, Germany). The statistical analysis utilized a simple linear regression model.

Results. Owing to possible fatigue, flight time and flight height decreased. The average flight height was 0.260 ± 0.063 m, and the average contact time equalled 0.54 ± 0.16 s. The average anaerobic power values calculated for the 60-s work period had the mean value of 21.9 ± 6.7 W · kgBW⁻¹; there was a statistically significant (p < 0.05) decrease in anaerobic power during the 60-s Bosco test.

Conclusions. The efficiency of mechanical work was highest at the beginning of the test, reaching values of up to 50%. The efficiency of mechanical work conversion into mechanical energy seems to be an appropriate determinant of rising fatigue during the 60-s Bosco jumping test.

Key words: velocity, contact time, vertical force, counter-movement jump, flight time

Introduction

The Wingate and repeated counter-movement jump (CMJ) tests are frequently used to assess anaerobic ability [1, 2]. The Bosco repeated vertical jump test is often applied during an athlete's annual training cycle [3–5], when performance is dependent on anaerobic capability. The test is also recommended as a diagnostic search tool for talented individuals involved in anaerobic activities [4, 6, 7].

During the CMJ test, multiple jumps are performed in a set time period to determine the height of the jumps and anaerobic performance. The CMJ variables that are monitored are the flight time (t_f), the time of contact with the floor (t_c), and the number of jumps per 60 seconds (*NoJ*/min). On the basis of these data and kinematic laws, it is possible to derive additional parameters to indicate an individual's anaerobic capabilities, such as flight height (h_f) and the mechanical power per body weight (W_{BW}) [2]. Furthermore, when monitoring anaerobic performance, the efficiency of take-off is a parameter that has received little attention as a factor influencing anaerobic performance but it can be calculated from the data obtained in our measurements.

For example, the mechanical power in jumping can be evaluated with the approximation of kinematic laws by measuring the flight time of consecutive vertical jumps during a certain time period [2]. The decisive parameter is thus flight time (t_f), which can be established by a variety of platforms with a digital timer or with the use of film analysis [8]. The force impulse is equal to the change of the exerciser's momentum (Formula 1):

$$F \,\Delta t = m \,\Delta \nu \tag{1}$$

where *F* is the force, Δt is the time change, *m* is the exerciser's mass, and Δv is the change of speed.

When all the measured forces are added (F) and each of them is multiplied by the intervals between particular measurements (e.g. at the scanning frequency

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of 100 Hz; dt = 0.01), the result is the integral of the force by the time, which means the total force impulse. It must be equal to the change of the exerciser's momentum, i.e. the product of their mass and speed change (Formula 2):

$$\int F dt = m \Delta v \tag{2}$$

where *F* is the force, *dt* is the interval between particular measurements, *m* is the exerciser's mass, and Δv is the velocity change.

The displacement of the centre of gravity (CG) during the contact phase can be estimated, assuming that the vertical velocity from the lowest point of the CG to the release is linearly increasing [9]. The model of a linear velocity rise reflects evenly accelerated motion, and thus a constant force on the mat during the contact phase. A detailed calculation of CG displacement during the contact and during the flight phase and also the total CG displacement are indicated by Bosco et al. [2].

During vertical jumps, the potential energy and kinetic energy are transformed mutually. During the takeoff phase, muscular work is performed by the exerciser, which is converted into mechanical energy during the flight phase. The aim of the study was to measure common parameters for the Bosco test and to determine the efficiency (η) of the transformation of an exerciser's mechanical work during take-off into mechanical energy of the flight phase. Not all of the exerciser's expended muscular work is transformed into kinetic energy, therefore the effectiveness of the transformation will be significantly lower than 100%. The study presents a method to calculate a new parameter of anaerobic ability on the basis of the Bosco repeated vertical jump test, which, as we argue, is effective in measuring the transformation of mechanical work into mechanical energy. We assume that the use of the laws of physics for CMJ, the measured vertical force component allows to establish the efficiency of the conversion of mechanical work into mechanical energy at the moment of take-off. We also presuppose that at the beginning of the test (in its first 1/3), η will be constant, and thereafter (influenced by fatigue) it will gradually decrease.

Material and methods

Measuring procedure

Measurements were performed among 15 tertiary physical education men students (age: 21.5 ± 2.4 years; height: 1.81 ± 0.08 m; mass: 76 ± 9 kg). The participants were healthy sport students after 1 semester jump training (once a week), with no current lower body injuries. Before participating in the test, each participant read and signed an informed consent that was approved by the institutional Review Board. The study was performed in accordance with the Declaration of Helsinki.

The participants were measured for height (portable Antropometr A 213, Trystom Comp. Ltd) and mass (by means of medical electronic scales, Amboss[©]), and their age was recorded in years. The students were then familiarized with the testing protocol. It consisted of a 60-second version of the Bosco repeated vertical jump test. The participants warmed up for 10 minutes before data collection by undertaking a series of jumps with appropriate recovery (15 minutes). After the warm-up, the Pedographic system (Pedar-x; Novel, Munich, Germany) with measuring insoles was calibrated. For this test, the participants performed a squat to a depth that achieved a 90° bend in their knees (visual observation plus verbal information) in accordance with LaPorta et al. [10] Afterwards, they performed repeated maximal-effort countermovement vertical jumps with their hands on their hips for the total of 60 seconds. The jumpers paid attention to achieving a 90° knee bend. If they did not bend their knees properly in some jumps, the measurement was stopped and the test repeated after rest. One participant was excluded from the measurement because he did not bend his knees to 90° in some jumps.

Three and five minutes after the test, blood lactate was measurement taken (Sirius; h/p/cosmos sports & medical GmbH, Traunstein, Germany).

Calculated parameters

The flight time (t_i), contact time (t_c), number of performed jumps (NoJ), and vertical force (F) were recorded. The flight height (h_f) was estimated by the time in the air. Other monitored parameters included jump frequency (f), but for clarity it was not expressed in the common unit of hertz (Hz), but in NoJ/min (number of jumps per minute). For these units, the conversion pattern of 1 Hz = 60 NoJ/min is valid. To calculate the frequency in units of NoJ/min, as well as for the calculation of all other monitored parameters, the minute segment was divided into sixths and calculations were performed for each sixth separately. The average jump frequency (f) specifies the number of jumps that the participants completed if they jumped at the appropriate frequency for 60 seconds.

The maximal displacement of CG during the contact phase (distance during knee bend, h_c) and flight height (h_f) became the basis for the calculation of the average mechanical power of the positive work phase (P) per body mass [2].

The average power for a single jump was calculated in accordance with Bosco et al. [2] by Formula 3:

$$P = \frac{m t_f t_t g^2}{4 t_c} \tag{3}$$

where *m* is the exerciser's mass, t_f is the flight time, t_t is the total time of a jump, t_c is the contact time, and *g* stands for acceleration due to gravity.

Power (performance) relative to the body weight (P_{BW}) was calculated with the following Formula 4:

$$PB\mathbf{w} = \frac{P}{m} = \frac{t_f t_t g^2}{4 t_c} \tag{4}$$

It was expressed in the units of $W \cdot kgBW^{-1}$.

New method for determination of efficiency during take-off

The new method of calculating the exerciser's efficiency relies on the transformation of mechanical work into mechanical energy, which is based on two different vertical velocities – calculated vertical velocity (v_t) and vertical velocity (v_v) , measured with the use of the flight time [2]. The calculation of v_t is based on the assumption that the velocities of landing and take-off are equal in size and differ only in sign (Formula 5). Therefore, it is necessary to divide the resulting integral by two and by the exerciser's weight (m). The result is the calculated vertical velocity at take-off (v_t) , which the exerciser would achieve if all the invested work was converted into kinetic energy:

$$v_t = \frac{\int F \, dt}{2 \, m} \tag{5}$$

The second method of calculating the exerciser's vertical velocity is based on the assumption that their jump is vertical at take-off. Therefore, it is a movement in the Earth's gravitational field; v_v is then calculated from the t_f in Formula 6.

$$v_v = \frac{1}{2} g t_f \tag{6}$$

where v_v is the vertical velocity, *g* is the acceleration due to gravity, t_f is the flight time.

The efficiency of the exerciser's work conversion during take-off into mechanical energy of their flight, which is a form of kinetic energy at take-off, can be calculated on the basis of two differently counted vertical velocities, applying Formulas 5 and 6. The takeoff efficiency is established as the ratio of the squares of velocities, which, after expanding the relevant fraction by half the exerciser's weight, corresponds to the ratio of the measured kinetic energy to the calculated kinetic energy given by theoretical 100% conversion of the exerciser's mechanical work during the take-off phase (Formula 7):

$$\eta = \frac{v_v^2}{v_t^2} = \frac{\frac{1}{2}mv_v^2}{\frac{1}{2}mv_t^2} = \frac{E_v}{E_t}$$
(7)

where η is the efficiency, v_v is the vertical velocity calculated from the exerciser's flight time, v_t is the calculated vertical velocity at take-off, *m* is the exerciser's mass, E_v is the measured kinetic energy, E_t is the calculated kinetic energy.

The physical definition of efficiency serves for evaluating the conversion of mechanical work into mechanical energy at the moment of take-off.

Statistical analysis

Descriptive statistics were calculated for height, body mass, and age. The results of the study were analysed with statistical software (Statgraphics; Statpoint Technologies, Inc., Warrenton, USA). To verify the hypothesis that η does not change at the beginning of the test and that there is a statistically significant decrease in η starting from the second 1/3, regression analysis was performed and a simple linear regression model in accordance with the previous publication was applied for the first 1/3 of the jumps, and also for the whole series at the 60-second Bosco test. All data were presented as means and standard deviations (*SD*), and the level of significance was set at p < 0.05 [11].

Results

Basic characteristics during take-off

During the 60-second Bosco test, a change in the parameters occurred due to possible fatigue (Table 1).

Take-off efficiency during the 60-second Bosco test

The values of the parameters for calculating the efficiency of the conversion of mechanical work into mechanical energy are shown in Table 2. The key parameters were the calculated velocity (ν_t), which is based on momentum change during the contact phase (Formula 5), and measured velocity (ν_v), which is based on the measured time of flight. The difference between these two velocities gradually increases (Formula 6).

The efficiency conversion of mechanical work into mechanical energy (η , calculated with Formula 7) gradually decreased. The time of take-off for the 60-second Bosco test also simultaneously decreased (Table 2). In the first sixth of the jumps, the efficiency was not significantly changed; for the whole 60-second test, a statistically significant relationship existed between η and n_j (p < 0.05).

Discussion

The Bosco jumping test [2] is a commonly used method for diagnosing anaerobic intensive short-term activity. Anaerobic parameters are recorded during each 10-second period, up to 60 seconds [5]. However, other researchers have employed other variants, such as 30-second [12, 13] and 15-second protocols [10, 14].

		I–VI (60 s)	Ι	II	III	IV	V	VI			
	\overline{x}	0.54	0.52	0.53	0.55	0.55	0.57	0.59			
$t_{\rm c}$ (s)	SD	0.16	0.13	0.14	0.14	0.15	0.16	0.16			
	lin. R.	-0.0007*	-0.007	-0.021*	-0.0224*	-0.0235*	-0.0201*	-0.01729*			
$t_{\rm f}$ (s)	\overline{x}	0.46	0.52	0.50	0.48	0.46	0.43	0.41			
	SD	0.06	0.03	0.04	0.04	0.04	0.04	0.04			
	lin. R.	-0.0018*	-0.0013	-0.0002	0.0007	0.0015*	0.0022^{*}	0.0025*			
<i>t</i> _j (s)	\overline{x}	1.00	1.03	1.03	1.03	1.01	1.00	1.00			
	SD	0.14	0.13	0.13	0.13	0.14	0.14	0.15			
	lin. R.	-0.0025*	-0.0083*	-0.0212*	-0.0217*	-0.022*	-0.018*	-0.0146*			
f (NoJ/min)	\overline{x}	61	59	59	59	61	61	62			
	SD	9	8	8	8	9	9	9			
nj	\overline{x}	59.4	9.8	9.8	9.8	9.8	9.8	9.5			
	SD	8.1	1.3	1.3	1.3	1.3	1.3	1.6			
Blood lactate	\overline{x}	3 min:	15.01		5 min:	19.4					
$(\text{mmol} \cdot l^{-1})$	SD		3.26			4.31					

Table 1. Average values measured for every 1/6 (I–VI) of jumps during the 60-second jumping test performed by physical education students (n = 15)

 t_c – contact time, t_f – flight time, t_j – total jump time, f – relative jump frequency, n_j – number of jumps, lin. R. – estimate of slope from simple linear regression describing the relationship between the jump number and the measured variable p < 0.05

Table 2. Average values calculated for every 1/6 (I–VI) of jumps during the 60-second jumping test performed by physical education students (n = 15)

		I–VI (60 s)	Ι	II	III	IV	V	VI
$FTI (N \cdot s^{-1})$	\overline{x}	628	635	656	665	653	643	628
	SD	137	103	112	131	129	124	135
	lin. R.	-1.3165*	–1.3787	–13.8633*	–14.8752*	–15.1395*	–11.735*	-9.2517*
h_{f} (m)	\overline{x}	0.26	0.33	0.30	0.28	0.26	0.23	0.21
	SD	0.06	0.04	0.05	0.04	0.04	0.04	0.04
	lin. R.	-0.002*	-0.0017	-0.0004	0.0008	0.0017*	0.0022*	0.0025*
$h_{\rm c}$ (m)	\overline{x}	0.30	0.33	0.32	0.32	0.31	0.30	0.29
	SD	0.08	0.08	0.07	0.08	0.08	0.08	0.07
	lin .R.	-0.0016*	0.0054*	-0.0135*	-0.0131*	-0.0128*	-0.0098*	-0.0074*
$\nu_{t} (m \cdot s^{-1})$	\overline{x}	4.26	4.30	4.44	4.49	4.41	4.35	4.25
	SD	0.79	0.60	0.64	0.67	0.71	0.71	0.80
	lin. R.	-0.008*	-0.0017	-0.0814*	-0.0847*	-0.0882*	-0.0671*	-0.0518*
$ u_{\rm v} ({\rm m} \cdot {\rm s}^{-1}) $	\overline{x} SD lin. R.	2.25 0.28 -0.0086*	2.53 0.17 -0.0067	2.42 0.20 -0.001	2.35 0.18 0.0034	$2.25 \\ 0.18 \\ 0.0073^{*}$	2.13 0.21 0.0106*	2.01 0.20 0.0124*
$P_{\rm BW} (\rm W \cdot kgBW^{-1})$	\overline{x}	22	26	24	23	22	20	18
	SD	7	5	6	6	6	6	5
	lin. R.	-0.0819*	0.1749	0.7108*	0.8421*	0.878*	0.676*	0.5606*
η	\overline{x} SD lin. R.	0.36 0.14 -0.0007*	0.37 0.10 -0.0016	0.32 0.11 0.012*	0.30 0.11 0.0137*	0.29 0.11 0.0148*	0.26 0.10 0.0113*	0.25 0.10 0.006

FTI – force time integral, $h_{\rm f}$ – height of flight, $h_{\rm c}$ – distance during knee bend, $v_{\rm t}$ – theoretical vertical velocity at take off, $v_{\rm v}$ – vertical velocity counted from flight time, $P_{\rm BW}$ – power per mass, η – efficiency, lin. R. – estimate of slope from simple linear regression describing the relationship between the jump number and the measured variable

* p < 0.05

The results of tests with different duration are difficult to compare because it appears that the duration of the test affects the measured anaerobic parameters [4].

In the current study, the 60-second duration of the Bosco test was assessed; the average number of jumps for the group of physical education students was 59.4 ± 8.06. Jumping frequencies of 55–65 Hz are generally reported when the knee is bent to approximately 90° [2]. In contrast, smaller jump frequencies have been reported in the literature (53.6 Hz in LaPorta et al. [10]), which may be associated with a shorter variant of the Bosco test (i.e. 15-second). Jump frequencies can also be influenced by such factors as the training level or the participants' age. The frequency of jumps per minute is the reciprocal of the total time of one jump t_c multiplied by 60 (because 1 minute equals 60 seconds). Owing to fatigue (average blood lactate value 3 minutes after the test: 15.01 mmol \cdot l⁻¹), a reduction of $t_{\rm f}$ (and thus $h_{\rm f}$) occurred. The best results were found with the participants who had the lowest blood lactate values 3 and 5 minutes after the test (7.8 mmol \cdot $l^{\text{-1}}$ and 7.9 mmol \cdot $l^{\text{-1}}$). The average $h_{\rm f}$ was 0.260 ± 0.063 m, which is identical to the values indicated by LaPorta et al. [10] and slightly lower than the results observed in top sportsmen - by Szmatlan-Gabryś et al. [5] in 400-m runners, and by Nikolaidis and Ingebrigtsen [4] in a group of handball players.

The average anaerobic power values calculated for the 60-second work period reached $21.9 \pm 6.7 \text{ W} \cdot \text{kgBW}^{-1}$, which is similar to the results reported by Bosco et al. [2]. The average score of all participants was also similar to the values noted in previous studies using a 30-second Bosco test in university athletes [13] (21.3 W \cdot kgBW⁻¹). Higher mean power output can be observed in top sportsmen whose performance is dependent on anaerobic capabilities; for instance, the mean power output equalled ca. 25 W \cdot kgBW⁻¹ in volleyball players [2], and ca. 26 $W \cdot kgBW^{-1}$ in handball players [14]. Nevertheless, the aforementioned studies were conducted over a shorter period of time (15 or 30 seconds). In the current test group, the mean power output in the first series of jumps (first and second 1/6) was comparable with that in top sportsmen (25.8 ± 4.7 W \cdot kgBW⁻¹). In addition, LaPorta et al. [10] reported lower values for men (15-second Bosco test, $18.93 \text{ W} \cdot \text{kgBW}^{-1}$) and Szmatlan-Gabryś et al. [5] indicated that the mean power per mass during the 60-second Bosco test was 16.4 W · kgBW⁻¹. For the current cohort of participants, there was a significant decrease in anaerobic power in the 60-second Bosco test.

When monitoring anaerobic performance, the efficiency of take-off is an important aspect that requires further scrutiny. It is influenced by fatigue but there is scant research of its contribution to anaerobic performance. Monitoring the transformation of the kinetic energy from the perspective of anaerobic exercise has its merits, and therefore the current study presents a new parameter, i.e. efficiency. The exerciser's kinetic energy is directly proportional to the square of the vertical velocity. At the time when the exerciser's feet leave the mat, the potential energy in the gravitational field on the Earth surface is taken as zero, thus the exerciser's total mechanical energy is also directly proportional to the square of the vertical velocity.

The vertical velocity at the moment of take-off can be perceived from two different perspectives. The impulse is measured as the numerical integral of the take-off power at the time of the feet contact with the floor until the change of the exerciser's momentum. To determine the calculated velocity of take-off, we simply assumed that the exerciser's momentum vector magnitude is the same as before making contact with the floor. Such moments, however, have opposite directions; therefore, the total change of the momentum is equal to twice the size of the momentum. Of course, this simplified model does not reflect the exact reality in 100%, but it provides adequate results which describe the change in the exercise efficiency during the physical test. The value of speed is then calculated from the time of the jump flight phase, which is, from the physical point of view, a vertical take-off. The measured velocity is always significantly smaller than the calculated velocity.

The efficiency of the conversion of mechanical work into mechanical energy statistically significantly depended on the number of the performed jumps. At the beginning of the 60-second test, the average efficiency was 37%. However, some jumpers attained values of over 50%; these participants also had the lowest blood lactate values. In the jumper with the highest anaerobic performance, the efficiency of conversion of mechanical work into mechanical energy was greatest. In turn, the lowest efficiency of the conversion was observed in the last vertical jumps of all jumpers. For some, the efficiency was approximately 10% in the last jumps. With the use of a simple linear regression model, the hypothesis was verified that at the beginning of the test, η did not significantly change (until the first 1/3 of the jumps) and that from the second 1/3 of the jumps till the end of the performance it significantly decreased.

Similar to the efficiency of any machine, the efficiency of mechanical work is reduced by the internal friction in muscles between individual muscle groups and joints. The decrease in efficiency due to fatigue can be explained because the force exerted by the exerciser's feet contributes not only to the jump take-off, but also to maintaining a stable position before the take-off. Therefore, η only rarely reaches the value of 50%, being usually lower with increasing fatigue, so jumpers should pay more attention to achieve the right knee bend position (90° bend was observed by video) and to stabilize their posture; they should focus less on their take-off. Thus, the η of individual take-offs will gradually decrease in the course of the test.

The limitations of the study include the fact that the participants took off at the end of the 60-second Bosco test not very simultaneously from both legs. When using the Pedar insole system, it was necessary to count the force (pressure) from both feet separately; this demanded extra time during the data processing. The system measures plantar pressure distribution separately on the left and on the right foot.

When comparing the Pedar insole measuring system with other measuring possibilities, the Bosco test is commonly used [2, 4, 5], including force plates and a digital timer, which enhance its validity. Pedar does not offer any direct information about the height of flight or power. On the other hand, the system measures the time of foot contact with the ground and shows temporal information about the non-contact phase. From this variable, it is easy to count the height of the flight. In the future, data achieved from the system can be compared with those provided, for example, from the Kistler plate. The study presents a new method to calculate a new parameter of anaerobic ability – efficiency – and the presented formulas will be applied in future research.

Conclusions

The anaerobic findings of the current study are in agreement with previous Bosco studies. Additionally, the authors present a new method for determining the efficiency of an exerciser's take-off (η) during the Bosco test by analysing the vertical velocity at the moment of take-off.

The efficiency of muscle work was the highest at the beginning of the test, reaching values of up to 50%. At 60-second CMJ, η significantly decreased, which can be explained by rising fatigue. Owing to fatigue, work needs to be employed to maintain a stable posture, which leads to a decrease in η . In the first 1/3 of the 60-second test, the reduction of η was not statistically significant. However, the anaerobic power decrease was statistically significant for the whole test duration. The statistical analysis results confirmed a positive correlation between performance and efficiency but the correlation seems to be quite weak.

The study also indicated that the student with the best jumping efficiency had the lowest lactate values measured 3 and 5 minutes after the test. However, the aim of the study was to present a new theoretical method of calculating take-off efficiency. The correlation between blood lactate values and other variables were not calculated.

For practical purposes of anaerobic performance, in addition to converting to body weight it can be recommended to calculate the efficiency of converting mechanical work into mechanical energy. This approach seems to be an appropriate determinant of rising fatigue during anaerobic testing.

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