

Countermovement depth – a variable which clarifies the relationship between the maximum power output and height of a vertical jump

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Purpose: The aim of this study was to identify the determinants of peak power achieved during vertical jumps in order to clarify relationship between the height of jump and the ability to exert maximum power. *Methods:* One hundred young (16.8±1.8 years) sportsmen participated in the study (body height 1.861 ± 0.109 m, body weight 80.3 ± 9.2 kg). Each participant performed three jump tests: countermovement jump (CMJ), akimbo countermovement jump (ACMJ), and spike jump (SPJ). A force plate was used to measure ground reaction force and to determine peak power output. The following explanatory variables were included in the model: jump height, body mass, and the lowering of the centre of mass before launch (countermovement depth). A model was created using multiple regression analysis and allometric scaling. *Results:* The model was used to calculate the expected power value for each participant, which correlated strongly with real values. The value of the coefficient of determination R^2 equalled 0.89, 0.90 and 0.98, respectively, for the CMJ, ACMJ, and SPJ jumps. The countermovement depth proved to be a variable strongly affecting the maximum power of jump. If the countermovement depth remains constant, the relative peak power is a simple function of jump height. *Conclusions:* The results suggest that the jump height of an individual is an exact indicator of their ability to produce maximum power. The presented model has a potential to be utilized under field condition for estimating the maximum power output of vertical jumps.

Key words: exercise, biomechanics, regression, allometry

1. Introduction

Power output is one of the critical variables that describe individual abilities to perform physical effort. It was demonstrated that the jump height correlates with sprint time in soccer players and track runners [9], [25]. The relationship between jumping power output and height of a jump is a particularly interesting topic [7], [17]. The precise nature of the relationship between the

two remains a source of controversy. The height of a jump correlates significantly and positively with peak power, but it is possible to achieve a good jump height, accompanied by a poor power output [17].

Harman et al. [7] established equations for both peak and average power through multiple regression procedures. Equation (1) presents Harman's peak power formula:

$$P_{\max} = 61.9 \cdot h + 36 \cdot m + 1822, \quad (1)$$

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Received: January 12th, 2017

Accepted for publication: January 6th, 2018

where:

m – body mass [kg],

h – jump height [cm],

P_{\max} – maximum power output [W].

Similar models (differing in regression coefficients) were proposed also by other researchers [3], [10], [22].

Since biological systems are inherently nonlinear, it has been suggested [19] that expressing interdependencies between their characteristics was to be done by the means of nonlinear allometric models. The complexity of a vertical jump suggests that the relation between power and the explanatory variables is not necessarily linear.

The inconsistencies in calculation of power present in all models described point out the possible existence of additional variables affecting the development of power. A number of more recent publications have drawn attention to the importance of joint angular values during launch [18]. These observations suggest that lowering of the body mass centre in the eccentric phase have significant influence on power output. Mandic et al. [14] stated that an increase in the countermovement depth caused a decrease in maximum power and had not influenced remarkably the height of jump. This can be attributed to performance of the stretch-shortening cycle (SSC), since the countermovement depth changes position of body segments, movement ranges and muscle lengths. The SSC allows muscles to develop greater force, but its potential depends on muscle pre-stretch range as well as on velocity and acceleration of its shortening [4], [14].

The purpose of this study was to identify the determinants of peak power achieved during vertical jumps and to examine interdependencies between those variables in order to clarify relationship between the height of the jump and the ability to exert maximum power. In present study the set of independent variables was supplemented by the countermovement depth. Because of non-linearity of the relationship an allometric model was adopted.

2. Materials and methods

2.1. Participants

The test group for this study consisted of 100 young male athletes with at least several years of training experience. Among test participants, there were groups of volleyball players ($n = 31$), handball players ($n = 14$), swimmers ($n = 22$), as well as canoeists ($n = 33$). All participants were informed of the procedure and purpose of the study. They were also informed about a possibility of quitting from participation at any time, without providing a reason. Written informed consent was obtained from each participant (or their parents if the subject was under 18 years old). The study was performed in accordance with the Declaration of Helsinki. An experiment design was approved by the Committee for Evaluation of Scientific Units of the Institute of Sport in Warsaw. All measurements were taken early in the morning. Table 1 presents detailed information on the examined group.

2.2. Procedures

Each subject performed nine vertical jumps on the force plate: three akimbo countermovement jumps (ACMJ), three countermovement jumps (CMJ) and three spike jumps (SPJ). The characteristics of each jumping test are as follows:

- ACMJ – a vertical jump from a standing position with hands on the hips and with lowering of the body mass centre before the take-off;
- CMJ – a vertical jump from a standing position, preceded by arm swing and lowering of the body mass centre before the take-off;
- SPJ – a vertical jump which is performed with a 3–4 step run-up before the take-off (similarly to a volleyball attack).

Table 1. Mean values (\pm SD) of variables used for groups' description

	All groups ($n = 100$)	Swimming ($n = 22$)	Volleyball ($n = 31$)	Handball ($n = 14$)	Canoeing ($n = 33$)
Body height [m]	1.861 ± 0.109	1.801 ± 0.058^{bc}	1.952 ± 0.069^{acd}	1.874 ± 0.054^{abd}	1.800 ± 0.122^{bc}
Body mass [kg]	80.3 ± 9.2	70.7 ± 6.9^{bcd}	85.1 ± 9.0^{ad}	83.3 ± 7.3^a	80.6 ± 6.7^{ab}
Age [years]	16.8 ± 1.8	15.4 ± 1.5^{bcd}	16.9 ± 1.8^a	16.7 ± 2.8^a	17.6 ± 1.0^a
Training experience [years]	6.6 ± 2.4	6.2 ± 1.1	5.7 ± 2.4^{cd}	8.1 ± 1.8^b	7.2 ± 2.9^b

Significant differences ($p < 0.05$) in relation to: a – swimming; b – volleyball; c – handball; d – canoeing.

The participants were told to jump as high as possible in every trial. The individual CMJ and ACMJ jumps were performed at 5-second intervals. The individual SPJ jumps were performed at intervals of approximately 30 s. The interval between each type of jump lasted about one minute. For each tested participant, only the highest of each type of jump was submitted for analysis.

All measurements of power output, body weight, and jump height were performed on a force plate with a 400 Hz sampling rate. The force plate was connected via an analog-to-digital converter to a PC with the MVJ v.3.4 software (“JBA” Zb. Staniak, Poland). The vertical component of ground reaction force was used to calculate a number of variables characterizing each jump, including peak power output (P_{\max}), height of jump (h), and countermovement depth (L). The model applied for all calculations implies a closed system where the body mass of a person launching vertically from a force plate is reduced to a material point affected by vertical force components: gravity and the reaction force of the platform. The mathematical formula used to estimate the net force acting on the body mass centre during jumping is presented by equation (2):

$$F(t) = R(t) - Q, \quad (2)$$

where:

$F(t)$ – force applied to body mass centre in the time domain,

$R(t)$ – vertical component of ground reaction force in the time domain,

Q – gravity force (body weight).

Using the measured body mass and a force developed during jumping, acceleration of the body’s centre of mass can be estimated according to formula (3):

$$a(t) = \frac{R(t) - Q}{m} = \frac{F(t)}{m}, \quad (3)$$

where:

$a(t)$ – acceleration in the time domain,

m – body mass,

$R(t)$ – vertical component of ground reaction force in the time domain,

Q – gravity force.

Having an acceleration course, one can determine velocity ($v(t)$) and displacement ($y(t)$) of the body mass centre according to formulas (4) and (5), respectively. The height of a jump and countermovement depth are expressed respectively by the maximum and minimum of the function presented in equation (5) which is used for CMJ and ACMJ jumps ($v_0 = 0$).

$$v(t) = \int_0^t a(\tau) d\tau, \quad (4)$$

$$y(t) = y_0 + \int_0^t v(\tau) d\tau, \quad (5)$$

where:

$v(t)$ – velocity in the time domain,

$y(t)$ – displacement in the time domain,

y_0 – boundary condition for displacement.

When the ground reaction force is equal to body weight (just before launch) the spatial placement (y_0) is adopted as 0.

A slightly different method was used for spike jumps (SPJ). Because of unknown initial conditions, the vertical velocity at launch (v_L) – when the ground reaction force is equal to body weight – was calculated from the flight time (t_F):

$$v_L = \frac{g t_F}{2}. \quad (6)$$

Velocity as a function of time was computed using backward integration:

$$v(t) = v_L - \int_T^t a(\tau) d\tau, \quad (7)$$

where T means time of launch.

The placement when the ground reaction force is equal to body weight is adopted as 0. These are initial conditions for backward integration of velocity, so one can compute also a displacement of the body mass centre

Power as a function of time is calculated for each jump according to the following formula:

$$P(t) = F(t) \cdot v(t). \quad (8)$$

Using the backward stepwise regression model (least squares method), the following variables were included in the model: body mass, jump height, and countermovement depth.

In order to demonstrate the examined dependency in the form of an allometric model, the variables: peak power, body weight, jump height, and depth of countermovement were transformed into their natural logarithms. Their regression coefficients were then calculated using the least squares method. The regression model was created separately for each of the three types of jumps tested. The formula illustrating the model is as follows:

$$\ln(P_{\max}) = a \cdot \ln(h) + b \cdot \ln(L) + c \cdot \ln(m) + d, \quad (9)$$

where:

\ln – natural logarithm,

a, b, c – regression coefficients,

d – intercept,

P_{\max} = maximum power output,

h – jump height,

L – countermovement depth,

m – body mass.

Using properties of logarithms, the above formula can be expressed as the following function:

$$P_{\max} = D \cdot h^a \cdot L^b \cdot m^c, \quad (10)$$

where $D = \exp(d)$.

2.3. Statistical analysis

The statistical analysis of data was conducted using the Statistica v. 9.1 (StatSoft) software and Gretl v. 1.9 software. Differences of mean values were assessed using analysis of variance (ANOVA), with Bonferroni *post hoc* test. The normality of distribution of variables was assessed using the Shapiro–Wilk test (criterion $p > 0.05$). In creating the model, the regression coefficients of each variable were calculated using the multiple regression procedure (stepwise, backward elimination method). The goodness of fit of the model was evaluated using the coefficient of determination R^2 . The coefficient of variation (CV) was used to estimate the quality of prediction. Structural integrity of the model was assessed using the Chow test. The significance level was set at $\alpha = 0.05$.

3. Results

The descriptive data are presented in Table 2. The groups were non-homogeneous with respect to achieved peak power and jump height. Mean values of the ACMJ parameters differed significantly among the groups tested (Wilks' $\lambda = 0.466$, $p < 0.001$, $\eta^2 = 0.250$).

The tested groups differed significantly regarding CMJ parameters (Wilks' $\lambda = 0.453$, $p < 0.001$, $\eta^2 = 0.258$) as well as SPJ parameters (Wilks' $\lambda = 0.381$, $p < 0.001$, $\eta^2 = 0.305$).

A Chow test was used for investigating the structural homogeneity of a logarithm model containing countermovement depth. The whole dataset (100 cases for each jump test) was divided into two equivalent groups. For each half, a regression equation was estimated. The model expressed with equation 9 has a homogeneous structure for each jump test ($p < 0.05$). The value of the determination coefficient R^2 was 0.895, 0.911, and 0.979, respectively, for the ACMJ, CMJ, and SPJ jumps, for all test participants. Formulas representing the obtained models expressed with equation 10 are presented in Fig. 1. As shown in the figure the predicted peak power values correlate strongly with the actual registered values for ACMJ, CMJ as well as SPJ.

Figure 2 illustrates the theoretical relation between maximum power output and countermovement depth in ACMJ, CMJ and SPJ. It reflects the change of developed power in the countermovement domain, when

Table 2. Mean values (\pm SD) of jump height, maximum power output, relative maximum power output, and countermovement depth measured in ACMJ, CMJ and SPJ

Group	h [m]	P_{\max} [W]	P_{\max}/m [W·kg ⁻¹]	L [cm]
ACMJ – akimbo countermovement jump				
Swimming ($n = 22$)	0.358 ± 0.033^{bc}	1641 ± 240^{bcd}	23.4 ± 3.7	0.371 ± 0.052
Volleyball ($n = 31$)	0.422 ± 0.054^{ad}	2144 ± 400^{ad}	25.5 ± 5.1^d	0.459 ± 0.082^{acd}
Handball ($n = 14$)	0.396 ± 0.037^{ad}	2124 ± 267^{ad}	25.7 ± 4.2^d	0.389 ± 0.063
Canoeing ($n = 33$)	0.0364 ± 0.042^{bc}	1843 ± 350^{abc}	22.8 ± 3.6^{bc}	0.386 ± 0.068
CMJ – countermovement jump				
Swimming ($n = 22$)	0.428 ± 0.048^{bc}	2149 ± 418^{bc}	30.6 ± 6.3^{bc}	0.407 ± 0.061
Volleyball ($n = 31$)	0.493 ± 0.058^{ad}	3156 ± 563^{ad}	37.5 ± 6.9^{ad}	0.415 ± 0.052
Handball ($n = 14$)	0.473 ± 0.049^{ad}	2888 ± 503^{ad}	34.8 ± 6.2^{ad}	0.412 ± 0.072
Canoeing ($n = 33$)	0.432 ± 0.047^{bc}	2379 ± 393^{bc}	29.6 ± 4.5^{bc}	0.426 ± 0.058
SPJ – spike jump				
Swimming ($n = 22$)	0.503 ± 0.052^{bc}	2975 ± 569^{bc}	42.5 ± 9.9^{bc}	0.353 ± 0.053
Volleyball ($n = 31$)	0.616 ± 0.071^{ad}	4659 ± 700^{acd}	55.6 ± 8.9^{ad}	0.378 ± 0.040
Handball ($n = 14$)	0.585 ± 0.065^{ad}	4168 ± 798^{abd}	50.1 ± 9.8^{ad}	0.379 ± 0.060
Canoeing ($n = 33$)	0.504 ± 0.65^{bc}	3168 ± 936^{bc}	39.2 ± 10.7^{bc}	0.383 ± 0.091

Significant differences ($p < 0.05$) in relation to: a – swimming; b – volleyball; c – handball; d – canoeing.

the two other variables are constant. This is a graphical representation of the model expressed by Eq. (10).

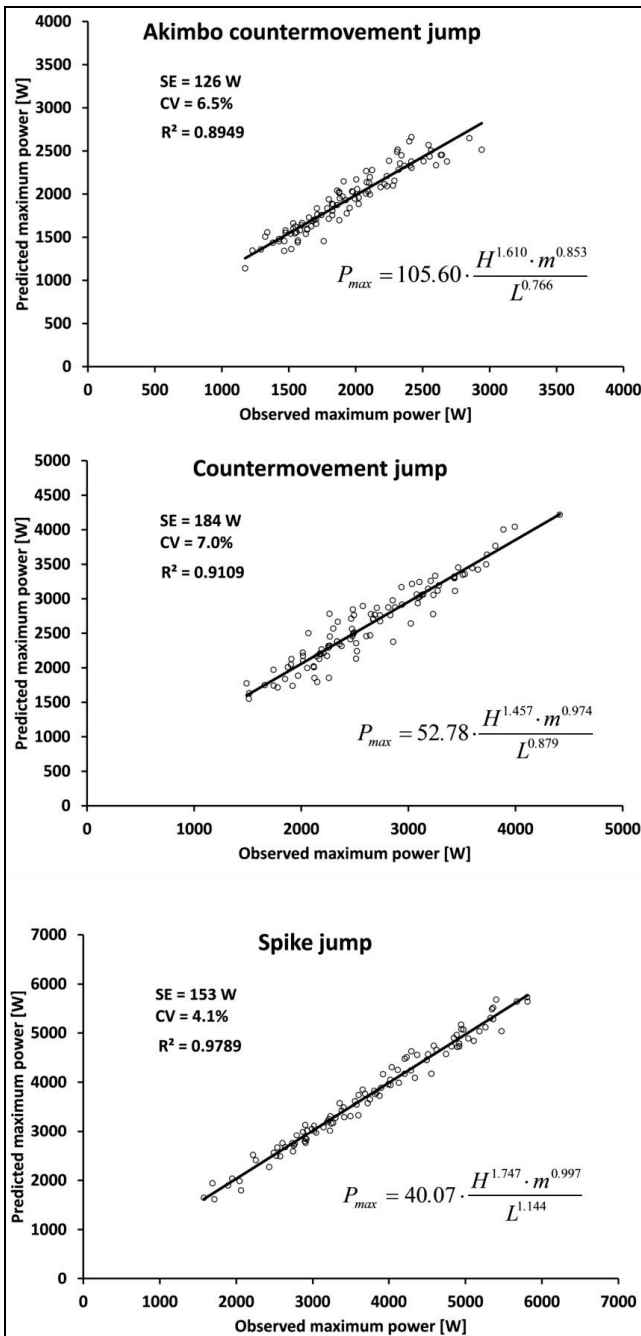


Fig. 1. Predicted vs. observed values of maximum power (P_{max}) in akimbo countermovement jumps (ACMJ), countermovement jumps (CMJ), and spike jumps (SPJ); where H – height of jump, m – body mass and L – countermovement depth

The residuals (differences between expected and observed values) did not significantly deviate from normal distribution. The coefficient of variation (CV) describing distribution of residuals amounted to 6.5%, 7.0% and 4.1%, respectively for the ACMJ, CMJ, and SPJ jumps.

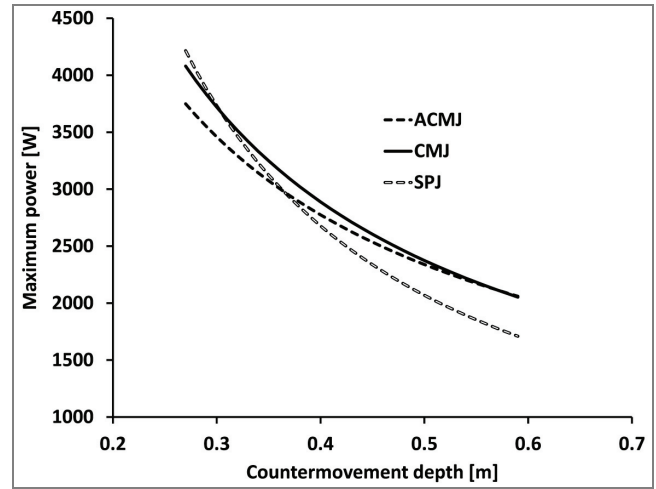


Fig. 2. Maximum power output as a function of the countermovement depth, with jump height set to 0.50 m and body mass set to 75 kg

It should be noted that the regression coefficient of body weight is very close to one (except ACMJ). Assuming that the coefficient would equal precisely 1 (Fig. 2), the following simplified model was build:

$$\ln\left(\frac{P_{max}}{m}\right) = a \cdot \ln(h) + b \cdot \ln(L) + d \quad (11)$$

Multiple regression procedure confirmed that the reduced model was still valid for ACMJ, CMJ as well as SPJ. The R^2 values were slightly less than in the three variables model and amounted to 0.863, 0.888, and 0.911, respectively for all jump types. Equation (11) could be reduced to the following formula describing relative power:

$$\frac{P_{max}}{m} = D \cdot h^a \cdot L^b \quad (12)$$

where:

- a, b – regression coefficients,
- $D = \exp(d)$,
- P_{max} – maximum power output,
- h – jump height,
- L – countermovement depth,
- m – body mass.

The following formulas were obtained for the jump tests considered:

CMJ:

$$\frac{P_{max}}{m} = \frac{46.89 \cdot h^{1.455}}{L^{0.883}}$$

standard error $2.29 \text{ W} \cdot \text{kg}^{-1}$, CV = 7.0%,

ACMJ:

$$\frac{P_{\max}}{m} = \frac{53.85 \cdot h^{1.605}}{L^{0.794}},$$

standard error $1.62 \text{ W} \cdot \text{kg}^{-1}$, $\text{CV} = 6.7\%$,
SPJ:

$$\frac{P_{\max}}{m} = \frac{41.58 \cdot h^{1.747}}{L^{1.144}},$$

standard error $1.89 \text{ W} \cdot \text{kg}^{-1}$, $\text{CV} = 4.1\%$.

This form of the model enables calculating of the relative maximum power output of an individual. Accuracy of the relative power estimation is on the same level as accuracy provided for maximum power by the three variables model (similar CV values).

4. Discussion

The nonlinear model presented in this paper describes peak mechanical power developed in the vertical jump as the power function of jump height, body weight, and the depth of countermovement before the take-off. Until now, most attempts to express this relationship quantitatively have focused on creating linear models [3], [7], [9], [22] and did not include countermovement depth as an explanatory variable. It is our firm belief that the omission of this variable limits the explanatory power of these models.

The method presented in this paper succeeded in matching the predicted peak power values with the observed peak power values (R^2 about 0.9). The regression model of Harman et al. [7] yielded much lower explanatory properties ($R^2 = 0.77$ and $R^2 = 0.53$, for peak power and average power, respectively). Johnson and Bahamonde [10] created a linear model which, as they claimed, explained 91% of the peak power variance. It should be noted that those investigators had access to a much larger test group ($n = 118$) than Harman ($n = 17$). Johnson and Bahamonde [10] included the body height into their model. They concluded that taller people develop less power during jumping, because of a greater range of motion, and in consequence, slower movement. This conclusion was not been confirmed in our research, since the body height was eliminated from the model at the initial stage of the work. Canavan and Vescovi [3] created a linear regression model for ACMJ, containing only two explanatory variables: body weight and jump height (similar to Harman et al. [7] and Sayers et al. [22]). Considerably high values of the

determination coefficient in the Canavan and Vescovi model might have been the result of a small and homogeneous test sample. Their test group consisted of only 20 women, all of whom had been practicing basketball for at least three years. Similar depth of countermovement before launch could be a possible reason of a high R^2 . Regardless of the fact that volleyball players and handball players have a good jumping technique and tend to jump higher than swimmers and canoeists, the presented model proves suitable for evaluating power output in each of the groups.

Lara-Sánchez et al. [12], who estimated maximum power in teenagers, stated that the model proposed by Canavan and Vescovi was the most accurate among available predictive formulas.

Ache-Dias et al. [1] presented another linear model taking into consideration the body mass and the jump height. The model explained 82% of maximum power variation. The authors tested a relatively large sample of 309 males practicing various sport disciplines and stated that the accuracy of the model left much to be desired. On the other hand, their model differed from previous ones only in the coefficients values.

Duncan et al. [6] proposed a nonlinear allometric model. Body mass, jump height, and calendar age were used as variables explaining maximum power variability. The authors tested a group of 12–16 year old children. In their next study Duncan et al. [5] presented the results of young basketball players. Trying to simplify the model, the authors proposed an alternative model in which maximum power could be processed as a product of body mass and jump height. They found that their models provided a better fit than the model published by Sayers et al. [22]. However, the countermovement depth was still not taken into consideration.

Moran and Wallace [18] pointed out that the explosive power of lower limbs was affected by the work done by the lower limbs during the concentric phase as well as the knee joint angle during launch. This latter variable seems to bring the same information as the depth of countermovement – a variable used in the present study. Both variables inform indirectly about using the neuromuscular phenomenon known as the stretch shortening cycle (SSC). Lowering of the body mass centre can be done in different ways by changing knee angle and hip angle. This may affect actual shortening of velocities of the muscles involved and then influence SSC utilization. The details of jump kinematics can be obtained by motion capture techniques. The force plate data enable to observe only a movement of the body mass centre.

It would be advisable to analyse a role of the countermovement velocity, too, however, this variable seems to be highly correlated with the countermovement depth: the greater the countermovement depth, the less its velocity. During ballistic movements, elastic energy is stored in muscles and tendons [13]. Their net force-length characteristic would be primarily affected by the stiffness of the most flexible component. Tendon stiffness is considerably high and practically constant, which indicates that stiffness of muscles plays a pivotal role both in the eccentric and concentric phases of jumps [11]. The stiffness of muscles strongly depends on their contractile force [23], [24]. To put it plainly, the net stiffness of muscles and their ability to store energy are directly dependent on muscle tension overload during countermovement (eccentric phase). This phenomenon is exploited in plyometric training, which significantly improves jumping ability [16]. In contrast to plyometric exercises, concentric training, such as pedaling on an ergometer, is not effective [2]. The tension overload of a muscle can only last for a short duration due to the characteristics of muscle spindles. Their action depends not only on the elongation, but also on its velocity. Pickar and Kang [20] stated that spindles' velocity sensitivity predominates over their length sensitivity. Neuromuscular and mechanical characteristics of a jump can explain the situation where an individual achieves a good jump height together with relatively low maximum power output. Increasing the countermovement depth decreases the amount of power output. This is a direct result of the decreased potentiation that comes from a SSC. But decreased power output is compensated by a longer time of force development in the concentric phase of a jump. This compensation is probably good enough to keep the jump height at a relatively constant level. For this explanation to make sense, the information about countermovement depth is necessary. Mandić et al. [15] demonstrated that even skilled subjects spontaneously select smaller countermovement depths below their optimum value for maximizing height in order to utilize more elastic energy. This means subjects tend to develop greater power.

It is worth mentioning that there are studies [18], [21] dealing with countermovement magnitude. Joint angles of the lower extremity were indicated as a factor modulating maximum power. The results of Marković et al. [17] directly support our findings. The authors noted that the correlation between maximum power and height of a jump distinctly increased (from 0.55 to 0.88) when body mass and countermovement depth were controlled.

Based on results of the present study one can assume that the maximum power is directly proportional to body mass (exponent of body mass equals 1). The formula for calculating relative power $\frac{P_{\max}}{m} = D \cdot h^a \cdot L^b$ can be

used as a practical tool for comparison of the results achieved by subjects of different body weight. This form of the created model seems to be the most relevant due to its simplicity and the ability to present the most important information. However, it should be noted that if the depth of countermovement remains constant, the relative peak power becomes a simple function of the jump height. From this point of view, the maximum height is the variable describing ability to exert power and seems more important for diagnostic purposes than maximum power itself (depending of jumping technique). However, in sports where instant, rapid jumps are essential, the maximum power value should be also taken into consideration.

To this date, the analytical approach adopted in most studies has made it possible to pinpoint the most important factors determining power in vertical jumps. The model presented in this paper is a generalization of the previously established mathematical formulas. Apart from its good predictive capabilities, the model can be used to quantitatively describe the contribution of each dependent variable in maximum power.

5. Conclusion

The countermovement depth proved to be a variable explaining relationship between the maximum power and height of jump.

The variation of the vertical jump peak power can be almost fully explained by jump height, body weight, and the depth of countermovement before launch. If the countermovement depth remains constant, the relative peak power (P_{\max}/m) is a function of jump height. It means that the height of vertical jump can be used as a measure of athlete's ability to exert power. One can easily imagine the system estimating the countermovement depth based on time of concentric phase of the take-off and velocity at take-off (based on flight time). It means that the presented model has a potential to be utilized under field condition for estimating maximum power output of vertical jumps.

Additionally, a new method for processing the spike (or drop) jump parameters was proposed. It can be implemented by those who utilize ground reaction forces for calculations.

Acknowledgements

The study was financed by the Fund for the Development of Physical Culture from the Ministry of Sport and Tourism, Republic of Poland no. 2014/0066/0223/SubB/DSW/DZK/JD.

The authors have no conflicts of interests to declare.

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