Is vertical jump height a body size-independent measure of muscle power?

Article *in* Journal of Sports Sciences · November 2007

Impact Factor: 2.25 · DOI: 10.1080/02640410601021713 · Source: PubMed

2 authors:

Goran Markovic
University of Zagreb
75 PUBLICATIONS **1,849** CITATIONS

Slobodan Jaric
University of Delaware
155 PUBLICATIONS **2,945** CITATIONS

Journal of Sports Sciences, October 2007; 25(12): 1355–1363

Is vertical jump height a body size-independent measure of muscle power?

GORAN MARKOVIC[1] & SLOBODAN JARIC[2]

[1]*School of Kinesiology, University of Zagreb, Zagreb, Croatia and* [2]*Health, Nutrition, and Exercise Sciences, University of Delaware, Newark, DE, USA*

Abstract
We tested the hypothesis that the performance of rapid movements represents body size-independent indices of muscle power. Physical education students ($n = 159$) were tested on various vertical jump (jump height and average power calculated from the ground reaction force) and muscle strength tests. When non-normalized data were used, a principal components analysis revealed a complex and inconsistent structure where jump height and muscle power loaded different components, while muscle strength and power partially overlapped. When the indices of muscle strength and power were properly normalized for body size, a simple and consistent structure of principal components supported the hypothesis. Specifically, the recorded height and muscle power calculated from the same jumps loaded the same components, separately for the jumps predominantly based on concentric actions and jumps based on a rapid stretch–shortening cycle of the leg extensors. The finding that the performance of rapid movements assesses the same physical ability as properly normalized tests of muscle power could be important for designing and interpreting the results of batteries of physical performance tests, as well as for understanding some basic principles of human movement performance.

Keywords: *Body size, power, rapid movements, allometric scaling*

Introduction

From the mechanical perspective, power represents a rate of performing mechanical work, or a product of force acting upon an object and the object's velocity. In human movement-related sciences, muscle power is generally considered to be an important factor responsible for successful rapid movements performed with maximum effort, including jumping, sprinting, throwing, and kicking (Newton & Kraemer, 1994). At the level of a single isolated muscle, maximum power is generally believed to depend on several "biological" (e.g. muscle size, percent of fast-twitch motor units, muscle architecture) and "mechanical" factors (muscle length and speed of shortening) (Fitts, McDonald, & Schluter, 1991; McMahon, 1984). Regarding the latter, due to the effect of speed of contraction, muscle strength (i.e. the ability to exert force under given conditions) and muscle power are only moderately related. That is, the highest force can be exerted against heavy external resistance (and, therefore, during slow and long-lasting movements), while maximum muscle power is recorded against moderate loads, which is often represented solely by weight and inertia of one's own body (Driss, Vandewalle, Quievre, Miller, & Monod, 2001; Dugan, Doyle, Humphries, Hasson, & Newton, 2004).

Several specific methods have been used for estimating the power-generating capacity of human skeletal muscle (for a review, see Van Praagh & Dore, 2002). However, it would appear that two general approaches have dominated, the first of which has often been applied by exercise scientists and we will refer to as the *direct* assessment of muscle power. It is based on the assessment of maximum muscle power either from measured or from assessed muscle force or work exerted during complex movements, such as cycling (e.g. Wingate test), running (e.g. Margaria step test), and jumping (e.g. Sargent jump), or during isolated joint rotations performed against an isokinetic apparatus. Note that although these tests are used to represent power (i.e. measured in watts), they represent only an *assessment* of muscle power obtained from measured external forces and work, since muscle power cannot be

---

Correspondence: S. Jaric, Department of Health, Nutrition, and Exercise Sciences, University of Delaware, 547 S. College Avenue, Newark, DE 19711, USA. E-mail: jaric@udel.edu

ISSN 0264-0414 print/ISSN 1466-447X online © 2007 Taylor & Francis
DOI: 10.1080/02640410601021713

measured directly in complex human movements. The second approach has often been applied in routine tests of physical performance in various human movement-related areas, which we refer to as *performance-based* assessment of muscle power. Specifically, muscle power is assessed from the recorded performance of various rapid movements (e.g. the length or height of various jumps, maximum running or throwing velocity, time to complete the tested rapid movement). For example, maximum vertical jump has routinely been used in the assessment of movement performance and many authors have interpreted the recorded jump height as an index of muscle power (Harman, Rosenstein, Frykman, Rosenstein, & Kraemer, 1991; Markovic, Dizdar, Jukic, & Cardinale, 2004; Sipilä *et al.*, 2004). Moreover, several different types of vertical jumps have been evaluated and applied, including countermovement jump, squat jump, drop jump, and hopping in place (Harman, Rosenstein, Frykman, & Rosenstein, 1990; Komi & Bosco, 1978; Markovic & Jaric, 2005; Markovic *et al.*, 2004). The main rationale behind this practice is the different roles of various factors that can contribute to the measured outcome (i.e. muscle power assessed through jump height). Specifically, while some of the above-mentioned vertical jumps include concentric-only muscle action (e.g. squat jump), others include a stretch–shortening cycle of muscle actions, which can be either relatively slow (e.g. countermovement jump) or fast (drop jump and hopping in place) (Young, 1995).

Although the direct assessment of muscle power is generally accepted as a logically valid approach, interpreting the recorded performance as an index of muscle power appears at odds with other approaches. Specifically, the same performance tests that have been used to assess muscle power are also frequently considered to be "tests of rapid movements". Relatively moderate relationships of these tests with the outcomes of the direct assessment of muscle power seem to speak in favour of this approach (Aragon-Vargas & Gross, 1997; Kukolj, Ropret, Ugarkovic, & Jaric, 1999; Nesser, Latin, Berg, & Prentice, 1996). Aragon-Vargas and Gross (1997) showed that peak power and mean power share only 46% and 43% of common variance respectively with vertical jump height, while Winter (2005) suggested that jumping performance is based on a muscle's ability to develop impulse, rather that muscle power. Therefore, it remains unclear whether the physical performance tests based on rapid movement can be used for the performance-based assessment of muscle power, or they assess the partly independent ability of the locomotor apparatus to perform rapid movements *per se*.

A potential solution to the above problem could be based on the fact that the outcomes of tests of direct assessment and tests of the performance-based assessment of muscle power are differently related to body size. Specifically, it is generally accepted that the outcome of tests based on direct assessment of muscle power (e.g. the power calculated from either ground reaction force or from a Wingate test) is positively related to body size, while the performance of rapid movements (discrete point-to-point movements, maximum jump height, maximum running speed) appear to be body size independent. Although these relationships have been demonstrated both theoretically (Åstrand & Rodahl, 1986; Hill, 1950; Jaric, 2003) and experimentally (Markovic & Jaric, 2004, 2005; Martin *et al.*, 2004; Nevill, Ramsbottom, & Williams, 1992), we have shown that inconsistent and/or incorrect normalization of physical performance has frequently been applied in contemporary literature (Jaric, 2002; Jaric, Mirkov, & Markovic, 2005). Therefore, it is possible that the neglected body size effect could explain the moderate relationship between the outcomes of these two groups of muscle power tests. For example, we recently demonstrated (Markovic & Jaric, 2005) that the power calculated from the ground reaction force recorded during different types of maximum vertical jumps (representing the direct assessment of muscle power) was strongly related to body size, while the height of the same jumps (representing performance-based assessment of muscle power) was mainly body size independent.

To test the hypothesis that the recorded jump height represents a body size-independent index of muscle power, we assessed several individuals on various types of vertical jumps and recorded both the jump height and the muscle power calculated from the measured ground reaction force. In addition, we tested muscle strength and body size and, finally, we applied principal component analysis to the entire data set. We predicted that the results would reveal that jump height and muscle power are partly independent abilities of the locomotor system (i.e. they belong to different principal components). We also predicted that they would be partly related to muscle strength and body size. Thereafter, we normalized muscle power for body size and repeated the data analysis. In this case, we predicted that jump height and normalized muscle power would belong to the same principal component. If in line with our predictions, the results would support our hypothesis, providing evidence that the tests of rapid movements (or, alternatively, performance-based muscle power tests) are also body size-independent tests of muscle power and, therefore, they can be used for the assessment of the same physical ability as properly normalized tests based on the direct assessment of muscle power. This finding could be of considerable importance not only for our understanding of some essential aspects of human movement, but also for designing and interpreting routine batteries of physical performance tests.

Methods

Participants

The present study applied a cross-sectional approach. One hundred and fifty-nine male physical education students aged 18 – 25 years participated after the risks of the study were explained to them. All participants regularly took part in courses of physical activity through their standard academic programme, and 14 of them were also athletes in either individual (mainly karate and swimming) or team sports (handball, volleyball, and soccer). The study was approved by the Ethics Committee of the Faculty of Kinesiology, University of Zagreb, and all participants signed an informed consent document according to the Helsinki Declaration. None of the participants reported any medical problems or recent injuries that would compromise their performance.

Test procedure

The test procedure consisted of three separate sessions. The first included an anthropometric assessment, as well as tests of squat jump and countermovement jump performance. Drop jump from a height of 30 cm, maximal hopping in place, and weighted squat jump were tested in the second session. Finally, the third session included measurement of isometric squat and back squat.

A standard warm-up and stretching procedure were performed before each test session. Although the participants were familiar with virtually all the tests through their regular activity courses, each test was demonstrated by a qualified individual. Thereafter, the participants performed two (for vertical jump tests), one (for isometric squat and squat jump with additional load), or no practice trials (for back squat). The tests that required repetition were performed with 2-min rest periods, while the pause between two consecutive tests was approximately 5 min. All tests except the back squat were performed on a force platform (Kistler type 9290AD; sampling frequency 500 Hz) mounted according to the manufacturer's specifications.

Vertical jump tests

Squat jump. The squat jump was performed from a semi-squat position, with the arms held akimbo to avoid arm swing (Komi & Bosco, 1978). The trials were repeated if a preparatory dip was observed from the force recording.

Countermovement jump. The countermovement jump was performed in a similar fashion to the squat jump except that the participant was instructed to perform an unconstrained vertical jump from a standing upright position that included the initial countermovement (Komi & Bosco, 1978).

Hopping in place. This test consisted of 10 consecutive maximal vertical rebounds on the force platform with the shortest ground contact times and with hands held akimbo (Dalleau, Belli, Viale, Lacour, & Bourdin, 2004).

Drop jump. The drop jump from a 30-cm high box was performed on a force platform. The test was conducted with the arms held akimbo to eliminate any mechanical effect of swing. Upon landing from a drop, the participant performed a jump for maximum height and minimum ground contact time.

For the first three vertical jump tests (i.e. squat jump, countermovement jump, and hopping in place), the force platform measurements were used to calculate the mean muscle power as a product of the vertical component of the ground reaction force and the velocity of the centre of mass (Dalleau *et al.*, 2004). The velocity was obtained from the integral of the acceleration provided by the vertical force signal, while the final result was the muscle power averaged over the propulsive jump phase (i.e. the time interval from the instant of the velocity turning upward to the end of the contact with the platform). Jump height was assessed as the maximum displacement of the centre of mass calculated from the vertical component of the recorded force and body weight. For the drop jump, the same method could not be used because maximum height before landing was unknown. Therefore, only jump height (h) was assessed using the standard ballistic formula based on the flight time (t_f) recorded from the force – time signal:

$$h = g \cdot t_f^2/8 \tag{1}$$

Maximal strength tests

Isometric squat. The isometric squat was performed based on a previously described method (Markovic & Jaric, 2004). In short, a squat rack was secured to the floor over a force platform. The bar was secured with metal stops within the squat rack, and was positioned to yield a knee angle of 120°. The participant was positioned in the squat rack with heels directly under the bar and instructed to exert force gradually until no further increase was detected. The force platform was reset to zero while the participant was standing on a plate to negate the weight of the participant. The test was repeated two times, and the better of the two trials was used for further analysis.

One-repetition maximum back squat. This test was performed on a standard Smith machine (Gym 80 International, Germany). In brief, each participant lowered the bar to the point where the knee angle was 80°, which was marked by adjustable mechanical stops (McBride, Triplett-McBride, Davie, & Newton, 2002). Before assessing a participant's one-repetition maximum (1-RM) squat, several warm-up trials were performed as follows: 30% (8 repetitions), 50% (5 – 6 repetitions), 75% (3 repetitions), and 90% (1 repetition) of an estimated 1-RM. Since each participant had at least one year's experience of training with free weights, the approximate value of 1-RM was known in advance. After 90% of 1-RM, loads were increased using small plates (5, 2.5, and 1.25 kg) until the 1-RM was reached. The assessment of 1-RM maximal squat generally required no more than 4 – 5 lifts.

Weighted squat jump force. Squat jump with the additional load was tested according to a slightly modified procedure applied by Newton, Kraemer, and Häkkinen (1999). In short, each participant performed a squat jump with additional weight applied by a standard Smith machine (Gym 80 International, Germany). The participant was positioned in 90° knee flexion (assessed by a goniometer) with the heels placed on a force plate directly under the bar. After holding this position for 2 s, the participant jumped vertically upwards from this position attempting to attain the maximum height. Trials were repeated if a preparatory dip was observed on the force – time graph. Peak force recorded during the propulsive (i.e. concentric) jump phase was used as a measure of dynamic strength. The test was repeated three times, and the best trial was used for further analysis. The rationale for using this test as a measure of leg extensor strength is based on the results of previous studies showing that the force and/or power exerted during the performance of various dynamic exercises, including squat jumps with loads representing 30% or more of 1-RM, is highly correlated with maximal dynamic and/or isometric strength of a particular muscle group tested (Moss, Refsnes, Abilgaard, Nicolaysen, & Jensen, 1997; Stone *et al.*, 2003a, 2003b). The participants wore a weightlifting belt when performing all three muscle strength tests.

Anthropometric data

Anthropometric assessment was based on the procedures recommended by the International Biological Program. Body mass and stature of all participants were measured to the nearest 0.1 kg and 0.5 cm, respectively. Thigh girth was measured using an anthropometric tape to 0.1 cm. Body composition was assessed through the estimation of body density using skinfold measurements taken at abdomin, chest, and thigh by an experienced technician (Jackson & Pollock, 1978). Skinfolds were measured in triplicate for all sites and the median of the three values was taken for further analysis. Percent body fat was assessed using a previously recommended method (Siri, 1956).

Normalization of strength and power tests for body size

To normalize strength and power data (S) for body size (M) appropriately, we applied an allometric scaling model ($S = a \cdot M^b$) based on the simple theory of geometric similarity (Åstrand & Rodahl, 1986; Hill, 1950; Jaric, 2003). This theory suggests that both muscle strength and muscle power should be proportional to muscle cross-sectional area, which is proportional to body mass M raised to the power of 2/3 (i.e. allometric parameter $b = 2/3 = 0.67$). A number of experimental results support these theoretical predictions (Atkins, 2004; Jaric *et al.*, 2005; Markovic & Jaric, 2004, 2005; Nevill *et al.*, 1992). Therefore, the following equation was used to obtain the normalized (i.e. body size-independent) values S_n from the recorded strength and power measures (S) and body mass (M):

$$S_n = S/M^{0.67} \qquad (2)$$

Statistical analyses

Descriptive statistics were calculated for all experimental data as means and standard deviations (s). The relationship among various indices of muscle power calculated from vertical jump tests, vertical jump heights, leg extensor strengths, and body size indices, both before and after the normalization of strength and power tests for body size, were calculated using Pearson's product – moment method. The corresponding inter-correlation matrices of all selected variables were factorized using principal components factor analysis (PCA) (Nunnaly & Bernstein, 1994). The data were analysed using a procedure called FACTOR in the SPSS (version 10.0) software package. The number of significant principal components in the factor pattern matrix extracted by the PCA was determined by the Kaiser-Guttman criterion (Nunnaly & Bernstein, 1994), which retains principal components with eigenvalues greater than 1. The original factor pattern matrix was rotated to improve the simple structure of the matrix. This rotation was non-orthogonal and used a Promax criterion with Kaiser normalization. The final outcomes of each PCA were commonalities and factor loadings for each manifest variable, eigenvalues, and percentages of variance explained by each rotated principal component. Inter-correlations among the extracted principal components were also calculated. Statistical significance was set at $P < 0.05$.

Results

The participants' mean body mass, stature, thigh girth, and percent body fat were 74.8 kg ($s = 7.6$), 1.81 m ($s = 0.07$), 57.0 cm ($s = 3.2$), and 8.3% ($s = 3.6$), respectively. Table I shows descriptive data of all vertical jump power, leg extensor strength, and vertical jump height tests applied.

Inter-correlations among the outcomes of the applied tests and body size indices calculated before (above diagonal) and after (below diagonal) the strength and power normalization for body size are provided in Table II. Note that on average the moderate positive correlations of strength and power measures with body size indices calculated before normalization were reduced after normalization. This finding suggests that normalization successfully accounted for the presumed effect of body size on the selected strength and power measures. Note also that the most of the correlation coefficients between power and jump height measures increased after normalization.

Table I. Results of the vertical jump and muscle strength tests (results averaged across participants; $n = 159$).

	Mean ± s	Range
Squat jump power (W)	1840 ± 243	1367–2452
Countermovement jump power (W)	2331 ± 347	1575–3312
Hopping in place power (W)	3466 ± 596	2312–5365
Squat jump height (cm)	45.1 ± 4.9	34.5–60.9
Countermovement jump height (cm)	48.9 ± 5.2	38.2–69.4
Hopping in place height (cm)	41.9 ± 4.7	31.0–54.0
Drop jump height (cm)	34.2 ± 4.4	21.6–48.7
Weighted SJ force (N)	913 ± 132	579–1348
Back squat (N)	1610 ± 250	1200–2230
Isometric squat (N)	2571 ± 599	1486–4760

The main findings of this study are related to the differences in results of PCA applied to the selected tests before and after the normalization of strength and power tests for body size (see Tables III and IV). Specifically, the first PCA (Table III) provided three principal components or factors that accounted for 73% of the variance in all selected manifest variables. The highest correlations ("loadings") with the first principal component (see Table III) were demonstrated by the power calculated from the squat jumps and countermovement jumps, as well as by all three muscle strength tests. Thigh girth was also correlated with this principal component. The second principal component was correlated with the height of all four vertical jumps. The third principal component was correlated with the power calculated from hopping in place, as well as with body mass and stature. Potentially, the most important finding is that, before normalization for body size, the heights of all four jumps belong to the same component and, therefore, jumping height could represent a separate physical ability separate from muscle strength and power.

In contrast, the second PCA (Table IV) resulted in an extraction of four principal components, which explained 75.5% of variance of all selected manifest variables. The first one was mainly loaded with the power and height of the squat jumps and countermovement jumps. Note that these jumps are performed either concentrically (squat) or as a stretch–shortening cycle (countermovement) of the leg extensors, but the stretching velocity of the countermovement jump is relatively slow. The second principal component was loaded with the power of hopping in place and height of drop jumps and hopping in place. Note that these jumps are

Table II. Inter-correlations among vertical jump power tests, vertical jump height tests, leg extensor strength tests, and body size measures before (above diagonal) and after the normalization of strength and power tests for body size (below diagonal; $r > 0.18$, $P < 0.05$).

	1	2	3	4	5	6	7	8	9	10	11	12	13
(1) SJ power	**1.00**	0.80	0.52	0.47	0.54	0.35	0.25	0.55	0.52	0.50	0.52	0.20	0.48
(2) CMJ power	0.71	**1.00**	0.64	0.57	0.66	0.51	0.37	0.63	0.57	0.52	0.60	0.30	0.48
(3) HOP power	0.32	0.45	**1.00**	0.36	0.38	0.80	0.42	0.44	0.41	0.47	0.56	0.38	0.34
(4) SJ height	0.54	0.68	0.42	**1.00**	0.90	0.49	0.50	0.41	0.35	0.35	0.03	0.02	0.00
(5) CMJ height	0.61	0.80	0.43	0.90	**1.00**	0.49	0.50	0.44	0.36	0.39	0.04	0.02	0.01
(6) HOP height	0.23	0.41	0.81	0.49	0.49	**1.00**	0.49	0.38	0.36	0.35	0.29	0.34	0.08
(7) DJ height	0.27	0.42	0.48	0.50	0.50	0.49	**1.00**	0.20	0.14	0.26	0.05	0.09	0.01
(8) Weighted SJ force	0.41	0.48	0.24	0.45	0.48	0.28	0.20	**1.00**	0.85	0.52	0.46	0.20	0.41
(9) Back squat	0.34	0.36	0.18	0.38	0.38	0.24	0.13	0.81	**1.00**	0.52	0.49	0.28	0.39
(10) Isometric squat	0.35	0.34	0.29	0.36	0.39	0.24	0.27	0.39	0.38	**1.00**	0.42	0.15	0.38
(11) Body mass	−0.01	−0.04	0.15	0.03	0.04	0.29	0.05	0.06	−0.07	−0.09	**1.00**	0.67	0.75
(12) Stature	−0.12	−0.11	0.12	0.02	0.02	0.34	0.09	−0.13	−0.05	−0.15	0.67	**1.00**	0.23
(13) Thigh girth	−0.09	0.03	0.05	0.00	0.01	0.08	0.01	0.08	0.03	0.07	0.75	0.23	**1.00**

SJ = squat jump; CMJ = countermovement jump; HOP = hopping in place; DJ = drop jump.

based on the stretch–shortening cycle of the leg extensors and a relatively high velocity of stretching. Finally, the third and the fourth principal component are apparently loaded with the indices of muscle strength and body size, respectively. However, of great importance for the present study, after normalizing strength and power for body size, the height and the calculated muscle power of the same jumps belonged to the same principal components.

Finally, note also that the extracted principal components in both analyses were interrelated. Specifically, correlations between the principal components before normalization for body size were low to moderate and ranged from 0.11 to 0.39, whereas after normalization for body size the same values ranged between −0.07 and 0.42.

Table III. Results of PCA before the normalization of strength and power tests for body size, showing commonalities and factor loadings for each manifest variable, eigenvalues, and percentage of variance explained by each rotated principal component.

	Factor loadings			
	1	2	3	Commonalities
Squat jump power	**0.81**	0.47	0.34	0.69
Countermovement jump power	**0.83**	0.61	0.45	0.80
Hopping in place power	0.54	0.60	**0.72**	0.79
Squat jump height	0.46	**0.87**	−0.06	0.82
Countermovement jump height	0.51	**0.87**	−0.06	0.86
Hopping in place height	0.36	**0.75**	0.54	0.79
Drop jump height	0.18	**0.73**	0.19	0.58
Weighted squat jump force	**0.85**	0.39	0.27	0.73
Back squat	**0.82**	0.32	0.32	0.67
Isometric squat	**0.70**	0.39	0.29	0.50
Body mass	0.69	0.02	**0.85**	0.92
Stature	0.27	0.08	**0.82**	0.67
Thigh girth	**0.68**	−0.11	0.53	0.68
Eigenvalue	5.99	2.20	1.31	
% of variance	46.09	16.89	10.05	

Discussion

Methodological considerations

The main aim of the present study was to test the hypothesis that vertical jump height represents a body size-independent index of muscle power. This hypothesis was tested by applying a PCA on a selected set of strength and power variables, vertical jump height measures, and body size indices both before and after an appropriate normalization of strength and power variables for body size. However, before discussing our results, two particular methodological aspects should be emphasized.

When studying the relationship between various human movement abilities and body size, the results obtained are affected by several confounding factors: age, sex, body composition, level of physical activity, and skill (Jaric, 2002). Therefore, it should be stressed that we tested a relatively homogeneous group of individuals who were not only of similar age and of the same sex, but also physically highly active and already familiar with the tasks tested. Their percent body fat was low and comparable to that of trained male athletes (Wilmore, 1983), thus reducing a possible confounding effect of body composition on performance.

Another relevant methodological issue in the present study is related to the use of PCA for data analysis. It has been suggested that particular attention should be paid to an appropriate selection

Table IV. Results of PCA after the normalization of strength and power tests for body size (for details, see Table III).

	Factor loadings				
	1	2	3	4	Commonalities
Squat jump power	**0.83**	0.18	0.41	−0.01	0.72
Countermovement jump power	**0.90**	0.41	0.44	−0.05	0.81
Hopping in place power	0.41	**0.85**	0.25	0.12	0.73
Squat jump height	**0.83**	0.55	0.43	−0.03	0.76
Countermovement jump height	**0.89**	0.54	0.46	−0.01	0.84
Hopping in place height	0.36	**0.92**	0.29	0.23	0.86
Drop jump height	0.50	**0.70**	0.14	−0.01	0.55
Weighted squat jump force	0.51	0.21	**0.92**	−0.01	0.86
Back squat	0.38	0.19	**0.93**	−0.01	0.88
Isometric squat	0.47	0.24	**0.60**	−0.04	0.38
Body mass	−0.06	0.31	0.00	**0.97**	0.94
Stature	−0.24	0.46	−0.14	**0.67**	0.67
Thigh girth	0.07	0.00	0.07	**0.85**	0.82
Eigenvalue	4.98	2.31	1.47	1.07	
% of variance	38.30	17.80	11.32	8.08	

of variables, the number of variables, as well as to the number of participants recruited (Nunnaly & Bernstein, 1994). Specifically, more than 10 moderately to strongly interrelated variables should be analysed using PCA, while the number of participants examined should be at least 10 times higher than the number of variables. In our study, we used 13 manifest variables measured on 159 participants, in line with the above-mentioned methodological recommendations. Note also that the number of participants exceeded by far the number of participants in most similar studies (for a review, see Jaric, 2002; Wilson & Murphy, 1996). Moreover, the variables were moderately to strongly interrelated (see Table II), suggesting that their selection was appropriate. This was further confirmed by the relatively high explained variance in both principal components analyses ($\sim 75\%$), together with moderate to high commonalities of variables (Tables III and IV). Finally, we applied the non-orthogonal promax rotation of the extracted principal components, which proved to be the right choice since the extracted components were interrelated. Therefore, from a methodological perspective, we believe that the present study provides a valid data set owing to the large and homogeneous sample of participants tested who were highly familiar with the applied tests, as well as an appropriate selection of variables for analysis.

PCA before and after normalization for body size

The main finding of our study is related to the observed difference in the results of PCA before and after the normalization of strength and power variables for body size. Although the variance explained by principal components extracted before and after normalization for body size was similar (73% and 75%, respectively), the number of components extracted and their factor structure are different. Specifically, before normalization for body size, the PCA revealed three principal components that are hard to interpret. The first component was mainly loaded with muscle power calculated from concentric-only and slow stretch – shortening vertical jump power tests, together with all three leg extensor strength tests. Thus, it appears that this principal component represents a mixture of the participants' ability to generate both high leg muscular force and power. Since both body mass and thigh girth are moderately associated with this principal component, the observed complex structure of the first principal component is probably mediated by body dimensions. Similarly, the third principal component was mainly loaded with body size measures, as well as with the power calculated from vertical jump based on a rapid stretch – shortening cycle. Only the second principal component appears to be relatively simple to interpret, since it is loaded with the heights of all four vertical jump tests. Therefore, this principal component could represent the participants' vertical jump ability or, more generally, ability to perform rapid movements. Taken together, the results of the PCA before the normalization for body size suggest that the height and muscle power obtained from the same set of vertical jumps belong to different principal components and, consequently, they could assess relatively independent physical abilities of the participants. This finding is in line with other studies suggesting a moderate relationship between rapid movement performance and muscle strength (see Introduction for details).

Following the normalization of the strength and power tests for body size, PCA was applied again. In contrast to the previous structure, this one is simpler and easier to interpret despite providing four instead of three principal components. Specifically, the first principal component is loaded with *both* muscle power and jump heights obtained from the concentric and slow stretch – shortening jumping tests. This finding suggests that after normalization for body size, muscle power and jump height appear to be closely related, which is in line with our hypothesis. Hence, the main and a rather novel finding of this study could be that the jump height and appropriately normalized muscle power calculated from the same jump belong to the same principal component and, therefore, could assess the same physical performance. If we interpret this physical performance as muscle power (due to the assessed normalized muscle power that loads the same component), one could conclude that jump height could also be an index of muscle power, but body size independent *per se*.

The second principal component revealed a structure similar to that of the first one – it was loaded with both the muscle power and jump height obtained from the same jumps. However, these jumps were based on a rapid stretch – shortening cycle of the leg extensors. As a result, the structure of the second principal component also provides results in line with our hypothesis. However, the relative independence of the first two principal components generally suggests that the ability to exert power in the jumps heavily based on a stretch – shortening cycle (i.e. hopping in place and drop jump) and those based on concentric-only or a relatively slow stretch – shortening cycle (i.e. squat jump and countermovement jump, respectively) could be relatively independent. Future studies should focus on the main phenomena generally believed to provide the advantage of the stretch – shortening cycle, such as the storage and re-use of elastic energy, reflex potentiation, potentiation of contractile machinery, and previous contraction of the agonist muscle (for a review, see van Ingen Schenau, Bobbert, & de Haan, 1997).

Finally, the third and fourth principal components were loaded with the tests of leg extensor strength and body size, respectively. Although these variables were not directly related to our hypothesis, their simple structure strongly suggests independence of body size and, in particular, muscle strength from muscle power (represented by the first two principal components). Therefore, in addition to muscle power developed through stretch – shortening and the predominantly concentric action of the agonist muscle, muscle strength could be also a relatively independent physical ability that needs to be considered and tested separately.

Limitations

Regarding the potential limitations, note that the applied normalization for body size was based on the assumption of geometric similarity. However, it is well known that human bodies are not geometrically similar because of prominent differences in body shape or body composition when different individuals and/or groups of individuals are compared (Åstrand & Rodahl, 1986). In particular, recent experimental evidence obtained from humans suggests that body transversal dimensions increase with body size at a higher rate than longitudinal ones (Nevill, Markovic, Vucetic, & Holder, 2004a; Nevill, Stewart, Olds, & Holder, 2004b), as predicted by the theory of elastic similarity (McMahon, 1984). This theory suggests that muscle strength and power should be proportional to body mass raised to the power of 0.75, instead of 0.67, used in this study. However, even if this is the case, it is not likely that this difference in the allometric exponent b would substantially change the results obtained in this study due to a relatively narrow range of human body sizes.

Another possible limitation of this study is related to the use of PCA. In particular, this multivariate statistical method is commonly used by researchers for the purpose of reducing a high number of interrelated variables into a smaller number of relatively independent principal components. How well the extracted components describe all the variables is a key issue for validity of the results, and that heavily depends on various methodological issues related to the selection of both participants and variables. Although we believe that the PCA was applied in the present study in a methodologically acceptable way (see first sub-section of Discussion for details), further complementary studies based on other methodological approaches are needed to explore the underlying processes and phenomena related to our main findings.

Conclusion

In conclusion, our results provide important information regarding the relationship between the direct assessment and performance-based assessment of muscle power (later also considered as tests of rapid movements; see Introduction) when applied to various vertical jumps. Specifically, the recorded heights of vertical jumps can be considered as a body size-independent index of muscle power. Another important and rather novel finding is that the ability to produce power (or rapid performance) in movements based predominantly on concentric actions and on the stretch – shortening cycle could be partly independent. If supported by similar results obtained from other physical performance tests based on rapid movements (e.g. running, throwing, kicking), this finding could be of considerable importance for both the design and interpretation of results of test batteries of physical performance. For example, the performance of rapid movements could replace complex measurements of directly assessed as well as normalized for body size measures of muscle power, while the assessment of the ability to exert muscle power in concentric actions and stretch – shortening cycle based rapid movements, as well as muscle strength, need to be tested separately. Further research based on alternative methodological approaches is needed to evaluate the observed findings.

Acknowledgements

The study was supported in part by grants from Croatian Ministry of Science, Education, and Sport (034-0342607-2623), from Serbian Research Council (#145082), and from Croatian National Science Foundation postdoctoral fellowship to G. Markovic.

References

Aragon-Vargas, L. F., & Gross, M. (1997). Kinesiological factors in vertical jump performance: Differences among individuals. *Journal of Applied Biomechanics*, *13*, 24 – 44.

Åstrand, P.-O., & Rodahl, K. (1986). *Textbook of work physiology*. New York: McGraw-Hill.

Atkins, S. J. (2004). Normalizing expressions of strength in elite rugby league players. *Journal of Strength and Conditioning Research*, *18*, 53 – 58.

Dalleau, G., Belli, A., Viale, F., Lacour, J.-R., & Bourdin, M. (2004). A simple method for field measurements of leg stiffness in hopping. *International Journal of Sports Medicine*, *25*, 170 – 176.

Driss, T., Vandewalle, H., Quievre, J., Miller, C., & Monod, H. (2001). Effects of external loading on power output in a squat jump on a force platform: A comparison between strength and power athletes and sedentary individuals. *Journal of Sports Sciences*, *19*, 99 – 105.

Dugan, E. L., Doyle, T. L., Humphries, B., Hasson, C. J., & Newton, R. U. (2004). Determining the optimal load for jump squats: A review of methods and calculations. *Journal of Strength and Conditioning Research*, *18*, 668 – 674.

Fitts, R. H., McDonald, K. S., & Schluter, J. M. (1991). The determinants of skeletal muscle force and power: Their adaptability with changes in activity pattern. *Journal of Biomechanics*, *24* (suppl. 1), 111 – 122.

Harman, E. A., Rosenstein, M. T., Frykman, P. N., & Rosenstein, R. M. (1990). The effects of arms and countermovement on vertical jumping. *Medicine and Science in Sports and Exercise*, *22*, 825 – 833.

Harman, E. A., Rosenstein, M. T., Frykman, P. N., Rosenstein, R. M., & Kraemer, W. J. (1991). Estimation of human power from vertical jump. *Journal of Applied Sport Science Research*, *5*, 116 – 120.

Hill, A. V. (1950). The dimensions of animals and their muscular dynamics. *Science Progress*, *38*, 209 – 230.

Jackson, A. S., & Pollock, C. M. (1978). Generalized equations for predicting body density of men. *British Journal of Nutrition*, *40*, 497 – 504.

Jaric, S. (2002). Muscle strength testing: Use of normalisation for body size. *Sports Medicine*, *32*, 615 – 631.

Jaric, S. (2003). Role of body size in the relation between muscle strength and movement performance. *Exercise and Sport Sciences Reviews*, *31*, 8 – 12.

Jaric, S., Mirkov, D., & Markovic, G. (2005). Normalizing physical performance tests for body size: A proposal for standardization. *Journal of Strength and Conditioning Research*, *19*, 467 – 474.

Komi, P. V., & Bosco, C. (1978). Utilization of stored elastic energy in leg extensor muscles by men and women. *Medicine and Science in Sports*, *10*, 261 – 265.

Kukolj, M., Ropret, R., Ugarkovic, D., & Jaric, S. (1999). Anthropometric, strength, and power predictors of sprinting performance. *Journal of Sports Medicine and Physical Fitness*, *39*, 120 – 122.

Markovic, G., Dizdar, D., Jukic, I., & Cardinale, M. (2004). Reliability and factorial validity of squat and countermovement jump tests. *Journal of Strength and Conditioning Research*, *18*, 551 – 555.

Markovic, G., & Jaric, S. (2004). Movement performance and body size: The relationship for different groups of tests. *European Journal of Applied Physiology*, *92*, 139 – 149.

Markovic, G., & Jaric, S. (2005). Scaling of muscle power to body size: The effect of stretch – shortening cycle. *European Journal of Applied Physiology*, *95*, 11 – 19.

Martin, R. J. F., Dore, E., Twisk, J., Van Praagh, E., Hautier, C. A., & Bedu, M. (2004). Longitudinal changes of maximal short-term peak power in girls and boys during growth. *Medicine and Science in Sports and Exercise*, *36*, 498 – 503.

McBride, J. M., Triplett-McBride, T., Davie, A., & Newton, R. U. (2002). The effect of heavy versus light-load jump squats on the development of strength, power and speed. *Journal of Strength and Conditioning Research*, *16*, 75 – 82.

McMahon, T. A. (1984). *Muscles, reflexes, and locomotion*. Princeton, NJ: Princeton University Press.

Moss, B. M., Refsnes, P. E., Abilgaard, A., Nicolaysen, K., & Jensen, J. (1997). Effects of maximal effort strength training with different loads on dynamic strength, cross-sectional area, load – power, and load – velocity relationships. *European Journal of Applied Physiology*, *75*, 193 – 199.

Nesser, T. W., Latin, R. W., Berg, K., & Prentice, E. (1996). Physiological determinants of 40-meter sprint performance in young male athletes. *Journal of Strength and Conditioning Research*, *10*, 263 – 267.

Nevill, A. M., Markovic, G., Vucetic, V., & Holder, R. (2004a). Can greater muscularity in larger individuals resolve the 3/4 power-law controversy when modelling maximum oxygen uptake? *Annals of Human Biology*, *31*, 436 – 445.

Nevill, A. M., Ramsbottom, R., & Williams, C. (1992). Scaling physiological measurements for individuals of different body size. *European Journal of Applied Physiology and Occupational Physiology*, *65*, 110 – 117.

Nevill, A. M., Stewart, A. D., Olds, T., & Holder, R. (2004b). Are adult physiques geometrically similar? The dangers of allometric scaling using body mass power laws. *American Journal of Physical Anthropology*, *124*, 177 – 182.

Newton, R. U., & Kraemer, W. J. (1994). Developing explosive muscular power: Implications for a mixed methods training strategy. *Strength and Conditioning*, *16*, 20 – 31.

Newton, R. U., Kraemer, W. J., & Häkkinen, K. (1999). Effects of ballistic training on preseason preparation of elite volleyball players. *Medicine and Science in Sports and Exercise*, *31*, 323 – 330.

Nunnaly, J. C., & Bernstein, I. H. (1994). *Psychometric theory*. New York: McGraw-Hill.

Sipilä, S., Koskinen, S. O. A., Taaffe, D. R., Takala, T. E. S., Cheng, S., Rantanen, T. *et al.* (2004). Determinants of lower-body muscle power in early postmenopausal women. *Journal of the American Geriatric Society*, *52*, 939 – 944.

Siri, W. E. (1956). The gross composition of the body. In W. E. Siri (Ed.), *Advances in biological and medical physics* (pp. 239 – 280). London: Academic Press.

Stone, M. H., O'Briant, H. S., McCoy, L., Coglianese, R., Lehmkuhl, M., & Schilling, B. (2003a). Power and maximum strength relationships during performance of dynamic and static weighted jumps. *Journal of Strength and Conditioning Research*, *17*, 140 – 147.

Stone, M. H., Sanborn, K., O'Briant, H. S., Hartman, M., Stone, M. E., Proulux, C. *et al.* (2003b). Maximum strength – power – performance relationships in collegiate throwers. *Journal of Strength and Conditioning Research*, *17*, 739 – 745.

van Ingen Schenau, G. J., Bobbert, M. E., & de Haan, A. (1997). Does elastic energy enhance work and efficiency in the stretch – shortening cycle. *Journal of Applied Biomechanics*, *13*, 389 – 415.

Van Praagh, E., & Dore, E. (2002). Short-term muscle power during growth and maturation. *Sports Medicine*, *32*, 701 – 728.

Wilmore, J. H. (1983). Body composition in sport and exercise: Direction for future research. *Medicine and Science in Sports and Exercise*, *15*, 21 – 31.

Wilson, G. J., & Murphy, A. J. (1996). The use of isometric tests of muscular function in athletic assessment. *Sports Medicine*, *22*, 19 – 37.

Winter, E. M. (2005). Jumping: Power or impulse. *Medicine and Science in Sports and Exercise*, *37*, 523.

Young, W. B. (1995). Laboratory strength assessment of athletes. *New Studies in Athletics*, *10*, 89 – 96.