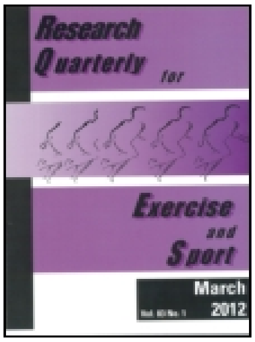

Research Quarterly for Exercise and Sport

ISSN: 0270-1367 (Print) 2168-3824 (Online) Journal homepage: www.tandfonline.com/journals/urqe20

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To cite this article: Iraklis Kollias, Vassilia Hatzitaki, George Papaiakovou & George Giatsis (2001) Using Principal Components Analysis to Identify Individual Differences in Vertical Jump Performance, Research Quarterly for Exercise and Sport, 72:1, 63-67, DOI: 10.1080/02701367.2001.10608933

To link to this article: https://doi.org/10.1080/02701367.2001.10608933

Published online: 26 Feb 2013.

Research Quarterly for Exercise and Sport

Vol. 72, No. 1, pp. 63–67

Using Principal Components Analysis to Identify Individual Differences in Vertical Jump Performance

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Key words: squat jump, force platform, sports, assessment

The standing vertical jump has been used by physical education teachers and coaches as one of the most common tests to evaluate muscular strength of the lower limbs, power, and the so called "jumping ability" in many different sports. Several investigators have used the vertical jump as an experimental paradigm to evaluate the role of different strength training protocols in basketball and volleyball (Bobbert & Van Soest, 1994; Brown, Mayhew, & Boleach, 1986). However, the validity of the vertical jump as a measure of muscular strength of the lower limbs has been questioned lately, mainly due to the moderate association reported between muscular strength and vertical jumping performance (Genuario & Dolgener, 1980). It has been shown that strength training results in just small improvements (8–12%) of jumping performance (Blattner & Noble, 1979; Brown et al., 1986). Subsequent studies have shown that other factors such as the sequence of muscle activation or joint reversals, individual joint contributions, optimal position of the body center of mass at the instant of take off, or the ability to transfer mechanical energy from the proximal to the more distal segments can also be important for determining successful performance in the vertical jump (Bobbert & Van Ingen Scheneau, 1988; Dowling & Vamos, 1993; Fukashiro, & Komi, 1987; Hudson, 1986). These studies allowed the identification of several predictor variables related to both timing and force amplitude factors that would better reflect jumping performance. At the same time, the large number of variables created a burden resulting in confusion and inconsistencies among different models attempting to predict vertical jump performance. Several studies have used multiple regression analysis techniques in an attempt to identify the most critical factors among those highly interrelated variables suggested by the literature as possible determinants of vertical jumping performance (Aragon-Vargas & Gross, 1997; Dowling & Vamos, 1993; Hay, Dapena, Wilson, Andrews, & Woodward, 1978; Podolsky, Kaufman, Cahalan, Aleshinsky, & Chao, 1990). Using such a multiple regression model, Aragon-Vargas and Gross (1997) showed that depending the level of analysis—whole body or segmental—a different set of predictor variables should be used. At the whole body level, the best models accounted for 88% of the variation in vertical jump performance, while at the segmental level, the best models accounted for 60% of the variation. However, none of the above studies were successful in selectively eliminating the large number of highly interrelated variables used to describe jumping performance.

The present study used Principal Component Analysis (PCA) to model the critical mechanical factors involved in the vertical jump in a simpler and more understandable way. PCA has been suggested as a useful methodological tool to address the problem of incorporating a large number of variables being highly correlated to each other by a much smaller number of computed variables or factors, which are usually required to be uncorrelated (Kleinbaum, Kupper, & Muller, 1988). PCA, which is a special case of factor analysis, applies a matrix operation called singular value decomposition (SVD), using a least squares approximation principle. In the present study, a PCA analysis was carried out to reduce the highly corre-

Submitted: March 17, 1999
Accepted: September 26, 2000

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lated force variables used in the literature to describe jumping performance to a fewer number of independent factors that can provide the same amount of information. Analysis was restricted to variables at the whole body level of analysis.

Method

Participants

After signing an informed consent form, forty-three male athletes competing in four different sports volunteered to participate in the present study as part of their basic training season program. From those, 12 were members of an elite national division soccer team (*M* age = 24.8 years, *SD* = 2.1, *M* mass = 79.1 kg, *SD* = 3.2), 12 were members of the Greek national handball team (*M* age = 19.5 years, *SD* = 1.9, *M* mass = 79.9 kg, *SD* = 2.5), 10 were members of an elite national division volleyball team (*M* age = 23.4 years, *SD* = 1.2, *M* mass = 76.7 kg, *SD* = 3.5), and 9 were track and field athletes participating in the Greek national men's team (*M* age = 22.6 years, *SD* = 1.5, *M* mass = 73.8 kg, *SD* = 2.0). All athletes were in good physical condition with no apparent or reported injury or disability and had records of regular participation in their training program.

Experimental Protocol

After a 20 min warm-up, which included bicycle and stretching exercises, each athlete was asked to perform three vertical squat jumps with maximum effort. A 30-s resting period was allowed between trials. At the starting position, the athlete was at the squat position with his knees bent at a 90° angle; his arms were stabilized around the waist, and the plantar surface of his foot was in full contact with the ground. At the "go" signal, he had to jump as high as possible, without using his arms and trying to eliminate any downward movement of the trunk. Participants performed all jumps barefoot. The best of the three trials, based on the maximum height achieved during the jump, was selected for further analysis.

Data Recording and Analysis

Ground reaction force data (Fx, Fy, Fz) during performance of the jumps were sampled at 500 Hz by a force platform and stored in 486/80 personal computer. Six force parameters proposed in the literature as potential predictors of take-off velocity and, subsequently, jump height at the whole body level of analysis (Aragon-Vargas & Gross, 1997; Dowling & Vamos, 1993) were calculated from the ground reaction force data. These were: (a) peak force scaled to body mass (RFMAX), (b) peak power scaled to body mass (RPMAX), (c) maximum rate of force development (RFDMAX), (d) impulse duration (TIME), (e) time to peak force (TFMAX), and (f) vertical displacement of center of gravity (H_{COM}). The rate of force development was obtained by directly calculating the first time derivative of the vertical ground reaction force. The vertical displacement of the center of mass (COM) during force application, from its initial position to the instant of take off, was calculated through integration of the vertical velocity of the COM. The vertical COM velocity during the force application phase was calculated through integration of the net vertical ground reaction force. Mechanical power was obtained by multiplying the vertical force by the vertical velocity during force application.

A PCA on the data from the 43 athletes was used to identify a fewer number of factors that determine jumping performance from the six interrelated force variables (Kleinbaum, Kupper, & Muller, 1988). The data were analyzed using a procedure called FACTOR in the Statistical Package for Social Sciences (SPSS, version 8.0) software package. This procedure applies a matrix operation called singular value decomposition (SVD) based on a least squares approximation principle to replace the original data matrix *Z*, having *n* columns and *p* rows, by a matrix *F* of factor scores having the same number of rows but only *k* columns, where *k* is much smaller than *p*. As a side condition, it is required that the correlation among the *F* columns is zero. In other words, the *p* correlated variables in the original matrix *Z* are replaced by *k* uncorrelated factors in matrix *F*. The new factors of the factor pattern matrix *F*, or principal components in this case, are labeled accordingly. The number of principal components in the factor pattern matrix extracted by the PCA was determined by the number of eigenvalues greater than 1. The original factor pattern matrix was rotated to improve the simple structure of the matrix. In the new rotated matrix, the original variables related more strongly to one of the two principal components, making labeling of the factors much easier. This rotation was orthogonal (90° angle) and used a Varimax criterion with Kaiser Normalization. Rotation converged at three iterations. Differences among athletes of different sports were investigated by plotting the individual scores on the two rotated principal components (factor scores).

Results and Discussion

Table 1 shows the correlation matrix among the six force variables derived from the ground reaction force data. Variables such as RFMAX, RPMAX, and RFDMAX were significantly correlated to each other, with correlation coefficients ranging from .494 to .897 ($p < .01$). Similarly, TIME and TFMAX were positively correlated with each other ($r = .915$, $p < .01$) but negatively, yet significantly, correlated with RFDMAX ($r = -. 589$, $p < .01$, and

$r = -.605$, $p < .01$, for TIME and TFMAX, respectively). The present findings suggest that PCA can be a valuable tool for selectively eliminating the highly interrelated force variables used in the past to assess jumping performance to a fewer number of factors explaining the same amount of data variance. The analysis revealed the existence of two factors or principal components (see Table 2). The first rotated principal component, which accounted for 38.65% of the variance in the force data, was associated with the temporal characteristics of the squat jump. Variables such as TIME and TFMAX loaded highly on this factor, with loadings of .924 and .972, respectively (see Table 2). RFDMAX also showed a moderate but negative loading (-.650) on the first component indicating a moderate yet significant relationship to time. A negative correlation of RFDMAX indicates that a long push-off phase and time to peak force resulted in a low rate of force development (RFD). The second rotated principal component accounted for 35.47% of the variance and was identified with the peak force characteristics of the jump. RFMAX and RPMAX loaded highly on the second component (factor loadings of .933 and .943, respectively), while they had a negative and low relationship to the first principal component (see Table 2). An almost 0 intercorrelation between the factor scores suggests the newly formed dimensions that can be used to further investigate jumping performance on the grounds of their strong relationships to jump height and take-off velocity were completely independent of each other. Five of the six force variables were well approximated by the principal components model, as indicated by the high communality scores, which ranged between .662 for RFDMAX and .954 for TFMAX. On the other hand, communality for H_{COM} was close to 0, suggesting a low prediction of this variable by the two principal components. For this reason, the vertical displacement of the COM during propulsion was not considered in the subsequent interpretation of the present findings. In total, the PCA model consisting of two principal components accounted for 74.12% of the total variance in the six original force variables selected as critical factors for assessing jumping performance on the grounds of their strong relationship to performance criteria such as jump height or take-off velocity. Such a model can, therefore, be a useful adjunct to a regression model for predicting jumping performance, as it can "group" together highly interrelated predictor variables eliminating the burden of dealing with too many variables at no cost of losing important information. It can be hypothesized that if the newly formed components were to enter a regression equation as predictor variables, prediction of jump height or take-off velocity would be much higher.

The PCA model also revealed an important "time" element of jumping performance that explained the same or greater amount of variation in the data than the "force" element. It can, therefore, be concluded that even in the case of a restrictive jumping performance, such as the squat jump, in which jumping height greatly depends on the muscular strength of the quadriceps (Voigt, Simonsen, Dyhre-Poulsen, Klausen, 1995), coordination and timing variables might also have an important contribution to jumping height. Previous studies have also shown there may be other factors, such as time and joint coordination characteristics, which can also affect vertical jump performance, while the relationship between muscular strength and jump performance is moderate (Aragon-Vargas & Gross, 1997; Brown et al., 1986; Genuario & Dolgener, 1980). Other studies have also pointed to the inconclusiveness of the effects of muscle strength training on vertical jump height (Bobbert & Van Soest, 1994). Although the PCA model presented here demonstrated a great pre-

Table 1. Correlation matrix showing the relationships among the six force variables

	RFMAX	RPMAX	RFDMAX	TFMAX	TIME	H_{COM}
RFMAX	1.000					
RPMAX	.897	1.000				
RFDMAX	.578	.494	1.000			
TFMAX	-.381	-.237	-.605	1.000		
TIME	-.483	-.391	-.589	.915	1.000	
H_{COM}	-.226	-.054	-.088	.087	.142	1.000

Note: RFMAX = peak force relative to body mass; RPMAX = peak power relative to body mass; RFDMAX = maximum rate of force development; TFMAX = time to peak force; TIME = impulse (push-off) duration; H_{COM} = vertical displacement of center of mass (COM).

Table 2. Results of PCA showing commonalties and factor loadings for each force variable, eigenvalues, and percentage of variance explained by each rotated principal component; factor loadings lower than 0.6 were not included in the table.

	Factor loadings 1	Factor loadings 2	Commonalities
TIME	.924		.911
RFMAX		.933	.945
TFMAX	.972		.954
RPMAX		.943	.909
RFDMAX	-.650		.662
H_{COM}			.064
eigenvalue	2.319	2.128	
% of variance	38.650	35.470	

Note: TIME = impulse (push-off) duration; RFMAX = peak force relative to body mass; TFMAX = time to peak force; RPMAX = peak power relative to body mass; RFDMAX = maximum rate of force development; H_{COM} = vertical displacement of center of mass (COM).

dictive power in accounting for both force and time characteristics of the jump, it should also be noted that it has been used to examine a very restrictive type of jump. There is no doubt that the same model needs to be validated for other types of jump such as a countermovement jump or a jump involving use of the arms as well.

Plotting the individual scores on the two principal components allowed for comparison of the individual jumping performances among the different sports athletes, as shown in Figure 1. The horizontal abscissa corresponds to the first principal component identified with the time variables, and the vertical corresponds to the second principal component identified with the force characteristics of the jump. Athletes with a strong negative relationship to the first principal component are more likely to be fast and exhibit short impulse duration, short times to peak force, and higher rates of force development. Athletes with high positive loadings on the second principal component seem to have better peak force and power outputs in the vertical jump. At first glance, scores seem to be widely spread in all directions. However, a closer look reveals a tendency for the track and field and volleyball athletes to display high positive scores on the vertical force component. On the other hand, most of the soccer and handball players scored close to or below the zero line in the vertical direction, indicating that their maximum force and power output during the jump was lower than the track and field or volleyball athletes. The factor scores of all athletes were evenly distributed along the time component (horizontal axis), suggesting no differences in the time characteristics of the jump among different sports athletes. However, a slight trend of the soccer and track and field athletes' scores to lie in the negative direction of the "time" axis suggests these athletes are faster, have higher rates of force development, and reach their peak level of force earlier. The "time" component revealed by the PCA model combines information from all three temporal variables and, therefore, provides a complete picture of the athlete's abilities with respect to temporal characteristics of the jump rather than the single total the time variable would have provided. Such an examination can be a useful tool for comparing individual jumping performances, identifying weaknesses, and classifying athletes based on their jumping characteristics. However, further

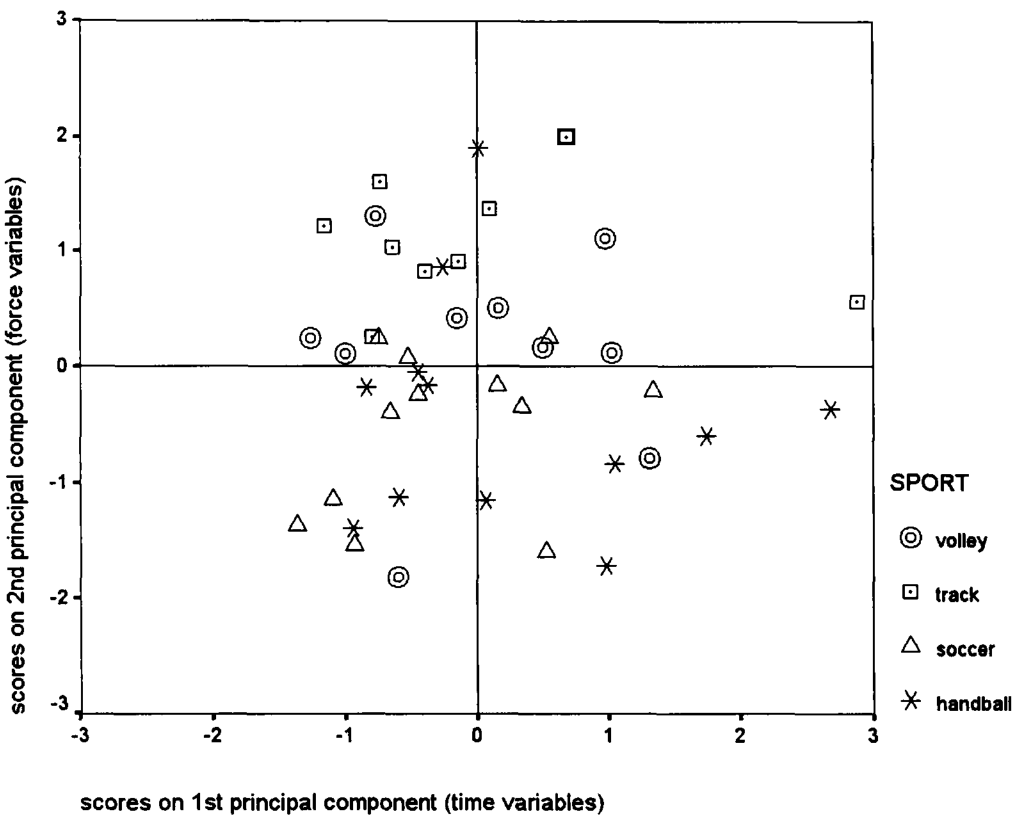

Figure 1. Factor scores for each athlete on the two rotated principal components. The x-axis represents the first principal component identified with the time variables (TIME, TFMAX and RFDMAX); the y-axis shows the regression scores on the second principal component identified with the force variables (RFMAX, RPMAX).

statistical analysis using the newly formed factor scores is required to substantiate such findings.

In conclusion, the results of the present study suggests that PCA can be a useful method for assessing jumping performance, because it can eliminate the large number of highly interrelated variables to a fewer number of independent factors that would better reflect the characteristics of the jump. It permits a quantitative evaluation of each athlete's performance while combining useful information from some of the most critical mechanical variables that have been proposed as potential predictors of jumping performance in the literature.

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Authors' Notes

This work was supported in part by a grant from the National Association for Sport and Physical Education. The authors wish to thank the two anonymous reviewers and the section editor for their valuable feedback in earlier versions of the manuscript. Please address all correspondence concerning this article to Iraklis Kollias, Department of Physical Education and Sports Sciences, Aristotelian University of Thessaloniki, Thessaloniki, 546 06 Greece.

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