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Kinesiological Factors in Vertical Jump Performance: Differences Among Individuals

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The purpose of this study was to investigate the kinesiological factors that distinguish good jumpers from poor ones, in an attempt to understand the critical factors in vertical jump performance *(VJP)*. Fifty-two normal, physically active male college students each performed five maximal vertical jumps with arms akimbo. Ground reaction forces and video data were collected during the jumps. Subjects' strength was tested isometrically. Thirty-five potential predictor variables were calculated for statistical modeling by multiple-regression analysis. At the whole-body level of analysis, the best models (which included peak and average mechanical power) accounted for 88% of *VJP* variation ($p < .0005$). At the segmental level, the best models accounted for 60% of variation in *VJP* ($p < .0005$). Unexpectedly, coordination variables were not related to *VJP*. These data suggested that *VJP* was most strongly associated with the mechanical power developed during jump execution.

Vertical jump performance *(VJP)* has been studied by researchers for decades. Early interest was related to jumping in sports such as basketball and volleyball. More recently, as a simple task where maximum performance is clearly and objectively defined, the vertical jump has been applied to understanding human motor control of a multiarticular movement. One major practical question, however, remains the same: Which kinesiological factors are critical for vertical jump performance? Coaches and trainers have tended to focus on lower limb muscular strength training as a means to improve *VJP*, but it seems that other factors can affect vertical jump performance as well.

Early research on the vertical jump focused on the role of muscular strength and the effects of various methods of strength training on *VJP* (Ball, Rich, & Wallis, 1964; Bangerter, 1968; Blattner & Noble, 1979; Brown, Mayhew, & Boleach, 1986; Eisenman, 1978; Genuario & Dolgener, 1980; McKethan & Mayhew, 1974). In general, these studies report a moderate association of muscular strength and *VJP* ($r \approx .50$; Genuario & Dolgener, 1980) and relatively small improvements (8–12%) in jump performance with strength training (Blattner & Noble, 1979; Brown et al., 1986).

There was also some early interest in storage and utilization of elastic energy and its effects on *VJP* (Asmussen & Bonde-Petersen, 1974; Komi & Bosco, 1978). These papers

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Glossary of Terms

AMECHP	Average mechanical power of the whole body.
AMP	Amplitude of the movement.
AVA	Average vertical acceleration.
BCOMNET	Net vertical position (position at takeoff minus standing position) of the body center of mass at takeoff. See Equation 11.
DISTAPRO	Distal-to-proximal sequence of the maximum velocity differences between proximal and distal joints for each segment.
DISTOPRO	Distal-to-proximal sequence of the joint reversals.
Height	Body height.
j	Denotes a joint. *ANK* is ankles, *KNE* is knees, and *HIP* is hips.
jACCPK	Peak joint acceleration during the negative phase.
jANGTO	Joint angle at takeoff.
jEXTIS	Joint extension isometric strength.
jFLXIS	Joint flexion isometric strength.
jMMAX	Maximum net joint torque.
jMREV	Net joint torque at the time of joint reversal.
jPFXIS	Joint plantar flexion isometric strength.
jPWRMAX	Peak joint power.
jREVTDIF	Time difference between first and last joint reversals.
JUMP2	Jump height calculated from BCOMNET and TOVEL.
MMTDIFF	Time difference between the first and last maximal joint torques.
NEGIMMAX	Peak negative impulse of the body center of mass.
PEAKPWR	Peak mechanical power of the whole body.
PRODISTA	Proximal-to-distal sequence of the maximum velocity differences between proximal and distal joints for each segment.
PROTODIS	Proximal-to-distal sequence of the joint reversals.
TOVEL	Vertical takeoff velocity of the body center of mass.
TPROP	Time of propulsion.
VJP	Vertical jump performance.
Weight	Body weight.

and others on the use of stored elastic energy in skeletal muscle (Cavagna, Dusman, & Margaria, 1968), on motor control of the locust jump (Heitler & Burrows, 1977a, 1977b), and on various manipulations of the vertical jump (Yamazaki, Suzuki, & Mano, 1989) suggest that high musculotendinous forces at the onset of the concentric action enhance jumping performance. Researchers have also studied the relative contributions of joint or segment actions to the jump (Fukashiro & Komi, 1987; Hubley & Wells, 1983; Pandy & Zajac, 1991; Robertson & Fleming, 1987), the role of biarticular muscles in vertical jumping (Bobbert & van Ingen Schenau, 1990; Pandy & Zajac, 1991; van Ingen Schenau, Bobbert, Huijing, & Woittiez, 1985), and specific motor control issues such as coordination of segmental actions (Bobbert & van Ingen Schenau, 1988; Hudson, 1986; Jensen & Phillips, 1991; Pandy & Zajac, 1991).

The work of these scientists has allowed a considerable refinement of the biomechanical techniques and models used to study *VJP* and has identified several variables common to maximum vertical jump performance: high musculotendinous forces and joint torques at the onset of the positive phase; high joint powers, especially toward the time of takeoff; close occurrence of a proximal-to-distal sequence of activation of muscle groups; close occurrence of a proximal-to-distal sequence of joint reversals; and an optimization of the vertical position of the body center of mass at the instant of takeoff. Most of these studies, however, have focused on similarities among good performers, and few comparisons have been made between good and bad jumpers. Identifying the variables associated with good but not with bad performance is necessary to determine which factors are most important for *VJP*.

Since most of the factors proposed as relevant to *VJP* are interrelated in a complex fashion, a sensible approach to their study is the use of multiple-regression analysis techniques. Multiple regression has been used previously in the study of *VJP* (Dowling & Vamos, 1993; Hay, Dapena, Wilson, Andrews, & Woodward, 1978; Jaric, Ristanovic, & Corcos, 1989; Podolsky, Kaufman, Cahalan, Aleshinsky, & Chao, 1990), but the variables studied were somewhat limited. The papers by Jaric and colleagues and Podolsky and colleagues focused on muscular strength measures, while Dowling and Vamos restricted their study to whole-body mechanics and timing issues. Hay and colleagues focused on average joint torques at particular intervals using a rather complex (11-segment) model; they did not include any of the coordination-related predictor variables that have been identified more recently. In the present study we collect those variables proposed in the literature as potential predictors, organize them according to a theoretical model, and study them in a group of men with a wide range of jumping abilities, in an attempt to identify the kinesiological factors critical for vertical jump performance.

Methods

Theoretical Model and Potential Predictor Variables

Figure 1 shows a theoretical model of the relevant factors in vertical jump performance. This model recognizes that variables are highly interrelated, while allowing for different levels of analysis.

The first level of analysis was concerned with a functional relation: The vertical position and vertical takeoff velocity of the body center of mass mathematically define *VJP*, as shown in Equation 11. This step in the analysis allowed us to verify the consistency of the results, by comparing the jump height results obtained from two different methods (i.e., *VJP* and *JUMP2*). It also allowed us to evaluate the relative importance of each of the two predictors, since a greater mathematical relevance (i.e., a squared term) does not necessarily imply a greater statistical relevance (i.e., a greater variance among jumpers).

The second level of analysis dealt with the variables that should contribute more directly to the vertical position of the body center of mass at takeoff (joint angles at takeoff) and to the vertical takeoff velocity (whole-body dynamics of the jump). Theoretically, the best jumpers could enhance takeoff velocity by maximizing the average force applied to the body center of mass, or by maximizing the distance over which this force is applied, or by selecting the best compromise between these options. Similarly (considering differences in body mass), the jumper could maximize average vertical acceleration, could maximize the time this acceleration was maintained, or could find a compromise. Another strategy might be to generate a greater negative impulse of the body center of mass, which could result in a greater ground reaction force from the onset of the positive phase of the jump, increasing the average force applied to the body center of mass. Two independent measures of power (mean and peak mechanical power) and two general anthropometric

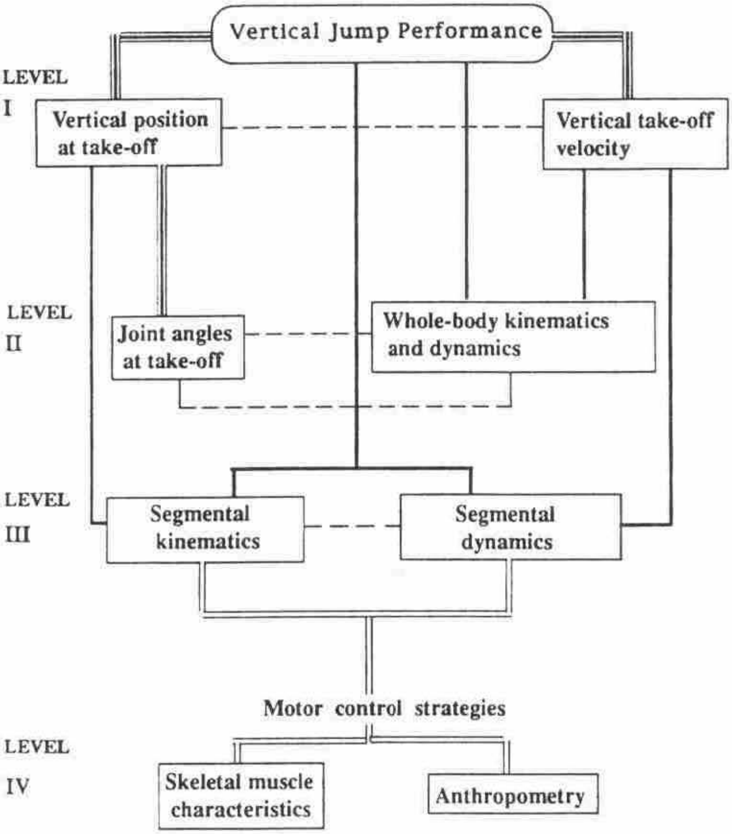

Figure 1 — Theoretical model of vertical jump performance. Triple solid lines denote functional relations. Solid lines indicate the statistical relationships under study. Dotted lines indicate other interrelationships.

characteristics (body weight and height) were also included to complete the list of variables that might contribute to vertical jump performance (Table 1).

The third level of analysis included some segmental kinematics and kinetics of the jump that theoretically combine in different ways to produce different body center of mass positions and velocities at takeoff. Segmental kinematic variables analyzed were primarily related to the description of coordination of segmental actions. Peak net joint torques and peak joint powers were included to examine muscular performance during the execution of the jump. Peak joint accelerations during the negative phase and net joint torques at the time of joint reversals were also included as these could be related to the role of the stretch–shortening cycle in muscle actions. Potential predictor variables related to whole-body and segmental mechanics of the execution of the jump are listed in Table 1.

A fourth level of analysis could be included to examine the effects of the skeletal muscle characteristics and anthropometric characteristics of each individual. Segmental kinetics and kinematics of the jump are the result of how the nervous system uses these characteristics to maximize performance. This study dealt only with the one aspect of this

Table 1 List of Level II and III Predictors of VJP

Whole-body kinematics and kinetics of the jump (II-B)	Segmental kinematics of the jump (III-A)	Segmental kinetics of the jump (III-B)
Average vertical acceleration *(AVA)*	Relative timing of joint reversals *(PROTODIS)*	Peak net joint torques *(jMMAX)*
Time of propulsion *(TPROP)*	Time difference between first and last peak net joint torques *(MMTDIFF)*	Net joint torques at time of joint reversals *(jMREV)*
Amplitude of the movement *(AMP)*	Relative timing of the peak velocity differences between proximal and distal joints for each segment *(PRODISTA)*	Peak joint powers *(jPWRMAX)*
Average mechanical power *(AMECHP)*	Peak joint angular accelerations during the negative phase *(jACCPK)*	
Peak mechanical power *(PEAKPWR)*		
Peak negative impulse *(NEGIMMAX)*		
Body weight *(weight)*		
Body height *(height)*		

fourth level of analysis that has been traditionally evaluated: muscular strength of the hip flexors and extensors, knee flexors and extensors, and ankle plantar flexors.

Data Acquisition

Fifty-two normal, physically active male college students each performed five maximal vertical jumps, starting from the position of their choice, with their hands on their hips (arms akimbo). Informed consent was obtained from all subjects in accordance with the policy statement of the University of Michigan. They completed three practice jumps before data collection and were required to wait for 1 min after each trial. Subjects performed the jumps barefoot, wearing only a swimsuit or pair of shorts. Five reflective markers were placed on the right side of the body, on the glenohumeral joint (shoulder *[SHO]*), the greater trochanter (hip *[HIP]*), the lateral condyle of the femur (knee *[KNE]*), the lateral malleolus (ankle *[ANK]*), and the fifth metatarsal (toe *[TOE]*). The best jump of each subject was selected for analysis, using the *VJP* criterion (maximum jump height) as defined in Equation 10.

Ground reaction forces and moments of force were collected with a Bertec force plate (Model 4060A) and were sampled at 300 Hz. A video-based (60 Hz), real-time, 3-D motion analysis system (Motion Analysis Corp.) was used to collect and process kinematic data. Kinematic data were filtered with a low-pass, fourth-order Butterworth filter with an effective cutoff frequency of 8 Hz.

Strength of the lower body was tested isometrically at the hip, knee, and ankle joints, at a separate session, using a Biodex machine. Standard Biodex procedures were used for the knee and ankle joint tests (Biodex Corporation, n.d.). The hip joint test was adapted from the procedures described in the Cybex II operation manual (Cybex, n.d.). Subjects had a brief warm-up period and three practice trials prior to each test. They were instructed to exert maximum force for 5 s, with 15 s rest between trials. Maximum torque averaged over three trials was obtained. Joint strength was defined as the average of both the right and left joints. Joint angles during testing were standardized according to Table 2.

Basic anthropometric data were obtained using standard sliding calipers, tape measures, and the force platform. Body mass and body height were measured according to the procedures of Lohman, Roche, and Martorell (1988). Thigh length, midthigh circumference, shank length, calf circumference, malleolus width, malleolus height, and foot length were obtained according to the procedures of Vaughan, Davis, and O'Connor (1992). These data were used to calculate segmental center of mass and moment of inertia values.

Data Analysis

The body was modeled as a planar, rigid-body system consisting of four segments linked by frictionless, hinge joints (Figure 2). Although the effects of an arm swing on *VJP* are relevant (Jensen, 1989), the utility of a four-segment model for the study of vertical jumping is well documented (Bobbert, Huijing, & van Ingen Schenau, 1987a, 1987b; Bobbert & van Ingen Schenau, 1988; Pandy, Zajac, Sim, & Levine, 1990; Pandy & Zajac, 1991; Zajac, Zomlefer, & Levine, 1981) and such a model allows a more specific focus on the lower limb muscle actions.

Segmental (COM_i) and whole-body (*BCOM*) center of mass positions in the horizontal (x) and vertical (z) axes were calculated from the video records, according to Vaughan et al. (1992). The procedure used for calculating the *HAT* parameters was based on data from Clauser, McConville, and Young (1969) and Hinrichs (1990). Segmental moments of inertia about the center of mass were calculated according to Vaughan et al. (1992), using their formulas for the sagittal plane.

Table 2 Joint Angles (in Degrees) Used for Isometric Strength Tests

	Hip	Knee	Ankle
Hip extension[a]	90	90	—
Hip flexion[a]	90	90	—
Knee extension[b]	120	120	—
Knee flexion[b]	120	120	—
Ankle plantar flexion[c]	110	140	80

[a] Based on Nemeth et al. (1983) and Waters et al. (1974). [b] From Lindahl et al. (1969) and Scudder (1980). [c] Based on Fugl-Meyer et al. (1980) and Sale et al. (1982).

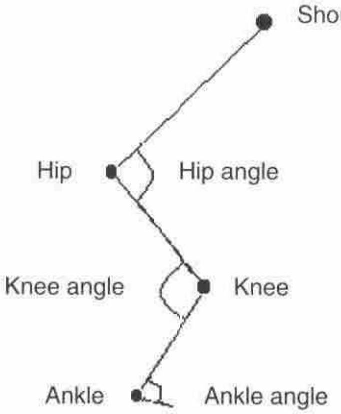

Figure 2 — Biomechanical model. Segments (i = 1 to 4) are defined by the markers: Segment 1 = head, arms, and trunk *(HAT)*, from shoulder to hip; Segment 2 = thighs *(THI)*, from hip to knee; Segment 3 = shanks *(SHA)*, from knee to ankle; Segment 4 = feet *(FET)*, from ankle to toe.

Vertical velocity of the whole-body center of mass ($\dot{z}BCOM$) was calculated from the force records, according to

$$\dot{z}BCOM = \frac{\int_{t_0}^{t_{t.o.}} F_{zp}dt}{m} \tag{1}$$

where F_{zp} is the propulsive force, obtained by subtracting body weight from the vertical ground reaction force, t_0 is the beginning of data collection, and t_{to} is the time of takeoff (when F_z falls below 3.0 N, or less than 0.005% of body weight). Numerical integration of the force curve was performed by simple summation divided by sampling frequency. The takeoff velocity of the center of mass ($\dot{z}_{takeoff}BCOM$ or *TOVEL*) was obtained from the instantaneous value of $\dot{z}BCOM$ at takeoff.

Kinematic analysis of the body center of mass included the time of propulsion, average vertical acceleration, and amplitude of the movement. Time of propulsion was defined as

$$t_{prop} = t_{t.o.} - t_{low} \tag{2}$$

where t_{low} is the instant when *zBCOM* reaches its lowest point during countermovement.

Average vertical acceleration of *BCOM* during propulsion was calculated as

$$AVA = {\dot{z}_{takeoff}BCOM} \big/ {tprop} \tag{3}$$

Amplitude of the movement was defined as the center of mass vertical excursion normalized for body height, to represent the extent to which each subject used his available range of motion. This was calculated according to

$$AMP = \left(\frac{z_{takeoff}BCOM - z_{low}BCOM}{body\ height} \right) * 100 \tag{4}$$

Whole-body mechanical power was calculated in two separate ways. Average mechanical power during propulsion was derived from the change in potential energy of the whole body, according to

$$AMECHP = \frac{mg(z_{peak}BCOM - z_{low}BCOM)}{t_{prop}} \tag{5}$$

where m is body mass and $g = 9.81\ \text{m} \cdot \text{s}^{-1}$. Peak mechanical power *(PEAKPWR)* was obtained from the instantaneous mechanical power of the whole body *($\dot{W}$)* calculated according to Dowling and Vamos (1993):

$$\dot{W} = F_z * \dot{z}BCOM \tag{6}$$

Peak negative impulse was calculated from the peak downward velocity of the body center of mass:

$$NEGIMMAX = m(\dot{z}_{min}BCOM) \tag{7}$$

Angular velocities and accelerations were obtained by differentiating joint angular displacement data, using finite differences. Joint angles are defined in Figure 2. According to this convention, when a joint is flexing the angular velocity is negative; it is positive when the joint extends.

Vertical velocity differences between proximal and distal joints for each segment (see Bobbert & van Ingen Schenau, 1988) were calculated from the first derivative of vertical joint displacements, according to

$$Vdiff_i = (\dot{z}_{prox} - \dot{z}_{dist})_i \tag{8}$$

using the instants of peak velocity differences of the segments to determine whether the sequence was proximal to distal *(PRODISTA: HAT, THI, KNE, FET)*, distal to proximal *(DISTAPRO)*, or something else.

Kinematic and kinetic data were used to obtain the instantaneous net joint torques using Newtonian equations of motion (Winter, 1990). Joint extensor torques are presented as positive and joint flexor torques as negative.

Instantaneous joint powers were calculated according to Robertson and Winter (1980):

$$\dot{W}_j = M_j * \omega_j \tag{9}$$

where $\dot{W}_j$ is the power for joint j at each point in time, M_j is the instantaneous torque for joint j, and ω_j is the instantaneous angular velocity at joint j.

The performance criterion was vertical jump performance *(VJP)*, defined as the peak vertical position of the center of body mass during flight, minus the center of body mass height while standing:

$$VJP = z_{peak}BCOM - z_{standing}BCOM \tag{10}$$

Jump height was also calculated from the vertical velocity and net position of the whole-body center of mass at takeoff (*TOVEL* and *BCOMNET*, respectively):

$$JUMP2 = \left[(\dot{z}_{takeoff}BCOM)^2 * (2g)^{-1}\right] + z_{takeoff}BCOM - z_{standing}BCOM \tag{11}$$

Statistical Analysis

Multiple-regression analysis techniques were applied at each level of the model in Figure 1 to identify the major predictor variables. The basic model used was the general linear model:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_{p-1} x_{p-1} + E_j \tag{12}$$

where y, the dependent variable, is normally distributed; x_i is the i^{th} predictor, $p-1$ is the number of predictors in the model, β_0 is the intercept, and E_j are the error terms, which are independent and normally distributed. Descriptive statistics were used to verify that the basic assumption of normality of the dependent variables was met and to investigate whether there was a reasonable variability of both dependent and predictor variables.

For each level of analysis, several statistical models were developed, using "all possible subsets" and "stepwise" regression techniques, and were compared. The "best" models were selected according to commonly used criteria, that is, Mallow's Cp ($Cp \cong p$), and R_a^2 (highest adjusted r-squared values). The adjusted r-squared takes into account how many predictors are included in the model, since additional variables will usually improve r-squared but at the expense of complicating the model. Interactive stepwise regression was used to verify the significance and the relative importance of each predictor in the models. Since the purpose of this study was to identify the relevant predictors and not necessarily to build the most accurate model possible, selection of several different models is a reasonable approach. These models were refined using residual analysis techniques, to check for the omission of important variables or the need for interaction terms or a curvilinear function. The presence of outliers was determined using leverage and Studentized deleted residuals; their influence was assessed using Cook's D. In addition, the aptness of each model in terms of the normality of E_i was evaluated using normal probability plots. Finally, specific levels of significance (p values) achieved by each model were obtained and reported, to allow us to evaluate the probability of selecting relevant predictors by chance alone.

Results

General characteristics of the subjects are presented in Table 3. Tables 4 and 5 list the jump execution results. Average body weight (74.3 kg) was slightly above the U.S. population average for a body height of 1.78 m (71.8 kg) (Metropolitan Life Insurance Company, 1959). Jump heights *(VJP)* ranged from 0.372 to 0.663 m (mean = 0.520 m) and had a coefficient of variation of 13.4%. There were 16 subjects, or 31% of the sample, outside ±1 *SD* of the average *VJP*. This average jump height is higher than reported in the literature for male college students jumping without an arm swing (i.e., 0.49 m, Brown et al., 1986; 0.42 m, Bosco & Komi, 1979) but is lower than reported for trained basketball players (0.55 m, Brown et al., 1986) or trained volleyball players (0.54 m, Bobbert et al., 1987a). Of special relevance to the present study is the fact that the group represented a wide range of jumping abilities and physical activity levels. At the higher end of physical activity, 7 subjects were members of the university's volleyball club, 4 were active in strength-related sports (college wrestling, recreational bodybuilding, and professional baseball), and 2 were endurance athletes (rowing, cross-country running). At the lower end were about 20 subjects who were only occasionally active in recreational basketball, jogging, or weight lifting.

Table 3 Subject Characteristics ($N = 52$)

Variable [variable name] (units)	Mean	*SD*	CV (%)
Age *[age]* (years)	20.2	2.1	10.4
Weight *[weight]* (kg)	74.27	8.65	11.6
Height *[height]* (m)	1.79	0.06	3.4
Hip extension strength *[HIPEXTIS]* (N · m)	160.46	34.55	21.5
Hip flexion strength *[HIPFLXIS]* (N · m)	101.57	18.79	18.5
Knee extension strength *[KNEEXTIS]* (N · m)	230.03	43.90	19.1
Knee flexion strength *[KNEFLXIS]* (N · m)	121.05	24.20	20.0
Ankle plnt. flexion strength *[ANKPFXIS]* (N · m)	130.66	19.91	15.2

Table 4 Jump Execution Characteristics ($N = 52$)

Variable name (units)	Mean	*SD*	CV (%)
VJP (m)	0.520	0.070	13.4
TOVEL ($\mathrm{m \cdot s^{-1}}$)	2.651	0.246	9.3
BCOMNET (m)	0.144	0.027	18.9
HIPANGTO (rad)	3.01	0.09	3.0
KNEANGTO (rad)	3.08	0.09	2.9
ANKANGTO (rad)	2.52	0.10	4.2
TPROP (s)	0.316	0.062	19.6
AVA ($\mathrm{m \cdot s^{-2}}$)	8.74	2.04	23.3
AMP (% body height)	31.33	5.44	17.4
AMECHP (W)	2,212.9	455.1	20.6
PEAKPWR (W)	3,863.2	687.7	17.8
NEGIMMAX ($\mathrm{kg \cdot m \cdot s^{-1}}$)	−87.8	36.6	41.7
HIPACCPK ($\mathrm{rad \cdot s^{-2}}$)	56.79	17.44	30.7
KNEACCPK ($\mathrm{rad \cdot s^{-2}}$)	34.66	15.31	44.2
ANKACCPK ($\mathrm{rad \cdot s^{-2}}$)	52.07	41.66	80.0
MMTDIFF (s)	0.158	0.093	58.8
JREVTDIF (s)	0.113	0.077	68.6
HIPMMAX (N · m)	295.51	74.26	25.1
KNEMMAX (N · m)	220.84	77.54	35.1
ANKMMAX (N · m)	244.80	48.25	19.7
HIPMREV (N · m)	280.32	86.46	30.8
KNEMREV (N · m)	206.07	80.44	39.0
ANKMREV (N · m)	215.32	64.24	29.8
HIPPWRMAX (W)	1,203.7	341.9	28.4
KNEPWRMAX (W)	1,487.5	447.4	30.1
ANKPWRMAX (W)	1,916.5	558.6	29.1

Table 5 Jump Execution Characteristics: Sequence Variables ($N = 52$)

Variable name	Frequency
PROTODIS	23
DISTOPRO	1
Other sequences of joint reversals	28
PRODISTA	42
DISTAPRO	0
Other sequences of peak velocity differences	10

Both *VJP* and takeoff velocity *(TOVEL)* were normally distributed, but the net position of *BCOM* at takeoff *(BCOMNET)* was positively skewed. We transformed the latter (base 10 logarithm) before completing the analyses. Variability was higher for *BCOMNET* (coefficient of variation [CV] = 18.9%) than for *TOVEL* (CV = 9.3%). Average values reported in Table 4 are comparable to those reported in other studies (Bobbert et al., 1987a; Bobbert & van Ingen Schenau, 1988; Hudson, 1986). Most subjects chose to perform a "countermovement jump" (Asmussen & Bonde-Petersen, 1974); the few who tried to do a "squat jump" actually used a small countermovement.

Figure 3 shows representative curves of joint angles, joint angular velocities, net joint torques, and joint powers. The curves were obtained from 1 subject with an average *VJP* (0.537 m); other average jumpers (within 0.25 *SD* of the average, $n = 11$) showed similar curves. These curves are comparable to those reported by Bobbert and van Ingen Schenau (1988). This subject shows a hip–ankle–knee sequence of joint reversals, a common pattern (21 out of 28) among subjects in the "other sequences of joint reversals" category (cf. Table 5).

Table 6 shows a summary of the best prediction models developed for the dependent variables, organized by levels of analysis. Up to three statistically significant multivariate models are included at each level. Best single predictors are also included at each level. Both R^2 and R_a^2 values are reported, since each could point to a different model as the best one and to allow comparisons among models with different numbers of predictors. Within each model, variables are presented in order of importance, according to their partial correlation coefficients. Several models not included in this table may have been reasonably good but not good enough to be among the best. Table 6 includes information about how many significant models were not included in the table and what their best R^2 values were. In addition, when a variable is discussed as not being relevant, additional information is provided about whether it was a significant predictor in any of the absent models.

At Level I, takeoff velocity *(TOVEL)* was a much more powerful predictor of *VJP* than the position of *BCOM* at takeoff *(BCOMNET)*: The partial coefficients of determination when the other variable was already in the model were .937 for *TOVEL* and .256 for *BCOMNET* (total $R^2 = .95$). Level II models show that it was possible to account for about 91% of the variation in *TOVEL* and 89% of the variation in *VJP*, using whole-body kinematics and kinetics of the jump. The two best single predictors of both dependent variables were peak mechanical power and average mechanical power.

Models at Levels 3 and 4 show smaller coefficients of determination. The best pre-

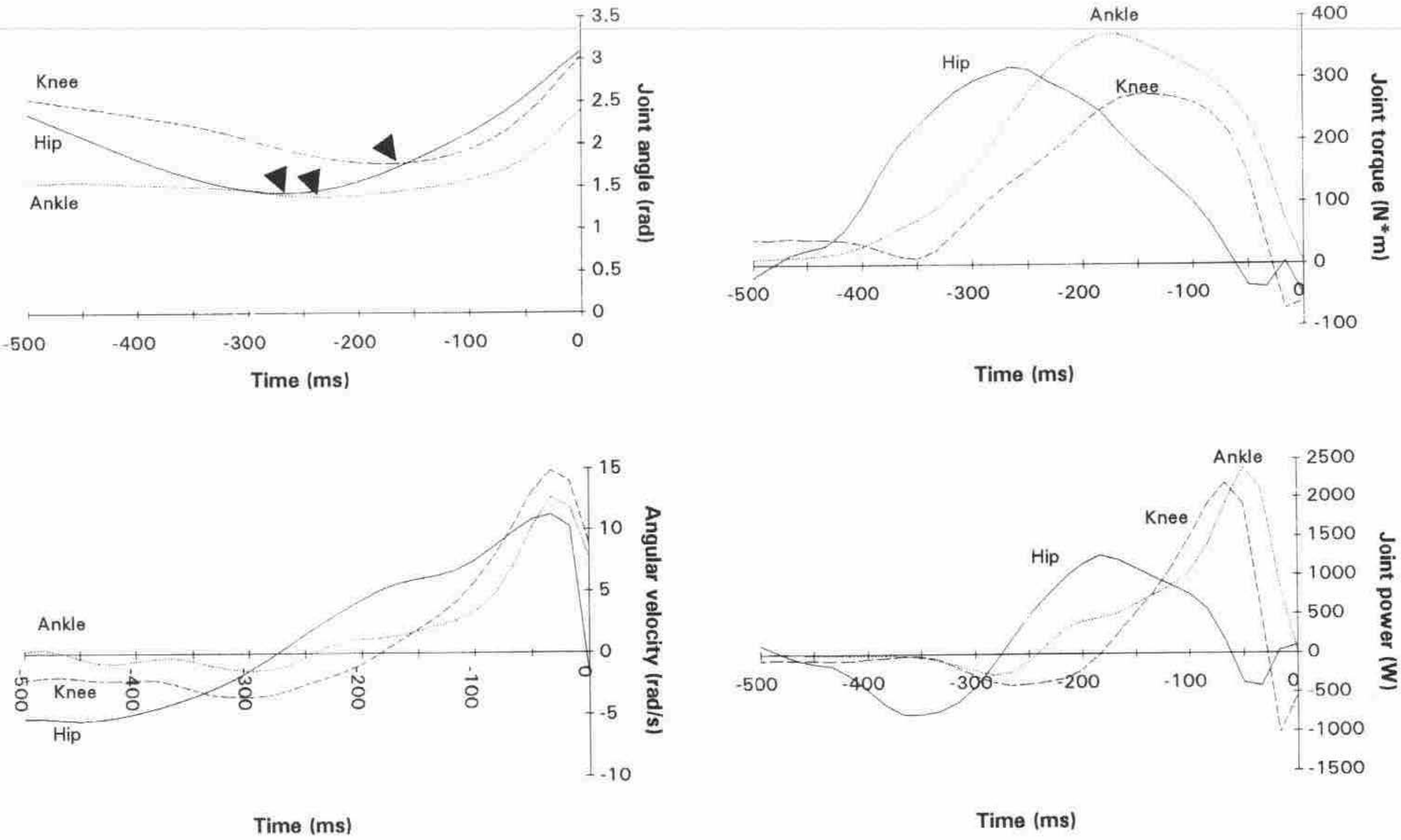

Figure 3 — Joint kinematics and dynamics for a maximum vertical jump, Subject db43t01. This is a representative subject with an average maximum vertical jump (0.537 m). Time = 0 represents the instant of takeoff. Arrows in top left figure show the instant of joint reversal.

Table 6 "Best" Prediction Models at Each Level of Analysis (All Models, Except When Noted, Were Significant at $p < .0005$)

Prediction model for *VJP*	R^2	R^2_a
Level I		
1. $VJP = k + TOVEL + BCOMNET$	.95	.94
2. $VJP = k + TOVEL$	.93	.93
Level II		
3. $BCOMNET = k + ANKANGTO + HIPANGTO$	.32	.29
4. $BCOMNET = k + KNEANGTO$	.24	.23
5. $TOVEL = k - weight + PEAKPWR + AMP + AMECHP$	.91	.90
6. $TOVEL = k + PEAKPWR - weight + AMP + AVA$	.91	.90
7. $TOVEL = k + PEAKPWR - weight + AMP - TPROP$[a]	.91	.90
8. $TOVEL = k + PEAKPWR$	.52	.51
9. $TOVEL = k + AMECHP$	.44	.42
10. $VJP = k - weight - AVA + AMECHP + PEAKPWR$	.89	.88
11. $VJP = k - weight + AMP + PEAKPWR + AMECHP$	.88	.87
12. $VJP = k + PEAKPWR - weight$[b]	.72	.70
13. $VJP = k + PEAKPWR$	.46	.45
14. $VJP = k + AMECHP$	.43	.42
Levels III and IV		
15. $VJP = k + HIPPWRMAX + HIPACCPK + KNEEXTIS - KNEFLXIS - HIPMREV + KNEPWRMAX$	.61	.56
16. $VJP = k + HIPPWRMAX + KNEEXTIS + KNEPWRMAX + HIPACCPK - KNEFLXIS - HIPMMAX$	.61	.56
17. $VJP = k + HIPPWRMAX - HIPMREV + KNEACCPK + HIPACCPK + KNEEXTIS$[c]	.59	.55
18. $VJP = k + HIPPWRMAX$	.44	.43
19. $VJP = k + HIPMMAX$	.28	.26
20. $TOVEL = k + HIPPWRMAX + KNEPWRMAX$	.48	.46
21. $TOVEL = k + HIPACCPK$[d]	.21	.19
22. $TOVEL = k + HIPPWRMAX$	.43	.42
23. $BCOMNET = k + ANKPFXIS + HIPPWRMAX$[e]	.30	.27
24. $BCOMNET = k + HIPACCPK$[f]	.07	.05
25. $BCOMNET = k + ANKPFXIS$	.25	.23

[a]Other models not included ($n > 10$) were statistically significant, with $R^2 = .89$ and lower. [b]Other models not included ($n > 10$) were statistically significant, with $R^2 = .87$ and lower. This particular model was included to illustrate the effect of these two variables alone. [c]Other models not included ($n = 3$) were statistically significant, with $R^2 = .51$ and lower. [d]$p = .001$. [e]*HIPPWRMAX* is borderline nonsignificant in this model ($p = .05$). [f]$p = .063$.

diction models for *VJP* had a large number of predictors, all of which had a significant effect on *VJP* ($p < .05$). The three best models included peak hip power *(HIPPWRMAX)*, knee extension strength *(KNEEXTIS)*, and a hip torque variable *(HIPMMAX* or *HIPMREV)*; these models accounted for about 60% of the variation in *VJP*. Peak knee power

(KNEPWRMAX) was also an important predictor, while ankle torque, power, and strength were not as relevant. Best single predictors of *VJP* at these levels were peak hip power *(HIPPWRMAX)* and torque *(HIPMMAX)*. The best models using segmental kinematics as predictors (Models 21 and 24) were not as powerful as those using segmental kinetics (20, 22, 23, 25) for predicting *TOVEL* and *BCOMNET*.

Table 7 presents the best prediction models from each type of muscle-performance predictor: muscular strength, net joint torques at the instant of joint reversal, peak joint torques, and peak joint powers. For most of these models, high intercorrelation among predictors resulted in only one of them being in the model at a single time. Table 8 shows the correlations between isometric muscle strength and dynamic muscle performance during vertical jumping. Note that ankle plantar flexion isometric strength was not significantly correlated with peak ankle torque or power.

Discussion

This study shows that vertical jump performance can be predicted from various kinesiological factors with different degrees of success, depending on the type of predictor variables used. Most models reported in Table 6 achieved a level of significance of $p < .0005$, meaning that the probability of having identified relevant predictors that may not be identified in a new sample of subjects is very small. Regarding Level I, it was shown that both *TOVEL* and *BCOMNET* were significant predictors of *VJP*. This is in good agreement

Table 7 "Best" Prediction Models From Each Type of Muscle-Performance Predictors (All Models Significant at $p < .0005$)

Type of predictors	Prediction model	R^2	R^2_a
Peak joint powers	$VJP = k + HPWRMAX + KPWRMAX$	.499	.478
	$VJP = k + HPWRMAX$	.443	.431
Peak joint torques	$VJP = k + HIPMMAX$	.275	.260
Torques at reversals	$VJP = k + HIPMREV$	.234	.218
Muscular strength	$VJP = k + KNEEXTIS$	.218	.203

Table 8 Correlations Between Muscle Strength and Muscle Performance During Vertical Jumping

	HIPMMAX	*HIPPWRMAX*	*KNEMMAX*	*KNEPWRMAX*	*ANKMMAX*	*ANKPWRMAX*
HIPEXTIS	.421^a	.361^a				
HIPFLXIS	.520^a	.376^a				
KNEEXTIS			.332^a	.559^a		
KNEFLXIS			.251^b	.547^a		
ANKPFXIS					.152^a	.183^b

$^a p < .05$. $^b p \geq .05$.

with the findings of Bobbert and van Ingen Schenau (1988), who stated that the optimization of *VJP* involves optimization of both *TOVEL* and *BCOMNET*. It is possible that some subjects' strategies would favor one in detriment of the other, but subjects with a higher takeoff velocity did not seem to achieve this velocity at the expense of *BCOM* position at takeoff (or vice versa); the correlation between *TOVEL* and *BCOMNET* was .247 (p = .078), indicating a nonsignificant tendency for subjects with a higher *TOVEL* to show a higher *BCOMNET* as well. These results, together with the high predictive power of *TOVEL*, suggest that little information is added by studying the *BCOMNET* part of the vertical jump performance equation, at least when making between-subject comparisons.

Joint angles at takeoff were significant but poor predictors of *BCOMNET*. Bobbert and van Ingen Schenau (1988) proposed that a greater ankle angle at takeoff may distinguish those jumpers who leave the ground with a higher *BCOM* position. The present data show that *ANKANGTO* was a significant predictor of *BCOMNET* (p = .001) but could only account for about 21% of the variation in *BCOMNET*. *KNEANGTO* had a similar predictive ability (24%). Because joint angles at takeoff were highly intercorrelated, the best model (Model 3) could only account for 32.2% of the variation in *BCOMNET*. Much higher coefficients of simple and multiple determination were obtained when studying individual subjects (see companion paper).

Whole-body kinematics and kinetics were good predictors, not only of *TOVEL* but of *VJP* as well. Peak power, body weight, and amplitude of the movement were common to almost all the best predictive models of *TOVEL* and *VJP* (Models 5–7 and 10–12, Table 6). The regression coefficients for weight and time of propulsion *(TPROP)* were negative, indicating an inverse relationship between these variables and the dependent variables. Surprisingly, peak negative impulse of *BCOM (NEGIMMAX)* was not present in the best models. *NEGIMMAX* has been proposed to influence *VJP* by allowing greater joint torques during propulsion (Cavagna, 1977; Komi & Bosco, 1978). In the present study, *NEGIMMAX* was moderately correlated with peak joint torques ($.35 < r < .70$) and had a significant effect on *VJP* ($p = .023$), but its coefficient of simple determination was rather low ($r^2 = .10$). With two exceptions ($VJP = k + AMP + PEAKPWR - weight - NEGIMMAX$, $R^2 = .85$; $VJP = k + TPROP + AMECHP - weight - NEGIMMAX$, $R^2 = .85$, not reported among best models in Table 6), *NEGIMMAX* was not a significant predictor of *VJP* when other whole-body variables were in the model. Apparently, negative phase impulse strategy is not a critical factor for vertical jump performance. It is possible that the timing of *NEGIMMAX* relative to the instant of lowest position of *BCOM* (t_{low}) had an effect on the association between *NEGIMMAX* and *VJP*, since timing issues are important in stretch–shortening cycle movements (Cavagna, 1977). This possibility warrants further study.

Other researchers have identified peak mechanical power as the best predictor of *VJP* (Dowling & Vamos, 1993; Harman, Rosenstein, Frykman, & Rosenstein, 1990). In those studies, *PEAKPWR* accounted for about 86.5% and 89% of the variation in jump height, respectively, compared with 46.4% in the present study. The difference may be explained by the fact that both Dowling and Vamos and Harman et al. included body mass in their calculations. They also obtained their jump height from takeoff velocity alone. A prediction model with our data including both *PEAKPWR* and weight accounts for 81.9% of the variation in *TOVEL*, which is more in agreement with the papers cited.

Bobbert and colleagues (1987a) showed that when a particular subject uses different jumping techniques, peak mechanical power during the jumps can vary significantly, while vertical jump performance (and external work done) remains constant. This suggests that while mechanical power is strongly correlated with *VJP*, it is not necessarily a limiting factor of *VJP*. Furthermore, whole-body peak power alone does not give insight into the specific aspects of performance that distinguish one jumper from another. How do good jumpers accomplish a greater power and a higher jump? Even though our models from Levels III and IV did not show such high coefficients of determination and tended to have a large number of predictors when *VJP* was the dependent variable, they are closer to the mechanical and physiological bases of performance than whole-body mechanical power (cf. Table 1).

Models from Levels III and IV show that when predicting *VJP*, joint strength measures were not as important as joint torques and powers during the jump. Table 7 shows how predictive ability improves moving from the muscular strength measures to the actual net joint torques during the jump, and then to the peak joint powers during the jumps. Bobbert and van Ingen Schenau (1990) showed how skeletal muscle performance is very different in the ankle plantar flexors during a vertical jump, compared to performance during uniarticular actions such as those commonly used during strength testing.

Skeletal muscles are expected to be able to generate greater torques during isometric than concentric actions, provided the isometric test is performed at the optimum joint angle (Lieber, 1992). Furthermore, during multiarticular movements, net joint torque measures may include the action of "antagonists." When that happens, the agonist torque is greater than the net joint torque indicates (Zajac & Gordon, 1989). Finally, unilateral strength has been shown to be greater than half the bilateral strength of leg muscles (van Soest, Roebroeck, Bobbert, Huijing, & van Ingen Schenau, 1985). All of the above factors should result in the peak net joint torques measured during the vertical jump being substantially lower than the strength test torques multiplied by 2 (cf. Tables 3 and 4). Our data show that this was not the case for hip extension (average difference was $-25.4\ \mathrm{N \cdot m}$, $p = .021$) or for ankle plantar flexion ($-16.5\ \mathrm{N \cdot m}$, $p = .044$), but it was for knee extension ($-239.2\ \mathrm{N \cdot m}$, $p < .001$). In addition, Table 8 shows low to moderate correlations between muscle strength and muscle performance during vertical jumping. The present data support the view that one reason why lower body strength is normally not a strong predictor of *VJP* may be because skeletal muscle behavior during a vertical jump is very different from the actions involved in isometric, isotonic, and isokinetic strength tests.

Table 7 also shows the lower predictive ability of peak hip torque *(HIPMMAX)* when compared to peak hip power *(HIPPWRMAX)*. This illustrates the importance of the muscle's ability to combine high torques with reasonably high joint angular velocities. Differences in *HIPPWRMAX* among subjects may be due not only to differences in muscle fiber type composition (Bosco & Komi, 1979) but to differences in coordination strategies that allow the relevant muscles to act at a more advantageous range of the force/velocity curve (a lower muscle–fiber shortening velocity at the same joint angular velocity would allow the muscle to generate more force; Bobbert, Huijing, & van Ingen Schenau, 1986).

Among the different muscle groups, performance of the hip muscles seems to be the most closely related to *VJP*, as seen in Table 7. Only knee muscle strength was a stronger predictor than its hip counterpart. This is in agreement with the findings of Pandy and Zajac (1991), who showed that gluteus maximus muscles, together with the vastii muscles, are the major energy generators during maximum vertical jumping.

Table 6 shows that the sequence of joint reversals (*PROTODIS*, *DISTOPRO*, other) and the sequence of segmental peak velocity differences (*PRODISTA*, *DISTAPRO*, other) were not included in the best prediction models for *VJP*. Several authors have confirmed the existence of a proximal-to-distal sequence of activation of muscle groups and sequence of joint reversals during maximum *VJP* (Bobbert & van Ingen Schenau, 1988; Hudson, 1986; Pandy & Zajac, 1991). More recently, Bobbert and van Soest (1994), using a dynamic simulation of the vertical jump, also found muscle activation patterns that show a proximal-to-distal tendency. They concluded that actual jumping achievement depends largely on the precise timing of muscle actions, but that the ideal timing of muscle activation may differ from one subject to another depending on the relative strength of the different muscle groups involved. In our study, we did not measure muscle activation sequence per se but looked at the kinematic results of the "coordination" of muscle actions. Bobbert and van Soest suggested that "it seems as if a kinematically optimal solution exists for the jumping motion, regardless of muscle properties" (1994, p. 1019). Furthermore, Bobbert and van Ingen Schenau (1988) suggested that a close occurrence of proximal-to-distal joint reversals is desirable in order to optimize the effective energy of *BCOM* at takeoff. It does not necessarily follow that the best jumpers use this approach and the worst do not. In fact, Jensen, Phillips, and Clark (1994) proposed that this proximal-to-distal sequence of joint reversals is a rather stable feature of vertical jumping in humans of all ages. In the present study, neither the sequence of joint reversals ($p = .93$) nor the sequence of segmental peak velocity differences ($p = .70$) was significantly related to *VJP*. It would be interesting to see whether *VJP* changes in a single subject as a result of changes in coordination patterns as defined herein.

Similarly, the time difference of joint reversals *(JREVTDIF)* was not an important predictor. It was significant neither as a single predictor of *VJP* ($p = .48$), *TOVEL* ($p = .48$), and *BCOMNET* ($p = .64$) nor when other variables were present in the models. This is in disagreement with the data from Hudson (1986), who reported a difference in sequence and timing of joint reversals ("initiation of segment extension" in her study) between the 5 most skilled and the 5 least skilled subjects. However, the definition of "skilled" jumpers in Hudson's study was related not to vertical jump performance as defined herein but to the ratio of countermovement jump height to squat jump height. In addition, the present study looked at the total time difference from first to last joint reversals, while Hudson looked at time differences between initiation of extension of adjacent segments. Jensen et al. (1994), on the other hand, looked at the absolute timing of each joint reversal with respect to the instant of takeoff and found no differences between adults and children or between groups of children with different jumping skill levels. Unfortunately, the way their data are reported does not allow for evaluation of joint reversal time differences.

Other segmental kinematics variables not included in this study may prove to be more strongly associated with *VJP*. More recent analyses show that the absolute values (not their timing) of peak velocity differences between the proximal and distal ends of *HAT*, *THI*, and *SHA* are significantly correlated with *VJP* (single r^2 values of .19, .56, and .22, respectively). Interpretation of these results is not possible at this point due to the nature of our statistical model development procedures.

This study presents several "best" models for each level of analysis, but no general, overall statistical model is reported. The theoretical model of *VJP*, presented in Figure 1, suggests that predictors from one level already include most of the information that could be provided by predictors from lower levels of analysis. We tested this assumption by building models using the best predictors from all levels of analysis. All possible subsets regression procedures were used to identify the best overall models. It was possible to find models that included variables from Levels II and III in addition to *TOVEL* and *BCOMNET* (the best model from Level I), but adding up to four variables at a time to $VJP = k + TOVEL + BCOMNET$ ($R^2 = .95$) only improved overall R^2 by .02. It was not possible to add any predictors from Level III to the best models from Level II (i.e., none of the predictors from Level III were statistically significant under those conditions). Furthermore, no combination of predictors from different levels was better than the best models from the higher level alone. Since significant models were developed even at the lowest level of analysis, it is apparent that the best models from a particular level include most of the information that could be provided by predictors from lower levels of analysis.

The horizontal takeoff velocity of *BCOM* could have contaminated the results of this study. Subjects did not necessarily jump directly upward, and the horizontal component of the takeoff velocity may have affected overall vertical jump performance. The absolute value of the horizontal velocity at takeoff was relatively small but varied considerably from subject to subject (mean = 0.098 m · s^{-1}, *SD* = 0.076, CV = 77.9%). The single coefficients of correlation between horizontal takeoff velocity and the dependent variables were poor (*VJP*, $r = .23$; *BCOMNET*, $r = .26$; *TOVEL*, $r = .36$), and only the latter was significant at $\alpha = .05$. Furthermore, horizontal velocity at takeoff was not statistically significant when added to any one of the models in Table 6. Therefore, there is no reason to believe that horizontal takeoff velocity had a significant effect in this study.

The conclusions from this study may be limited by our choice of 8 Hz as the filter cutoff frequency for the kinematic data. Although this filter retained 85% of the signal at all markers, it may have reduced the peak values of the joint powers, joint torques, and joint accelerations during the negative phase and the joint angles at takeoff. This effect should be about the same for all subjects, however, and the focus of this study was not on the absolute values but on comparisons among subjects. Some authors believe that a higher sampling frequency (100 Hz) and a higher filter cutoff frequency (16 Hz) are necessary to measure correctly the variables of interest during human vertical jumping (Bobbert et al., 1987a, 1987b). We recommend using these higher frequencies in future studies in an attempt to reduce synchronization errors and excessive smoothing of the data.

A final comment is necessary regarding the four-segment biomechanical model used. This model does not account for the effects of using an arm swing, which is the way humans normally jump. Among other things, the arm swing allows individuals to jump about 10 cm higher (Brown et al., 1986; Harman et al., 1990). Part of this improvement comes from the direct contribution of the arm swing to positive vertical impulse, but part of it comes from allowing a greater force production by the lower limbs (Jensen, 1989). We believe there is a tradeoff between the limitations of excluding the arms and the greater confidence that comes from using a well-tested model. Although the presently identified predictor variables would probably change in magnitude if an arm swing were included in the jumping task, their relative importance for *VJP* would probably remain the same. Future studies can look at the predictive ability of our statistical models under that condition.

It was possible to predict differences in *VJP* among a group of normal, healthy males, using different subsets of kinesiological variables as predictors. The net position of the body center of mass at takeoff contributed little information to the prediction of *VJP* compared to the vertical takeoff velocity. Whole-body peak mechanical power was the best single predictor of *VJP*, but it provided no insight into the segmental actions that result in higher jumps. At a segmental level of analysis, the present data offer little support for the relevance of some coordination variables as defined in previous studies, such as the sequence and timing of joint reversals. Peak joint powers and joint torques, particularly those at the hip, were the main factors that distinguished good and bad jumpers. How to modify these factors by training and practice, and how much of an effect that modification can have on *VJP*, are questions that warrant further study.

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