Identification of Kinetic and Temporal Factors Related to Vertical Jump Performance

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Subjects performed maximum vertical jumps on a force platform to reveal whether resulting force–time curves could identify characteristics of good performances. Instantaneous power–time curves were also derived from the force–time curves. Eighteen temporal and kinetic variables were calculated from the force– and power–time curves and were compared with the takeoff velocities and maximum heights via correlation and multiple regression. The large variability in the patterns of force application between the subjects made it difficult to identify important characteristics of a good performance. Maximum positive power was found to be an excellent single predictor of height, but the best three-predictor model, not including maximum power, could only explain 66.2% of the height variance. A high maximum force (> 2 body weights) was found to be necessary but not sufficient for a good performance. Some subjects had low jumps in spite of generating high peak forces, which indicated that the pattern of force application was more important than strength.

One of the fundamental objectives of the vertical jump is to achieve the greatest vertical velocity at takeoff, because the height achieved by the body's center of gravity is a function of vertical velocity and takeoff position. The vertical jump is easily performed by most healthy individuals, yet some are considerably more proficient than others. The reasons for this are due at least in part to differences in strength, speed, and coordination between the individuals, but how does the sport scientist identify the aspect in which a particular individual is deficient or the modality that will best improve the performance?

According to Hochmuth (1984), force–time curves contain kinetic and temporal information that can be used objectively in the selection of the most suitable curve for optimizing various types of athletic movements. Hochmuth and Marhold (1977) used mathematical modeling of particle dynamics to demonstrate that achievement of peak acceleration or force late in the movement was optimal for movements requiring a high final velocity such as jumping. Dowling

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(1992) showed that the direct application of this principle to human movement was complicated by initial conditions and interactions of nonlinear elements of muscle mechanics. It was also shown that maximizing force late in the movement requires considerably more muscle power, which may make the optimal pattern of Hochmuth and Marhold (1977) impossible to achieve due to physiological constraints.

Recently, computer simulations employing muscle activation dynamics, nonlinear elements of muscle mechanics, and physiological constraints have been used in multisegment human movements. This method has been called the direct dynamical approach, and the reader is referred to Zajac and Winters (1990) for a more complete description. The advantage of using these simulations is that they can be used with optimization methods to strictly control hypotheses testing about the roles of the different force-generating structures in terms of the movement goal.

Van Soest, Schwab, Bobbert, and Van Ingen Schenau (1992) as well as Pandy (1990) have developed simulations of the vertical jump, but contradictory results were found with respect to the role of biarticular muscles and the contribution of tendon to countermovement jumping performance. The disadvantage of the computer simulation is that in order for the results to be trusted, the model must be an adequate representation of the real system, which is difficult to determine. Researchers have evaluated the simulations by comparing the optimized output with kinematic data of actual jumps. Both models claim good agreement with actual kinematics yet they come to different conclusions. The reason for this may be due to the insensitivity of movement kinematics to the redundancy of the internal kinetics.

Winter (1984) has shown that in walking, the joint angle–time graphs have very little variability between subjects but the joint moments are highly variable. Shiavi (1988) has termed this the "gait problem" although it probably applies to all multisegment human movements. He has shown that the kinetic variability is even greater when one examines the myoelectric activity patterns of the individual muscles responsible for the joint moments. A stronger evaluation of the simulation models may require that a typical pattern of vertical jumping kinetics be identified.

When examining the force– and power–time curves of a vertical jump, the experimenter can quickly measure certain characteristics. These characteristics can be the durations of certain phases (temporal variables) or peaks, slopes, and areas (kinetic variables) of the force– and power–time curves. If a large number of individuals attain a level of excellence in a particular skill, a strong relationship may exist between some of the characteristics of the movements and the objective of the skill. Recently, Oddsson (1989) and Jaric, Ristanovic, and Corcos (1989) have shown that a considerable amount of vertical jump performance variance can be explained by temporal, kinematic, or kinetic features. It may therefore be possible to determine faults in technique by comparing an individual's performance with an optimized curve. It may also be possible to discover common characteristics of good performances that can then be used to assess possible weaknesses in less proficient performances.

The purpose of this study was to use the biomechanical force–time curve of the vertical jump to identify kinetic and temporal characteristics that were strongly related to performance. It was hoped that the information could be used to assess the principle of late force development of Hochmuth and Marhold

(1977), to establish a characteristic kinetic pattern that could be used to better evaluate computer simulations, and to allow sport scientists to better assess and improve the performance of athletes.

Methodology

Ninety-seven young adults (46 male, 51 female) whose activity levels ranged from moderate to highly trained volunteered as subjects for this study. Informed consent was obtained from each of the subjects prior to their participation in the study. The mean body masses for the males and females were 75.1 ± 6.3 kg and 59.8 ± 7.7 kg, respectively. Each subject was instructed to perform a maximum effort, countermovement jump with arm swing from a static, upright posture. The jumps were performed on a multicomponent force platform (AMTI model OR6-5) and the vertical force component was digitally converted (Data Translation model DT2801A-12-bit resolution) at 100 samples per second and stored on computer disk.

We calculated mechanical power for each sample by multiplying the vertical force by the vertical velocity of the subject's center of gravity. We determined these velocities by subtracting body weight from the force–time curve, dividing by body mass, and integrating with respect to time using the trapezoidal rule for numerical integration (Hornbeck, 1967). Vertical impulse was calculated by subtraction of body weight and integration of the force–time curve. We normalized all force values to units of body weight (BW) by dividing the ground reaction forces by the subject's body weight in Newtons. Similarly, all power values were normalized to Watts/BW, and all impulse values were normalized to BW·s. This normalization was performed to control for the confounding effects that mass may have had on the relationships between certain variables. An example of a typical force–time curve is shown in Figure 1 and of a typical power–time curve in Figure 2.

The instant of takeoff was defined as the instant that ended the takeoff phase and began the flight phase. The low point was defined as the instant that the center of gravity had zero velocity and was at a minimum height during the takeoff phase. The temporal variables are labeled with uppercase letters and the kinetic variables are labled with lowercase letters in Figures 1 and 2 and are summarized in Table 1. Ensemble averages were plotted of the five highest and the five lowest jumps to allow qualitative examination of the characteristics of good and poor performances. We performed an independent t test comparing the means of the height attained by jumps that had a single maximum peak of force with the height attained by jumps that had two or more peaks in the takeoff phase.

In addition to the 15 variables identified in Figures 1 and 2, four additional calculations were made. The average slope from the minimum force to the maximum force (p) was calculated as

$$p = (e-b)/C. \tag{1}$$

The second calculation involved the estimation of a shape factor of the major positive impulse phase. It was thought that when limited by a certain maximum of force that can be developed over a certain time duration, an optimal
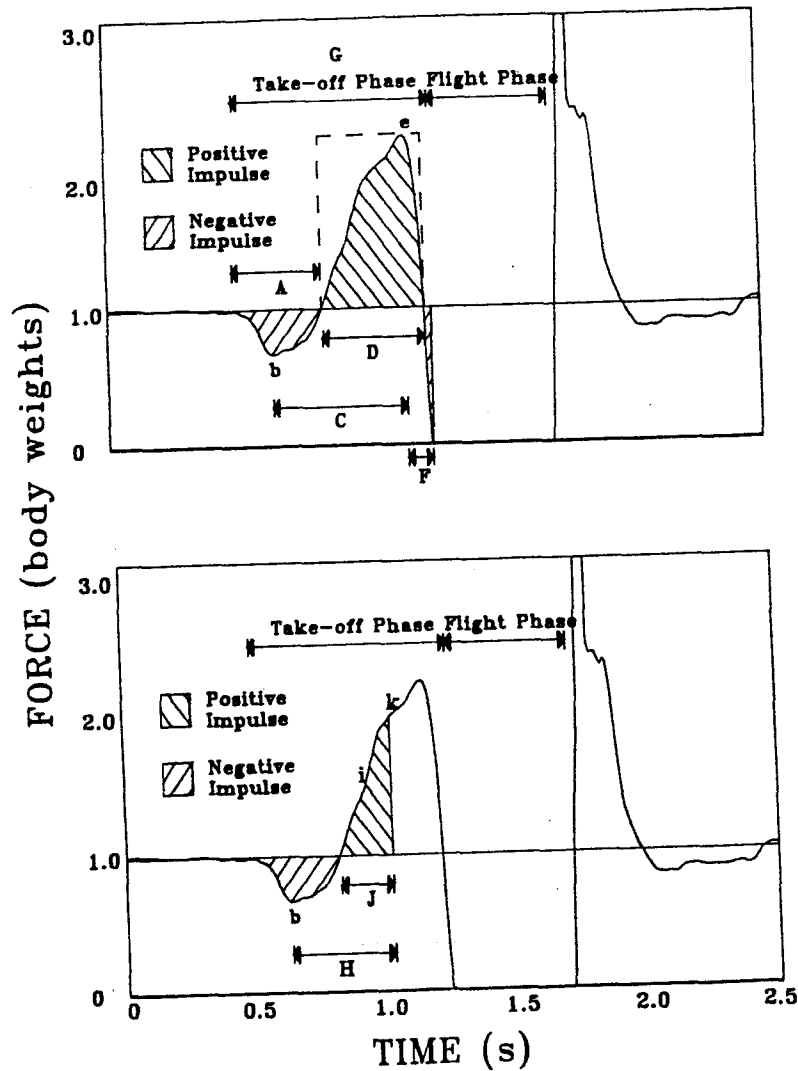
Figure 1 — Temporal and kinetic variables measured from the force–time curves of the vertical jumps. A = duration of major negative impulse; b = minimum force; C = duration from minimum to maximum force; D = duration of major positive impulse; e = maximum force; F = duration from maximum force to takeoff; G = duration of takeoff phase; H = duration from minimum force to low point; i = maximum positive slope of force; J = duration from maximum negative velocity to low point; k = force at low point.
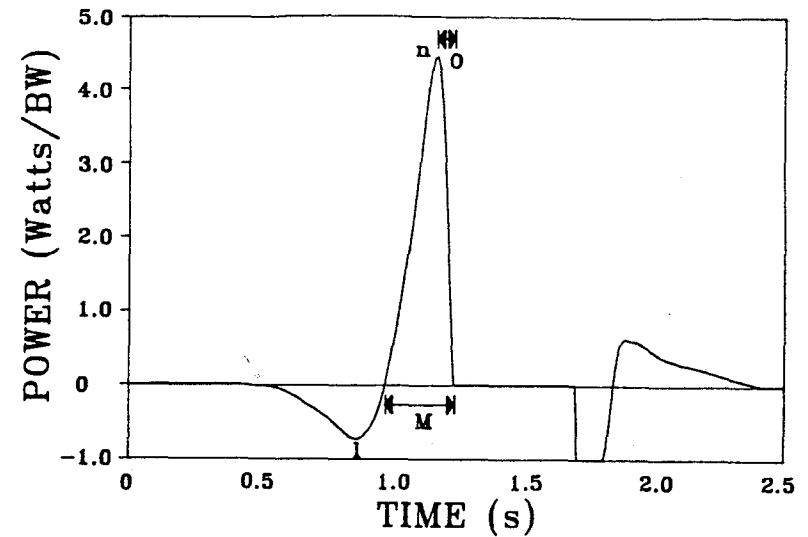
Figure 2 — Temporal and kinetic variables measured from the power–time curves of the vertical jumps. l = maximum negative power; M = duration of positive power phase; n = maximum positive power; O = duration from maximum positive power to takeoff.

pattern of force application would be rectangular in shape (Adamson & Whitney, 1971; Dowling, 1982). The shape factor was defined as that portion of a rectangle bounded by the maximum force and duration of the major positive impulse phase that was filled by the positive impulse during that phase. The rectangle is shown as a dashed line in Figure 1 (top), and the shape factor (q) was calculated as the ratio of the shaded area to the area bounded by the dashed line.

The third calculation involved the ratio of negative to positive impulse. It was found by previous investigators (i.e., Cavagna, Dusman, & Margaria, 1968) that vertical jump performance is enhanced when the subject performs negative work prior to the positive work phase. This technique, often called the stretch-shortening cycle, has a limit beyond which further increases in negative work cause decreases in performance (Komi, 1983). The greater the negative impulse, the greater the amount of negative work that must be performed prior to the positive work phase. It was thought that calculating a ratio of the impulses (r) would create a more sensitive variable to the stretch-shortening optimum. This impulse ratio calcuation is

$$r = \text{negative impulse/positive impulse.} \qquad (2)$$

The fourth calculation (s) was of the maximum negative velocity. It was thought that because force and work enhancements may have been influenced by eccentric contraction velocity in animal experiments, this calculation may be a good predictor of jump height.

Contrary to the statements of some previous investigators (i.e., Asmussen &

Table 1

Descriptions and Correlation Coefficients (*r*) of the 18 Independent Variables With Height of the Jumps

Variable	Description	*r*
A	Duration of major negative impulse	0.101
b	Minimum force	−0.103
C	Duration from minimum to maximum force	0.164
D	Duration of major positive impulse	−0.055
e	Maximum force	0.519*
F	Duration from maximum force to takeoff	−0.274*
G	Duration of takeoff phase	−0.062
H	Duration from minimum force to low point	−0.068
i	Maximum positive slope of force	0.138
J	Duration from maximum negative velocity to low point	−0.026
k	Force at low point	0.173
l	Maximum negative power	−0.298*
M	Duration of positive power phase	−0.010
n	Maximum positive power	0.928*
O	Duration from maximum positive power to takeoff	−0.406*
p	Average slope from minimum to maximum force	0.027
q	Shape factor of major positive impulse phase	−0.111
r	Ratio of negative impulse to positive impulse	−0.514*
s	Maximum negative velocity	−0.295*

Note. N = 97.
*p > .01.

Bonde-Petersen, 1974) the height of a vertical jump is not equal to 1.226 times the square of the flight phase duration. This would be true only if the height of the center of gravity of the body were the same at landing as at takeoff. In the standard vertical jump, the knees and trunk are extended and the arms are elevated over the head at the instant of takeoff, but at landing, the knees and trunk are more flexed and the arms are lowered. This causes the center of gravity to be lower at landing than at takeoff and results in an overestimation of height if the flight duration is used even if the arm swing has been limited. The numerical integration used in this study to calculate velocity allowed the height to be calculated with

$$Ht = v^2/2g \qquad (3)$$

where Ht = maximum height of the center of gravity above its height at takeoff (m), v = vertical velocity at takeoff (m/s), and g = gravitational constant (9.81 m/s/s).

This calculation of height should not be confused with absolute height, which may differ between subjects due to different center of gravity heights at takeoff. Both Ht and v were used as dependent variables in this study. Pearson product moment correlations were performed between each of the independent variables and both dependent variables.

We subsequently measured one subject during five successive vertical jumps in order to examine the intrasubject variability. The use of only one trial per subject in the main study was based on the assumption that there was very little variability within one subject relative to the variability between subjects (Miller & East, 1976).

Results

The takeoff velocities of the 97 vertical jumps ranged from 1.72 m/s to 3.24 m/s (*M ± SD*, 2.41 ± 0.35 m/s) which resulted in a range in heights of 15.1 cm to 53.6 cm (*M ± SD*, 29.7 ± 10.1 cm). In contrast, the repeated trials of the single subject resulted in a mean takeoff velocity of 2.84 ± 0.04 m/s. The coefficient of variation (standard deviation/mean) was only 1.7% within subjects compared to 14.7% between subjects. This low intrasubject variability was supported by the findings of Miller and East (1976) and was used to justify the selection of only one trial for each of the subjects performing in the remainder of the experiment.

From Equation 3, it can be shown that takeoff velocity and height are monotonically but nonlinearly related; prior to this study it was not known if characteristics of the vertical jump takeoff would be better related to height or to takeoff velocity. It was found that some variables were slightly better related to height and others to velocity. The differences, however, were quite small and height was chosen as the only dependent variable in all subsequent analyses. The correlation coefficients of the 18 independent variables with height are shown in Table 1.

Only six independent variables related significantly to the height achieved. These variables were the maximum force developed (e), the time between this maximum force and takeoff (F), the maximum negative power (l), the maximum positive power (n), the time between this maximum power and takeoff (o), and the ratio of negative impulse to positive impulse (r). The scattergrams of four of these variables are shown in Figure 3.

The high positive correlation between maximum power and height achieved can be seen in Figure 3c. The regression line is given by

$$Ht = -0.081 + 0.075n. \qquad (4)$$

The root mean square error (RMS error) of this regression equation is 2.9 cm, meaning that in general, the maximum height achieved during a given vertical jump can be predicted within 2.9 cm if only the maximum instantaneous power generated during the takeoff phase is known. These results are similar to those of Rosenstein, Frykman, and Rosenstein (1990), who found peak power to be a much better predictor than peak force (r = 0.88 and r = 0.49, respectively). Although these correlations are lower, the values in the present study were normalized to body weight. When Harman et al. (1990) included body weight as a predictor, the correlation of peak power was improved to 0.92. Perrine, Gregor, Munroe, and Edgerton (1978) found a correlation of r = 0.85 for peak power and vertical jump height.
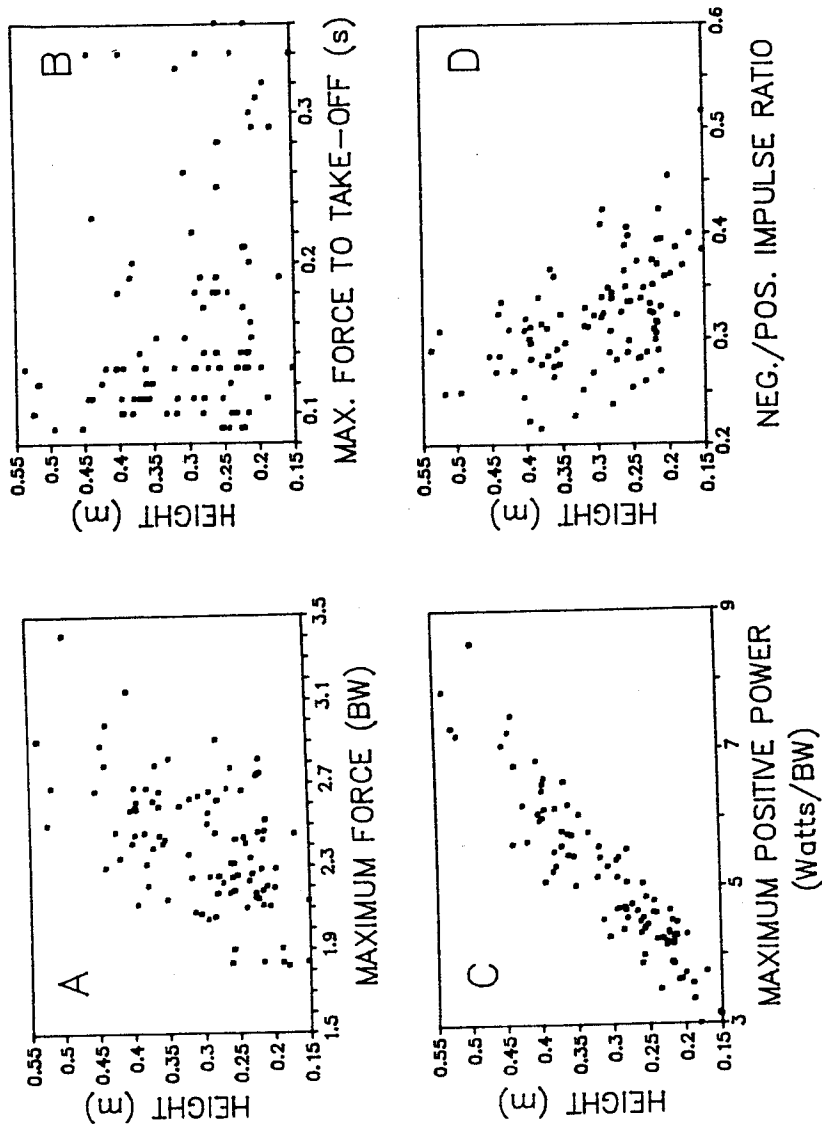
Figure 3 — Scattergrams of vertical jump height versus (a) maximum force, (b) time from maximum force to takeoff, (c) maximum positive power, and (d) negative/positive impulse ratio.

Many of the other predictors shown in Figure 3 demonstrate triangular-shaped scatters. For example, closer examination of Figure 3 shows that the highest jumps generally had high maximum forces but some very poor jumps also had similarly high maximum forces.

The scattergram of the negative/positive impulse ratio versus height (Figure 3d) shows that the smaller the ratio, the higher the jump. It should be pointed out that because this study did not include squat jumps (zero negative impulse), and because previous investigators have found that greater height is achieved in counter movement jumps (i.e., Komi & Bosco, 1978), an inverted-U relationship might exist if the data range were extended to the left. If indeed this were the case, an optimal ratio may be about 0.27, but it should be cautioned that there were also some poor performances with this same ratio.

With the exception of the maximum positive power, many of the single-predictor variables that had triangular-shaped scattergrams seemed to require more information to improve the prediction of height. Multiple linear regression was performed on 17 variables (peak positive power was not included). The best double- and triple-predictor models are shown in Table 2 with the coefficients of determination (r^2) and the RMS errors. The sample size ($n = 97$) was not considered large enough to provide the statistical power to justify more than three predictors.

The best double predictor was the combination of maximum force (e) and the duration of the positive power phase (M). The explained variance was well below that of peak positive power alone ($r^2 = 0.861$). The best combination of three predictors was the duration of the major positive impulse phase (D), the maximum force (e), and the time from maximum negative velocity to the low point (J). The regression equation of the best three-predictor model resulted in an RMS error of 4.8 cm and is given by

$$Ht = -0.86 + 1.51D + 0.35e - 1.69J. \qquad (5)$$

Table 2

The Best Two- and Three-Predictor Statistical Models of Vertical Jump Height

Model			r^2	RMS error (cm)
e	M		0.543	5.4
l	r		0.457	5.8
b	r		0.445	6.1
D	e	J	0.662	4.8
O	e	M	0.637	4.9
l	e	r	0.617	5.0

Note. e = maximum force; M = duration of positive power phase; l = maximum negative power; r = ratio of negative impulse to positive impulse; b = minimum force; D = duration of major positive impulse; J = duration of maximum negative velocity to low point; O = duration from maximum positive power to takeoff.

impulse is necessary but larger amounts are not associated with high jumps. This is supported by the findings of Van Ingen Schenau (1984), who suggested that the purpose of the negative work phase is not so much to store energy but to take up ''the slack of muscle'' at the onset of contraction. The purpose of the countermovement may also be to allow the muscles enough time to reach maximum activation at the joint angles that allow the greatest torque and at a more favorable velocity for force generation (Chapman & Sanderson, 1990; Dowling, 1992). If this is the case, then the negative work phase only needs to be of short duration and the absolute amount of negative work done above a certain minimum is relatively unimportant. This concept was supported by the poor correlation between negative impulse and height jumped even though the countermovement is known to cause significant improvements in vertical jump performance (Asmussen & Bonde-Petersen, 1974; Bosco, Tihanyi, Komi, Fekete, & Apor, 1982; Komi & Bosco, 1978). Furthermore, Bedi, Creswell, Engel, and Nicol (1987) found that increasing the negative work beyond the countermovement by having subjects drop from various heights did not improve jumping performance.

Oddsson (1989) found that a combination of 10 force–time parameters yielded a correlation coefficient of 0.86, which explained 73% of the variability in vertical jumping performance. He concluded, ''If the force–time parameters could be selectively influenced by different types of training programs it would be possible to test an athlete for these parameters and then give him/her a highly specific and individual training program based on his/her actual weaknesses'' (p. 400). Although the correlations were not much different in this study, the conclusions are opposite. When several predictors are required, even if the explained variance is 100%, the interactions of the predictors in causing a good performance cloud the situation tremendously. Even if a certain training program was known to effect peak force, for instance, unless the causal interactions of the other predictors were known, no conclusion could be drawn about the training program's potential to improve jumping performance. The identification of an excellent single predictor such as peak power is better than multiple force–time predictors, but the causal relationships are still unknown.

The inability to determine causal relationships from force–time records is well demonstrated when the arm swing is examined. Payne, Slater, and Telford (1968) claimed that the arm swing improved jump height and caused a second peak in force during the positive impulse phase. In the present study all subjects used an arm swing, but 54 of the 97 subjects had a single peak of force during the positive impulse phase. Shetty and Etnyre (1989) also found that the arm swing improved the jump height, but they obtained single peak forces and they could not determine from their force–time records the reason why the arm swing improved height. Miller (1976) found that the double peak is due to trunk acceleration and the arm swing serves to reduce the depression separating the two peaks. At the present time it is unknown whether the arm swing increases the downward load on the legs in the stretch phase of the stretch-shortening cycle (Khalid, Amin, & Bober, 1989) or simply transfers momentum to the rest of the body near takeoff, or if a combination of both is the cause of the height increase. Recently, Harman et al. (1990) found that no net gain of impulse is achieved via the arm swing but the arm swing enhances the impulse generated by the lower extremities by lengthening the time of force application and taking advantage of the force–velocity relation of muscle.

There was a great deal of variability in the force–time records even when only the best performances were analyzed. A high degree of variability made it difficult to identify symptoms of a poor performance and even more difficult to identify the causes. Although peak instantaneous power is an excellent indicator of jump performance, the causes of low power values are still not known. One reason for the lack of prediction from the force–time record may be due to the anatomical constraint and the transformation of rotation into translation (Van Ingen Schenau, 1989). It has been argued that effective use of biarticular muscles and a proximo-distal sequence of activation prolongs the positive impulse phase that would normally be minimized if all muscles crossed only one joint. Although this may result in many different strategies of muscular activation employed by the subjects in this study and, therefore, account for the lack of prediction from the force–time records, it does not explain the exceptional predictions from the power–time curves.

It was stated in the introduction that recent attempts at establishing causal relationship have employed computer simulations of vertical jumping (Pandy, 1990; Van Soest et al., 1992). The validity of such simulations could be improved if the models were evaluated with typical joint kinetics. The variability in the vertical jump force record was greater than Winter (1984) found for walking. In that study it was found that due to the compensating ability of the multilinked human system, the joint torques were more variable than the vertical ground reaction forces. If this is also true for vertical jumping, then it will be very difficult to establish typical joint kinetic patterns in order to evaluate the accuracy of computer simulation models. Two studies that examined joint kinetics in the vertical jump (Hubley & Wells, 1983; Robertson & Fleming, 1987) disagreed about the amount each joint contributed to the net amount of work done. This disagreement may have been due to large intrasubject variability and should be further examined.

Attempts to determine the causes of good jumping performances have examined different physiological aspects of strength at isolated joints. Jaric et al. (1989) stated that dynamic leg strength was not related to vertical jump performance; this was supported by Genuario and Dolgener (1980), who found that isokinetically tested peak torques at high velocity were better related to vertical jump performance than were torques at low velocity, but neither were good predictors. Perrine et al. (1978) found that peak isokinetic knee extension power was highly correlated ($r = 0.888$) with vertical jump performance. These findings were corroborated by Viitasalo and Aura (1984), who found that strength training with high eccentric and/or concentric loads alone does not improve ''explosiveness.'' They claimed that the training must involve the stretch-shortening cycle and that the rate of isometric force development was better related to jumping performance than simply to the amount of force.

Jaric et al. (1989) have shown that there is almost no relationship between maximum force and the rate of force development, which might partially explain the triangular shape of the scatter plot between height and maximum force that was found in the present study. If rate of force development is also important in the vertical jump (Viitasalo & Aura, 1984), then it is possible that strong subjects with poor rates of force development achieved high peak forces without a good jump performance. Bell and Jacobs (1986) also found a poor relationship between maximum force and rate of force development. If, as mentioned earlier,

the countermovement lessens the effect of rate of force development by allowing time to reach maximum force (Chapman & Sanderson, 1990), then this could explain why in some studies (Bosco et al., 1982; Komi & Bosco, 1978) men and subjects with a high percentage of fast-twitch fibers were thought to utilize less stored elastic energy than women and subjects with a higher percentage of slow-twitch fibers when squat jumps were compared to countermovement jumps.

Adamson and Whitney (1971) objected to the comparison of peak power in the vertical jump with the power output during cycle ergometry by Davies and Rennie (1968). The reason for the objection was that in ballistic movements, the performance is based on force application and time (impulse) and not necessarily on an instantaneous value such as peak power. Adamson and Whitney (1971) correctly pointed out that instantaneous power should not be used for assessing the working capacity of muscle, but the present study has shown that it is highly correlated with performance. In their argument, Adamson and Whitney state that the positive impulse is maximized by "(i) increase of peak force, (ii) increase of pulse duration, (iii) squaring of the pulse—particularly by making the rising phase as steep as possible" (p. 211). In this study, peak force, pulse duration, pulse shape, and even the peak slope of force were all found to be much weaker predictors ($r^2 = 0.269, 0.003, 0.012$, and 0.019, respectively) of performance than peak power ($r^2 = 0.861$).

The peak power may not teleologically be a good measure of the working capacity of any one muscle group or even of all muscles involved in jumping. The peak power delivered to the ground may be an indication of how effectively energy is transferred between body segments in the execution of the movement. Future studies should examine the relationship between peak power of individual muscle groups and the effectiveness of intersegmental power flow with jumping ability to better explain why peak power correlates so well with jumping performance and to clarify the relationship between muscular capacity and technique in the performance of a ballistic skill such as jumping. Other aspects that need to be further investigated include the variability of joint torques and muscle activations and the role of utilization of previously stored elastic energy.

Conclusions

The redundancy of the human musculoskeletal system and the vast variability in individual performances of the vertical jump render the biomechanical force–time curve a rather weak diagnostic tool. There is, however, a very strong positive relationship between peak positive power and vertical jumping ability, which may dictate that athletic training specifically target muscular power, rate of force development, and multisegment coordination rather than muscular strength development alone.

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Extrinsic Feedback and the Learning of Kinetic Patterns in Cycling

Jeffrey P. Broker, Robert J. Gregor, and Richard A. Schmidt

This study evaluated the retention of a cycling kinetic pattern using two different feedback schedules and evaluated the potential for feedback dependency in a continuous-task learning environment. Eighteen inexperienced cyclists rode a racing bicycle mounted to a fixed-fork Velodyne Trainer, with pedal forces monitored by dual piezoelectric transducers. Subjects received right-pedal shear force feedback and a criterion pattern emphasizing "effective" shear. Concurrent feedback (CFB) subjects received concurrent feedback 140 ms after the completion of every other revolution, while summary feedback (SFB) subjects received averaged feedback between trials. All subjects performed 10 retention trials without feedback 1 week later. Both groups improved significantly during practice, and performance decay in retention was negligible. Group differences during all phases were not significant. High CFB group proficiency in retention indicated that the detrimental aspects of frequent feedback were not significant. High SFB proficiency in retention suggests that large changes in kinetic patterning are achievable with relatively few feedback presentations.

Scientific research related to cycling has grown considerably in recent years. In addition, whereas the majority of cycling-related studies conducted 25 years ago focused on global measures of physiological response, cycling research today represents a highly technological discipline, addressing specific topics such as physiological adaptation, musculoskeletal loading, neuromuscular coordination, and optimization of the human/machine system. Recently, an increased emphasis on pedaling techniques has begun, particularly with respect to how they can be modified with practice.

One aspect of cycling research that has important implications for learning, specifically with respect to competitive and rehabilitative applications, involves the modification of pedaling technique through feedback. By presenting kinetic

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