ABSTRACT
González-Badillo, JJ and Marques, MC. Relationship between kinematic factors and countermovement jump height in trained track and field athletes. J Strength Cond Res 24(12): 3443–3447, 2010—Countermovement jump (CMJ) has been extensively used in training, yet kinematic data for a large sample of trained athletes are limited. The aim of this study was to determine the relationship between kinematic factors of CMJ height in a large sample of trained track and field athletes. Forty-eight adult athletes performed 3 maximal CMJ-weighted jumps while ground reaction forces were sampled using a force platform synchronized with a linear transducer. The CMJ height presented significant relations with both eccentric (descending) and concentric (ascending) phases. In addition, strong correlations were observed between CMJ performance and the peak power produced during the concentric phase (r = 0.812–0.851) and with the average power generated in the same phase (r = 0.829–0.870). Finally, maximal negative velocity was low to moderate in its association with CMJ performance (r = 0.57–0.65). The present data contribute important knowledge concerning determinant factors of vertical jump performance that have not been analyzed in trained athletes. As predictors, it is important to observe high values of correlation between the force produced during the concentric and eccentric phases with the height of all the CMJ trials. In this way, our study confirms previous findings in which peak power was shown to be the best predictor of CMJ height. Nevertheless, the moderate but significant predictive value of negative velocity was even more noticeable.

KEY WORDS power, force, impulse, negative velocity

INTRODUCTION
Jumping ability has been studied within the scientific community for decades (2,6–8). More recently, researchers have focused on gaining an understanding of the parameters that can best explain jump performance in several sports (3,4,16). Studies on maximum vertical jump performance so far have identified diverse factors that contribute to vertical jump success, including peak power and vertical velocity (3,4,10,16). However, these studies were not able to identify variables that accurately predict performance (3,4,7,10).

To determine which factors correlate with vertical jump performance, Dowling and Vamos (10) examined 15 kinetic and temporal parameters in 97 trained/untrained men/women and reported that positive peak power was a strong predictor of vertical jump performance. Using positive peak power as a predictor, Dowling and Vamos (10) were able to estimate vertical jump height within 2.9 cm but were unable to determine a causal relationship between any of the other parameters assessed and vertical jump performance. The authors suggested that multisegment coordination may be a more important determinant of vertical jump performance than the ability to generate high peak forces. Ashley and Weiss (5) also observed that peak power was the single best predictor of vertical jump ability in women. Aragon-Vargas and Gross (3) examined within-subject differences in kinematics factors related to vertical jump performance in 8 participants and found that the take-off velocity was a significant predictor and accounted for approximately 60% of explained variation in jump height. Differences in vertical jump technique or coordination may exist between athletes and nonathletes (17), and therefore it would be distinctive to evaluate kinematic parameters during countermovement jump (CMJ) in highly trained individuals.

To our knowledge, there are no studies that have evaluated the relationship between kinematic variables of jumping with CMJ height in trained track and field athletes. Thus, the aim of this investigation was to examine the contribution of force, power, impulse, and velocity with CMJ height in a group of trained male track and field athletes.

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METHODS
Experimental Approach to the Problem
The present study used a cross-sectional experimental design to examine the relationship between kinematic factors during a jump and CMJ height in a group of trained male track and field athletes. All testing was carried out at the completion of the first phase of the outdoor track and field season. Each athlete participated in national and international events during this period and had experience with resistance training. In addition to normal technical and tactical practice sessions (2–3 hr/day timed for 4:00 PM) and weekend competitions, all volunteers were involved in a 16-week resistance training program. Two to 3 resistance training sessions were completed per week and included 2 maximal dynamic strength exercises (bench press and half squat) and 3 power exercises such as power clean, snatch, and weighted CMJs. Consequently, all the athletes were highly trained and familiar with the testing exercise.

Subjects
A group of 48 trained male track and field (sprinters, long and triple jumpers, indoor hard court) athletes (average age 22.5 yr; range 18–28 yr) participated in the study. Included in the sample were 25 Spanish international athletes. Before beginning the study, all participants underwent physical examination and were cleared of any medical disorders that might limit full participation in the investigation. No athlete was found to be taking exogenous anabolic–androgenic steroids or other drugs or substances expected to affect physical performance or hormonal balance during this study. In addition, baseline nutritional status was controlled because all athletes were measured in a track and field training campus. This was controlled by the medical department and by one of the researchers. The study protocol was approved by the research ethics committee, and all volunteers provided informed consent after a verbal explanation of the study procedures and risks associated with participation.

Testing Procedures
Participants were familiar with the testing procedures because they had been performing the exercises as part of their normal training routine. After standardized warm-up, participants performed 3 maximal CMJ trials on a Smith machine while standing on a portable force platform (Isonet, JLML, Madrid, Spain). The bar of the Smith machine had a linear transducer attached to it (Isocontrol, JLML, Madrid, Spain), which was synchronized with the force platform. The force platform was connected to a portable computer and recorded data at a sample rate of 1,000 Hz. The rotary encoder of the linear transducer recorded the position and direction of the bar to within an accuracy of 0.0002 m. Peak power was calculated by the product of velocity taken with the linear transducer and the ground reaction force measured by the portable force platform.

Participants stood on the Smith machine and rested the bar (17 kg) on their shoulders. Participants initiated the CMJ from a standing position and performed a crouching action followed immediately by a jump for maximal height. Hands remained holding on to the bar for the entire movement to maintain contact between the bar and shoulders. Three minutes of rest were provided between each trial to minimize the likelihood of fatigue.

For the propose of this study, the CMJ was divided into the following 3 segments. The eccentric segment was defined as being from the initiation of movement until maximum negative velocity occurred (i.e., the center of mass acceleration was 0 m/s/s). The transition segment was defined as being from the moment after maximum negative velocity until the end of the eccentric phase when velocity is 0 m/s. The concentric segment was defined as being from the moment after the end of the eccentric phase until maximal positive velocity was achieved.

Statistical Analyses
Standard statistical methods were used for the calculation of means and SD. Intraclass correlation coefficient (ICC) was used to determine between-subject reliability of jumping tests (Table 1). Within-subject variation for all tests was determined by calculating the coefficient of variation (CV) as outlined by Hopkins (13). Correlations were determined using Pearson’s r. Statistical significance was accepted at p ≤ 0.05 for all analysis.

RESULTS
The present study found important relationships between CMJ height and several metrics of strength as measured with

| Table 1. Intraclass correlation coefficients (ICC) and coefficient of variation (CV) for linear transducer and force platform.* |
|-----------------------------------------------------------|
| **Linear transducer parameters**                          | **ICC (range)** | **CV (%)** |
| RFD<sub>max</sub> (N × s<sup>−1</sup>)                    | 0.94 (0.88–0.97) | 17 |
| Peak force (N)                                            | 0.98 (0.97–0.99) | 3.6 |
| RFD<sub>max</sub> at peak force (N × s<sup>−1</sup>)      | 0.93 (0.87–0.96) | 15.7 |
| **Force platform parameters**                             |                |        |
| Concentric peak force (N)                                 | 0.97 (0.96–0.98) | 6.4 |
| Concentric peak power (W)                                 | 0.99 (0.98–0.99) | 5.8 |
| Maximum negative velocity (m/s)                           | 0.87 (0.8–0.93)  | 9.9 |

*RFD<sub>max</sub> = maximum rate of force development.
the force platform (Table 2). The vertical jump height presented significant relations with both eccentric (descending) and concentric (ascending) phases. In addition, strong correlations were observed between CMJ performance and the peak power produced during the concentric phase \((r = 0.812-0.851, p < 0.001)\) with the average power generated during the same phase \((r = 0.829-0.870, p < 0.001)\). Finally, maximum negative velocity was low to moderate in association with CMJ performance \((r = 0.57-0.65, p < 0.01)\).

**Discussion**

The purpose of the present study was to examine the factors causally related to the CMJ performance of trained male athletes involved in track and field running and jumping events. To the best of our knowledge, this is the first study that examined in this much depth the variables that explain CMJ performance in trained track and field athletes. This study had to measure the different variables with great instrumental accuracy and high reliability. Moreover, the number of subjects was considerable (approximately 50), and these subjects were part of the population of trained sportsmen, which permits us to have greater confidence in our results.

The data observed in this study showed that both eccentric and concentric phases are poor indicators of CMJ performance because both explain approximately only 9–16% of the height reached in the CMJ. Our laboratory (unpublished data) observed that the concentric time was significantly related to CMJ height \((r = -0.57, p < 0.05)\) to \(r = -0.87, p < 0.001)\) in an intrasubject analysis of a group of 10 trained athletes who performed a series of 10 CMJs. The same laboratory was able to observe (unpublished data) that subjects who attained higher eccentric times tended to jump transition segments and CMJ height (from \(r = 0.280, \text{not significant}\) to \(r = 0.432, p < 0.05\)). These results are similar to those published by Aragón-Vargas and Gross (3), who also found a weak positive relationship between vertical jump and negative impulse \((0.35 < r < 0.7)\). These outcomes are relatively weak, suggesting that the negative impulse is not a strong predictor of CMJ height. The present study contradicts the findings reported by Ferragut et al. (11) showing the importance of the negative impulse in predicting CMJ. Nevertheless, it should be kept in mind that the samples used by Ferragut et al. (11) comprised subjects from different sports, levels, and sexes, which may account for the variation in results as compared with our study. It is important to note that although the force developed during a jump can vary between subjects, the time to achieve this force during takeoff is more stable. Thus, a certain discrepancy should be expected between the CMJ height measured by impulse and the jump performance obtained by flight time.

In the present study, concentric peak force was significantly related with CMJ performance for each trial \((r = 0.70-0.82, p < 0.001)\). Nevertheless, Cordova and Armstrong (9) did not find any relation between the peak force applied on the force platform and jump performance with a single leg. According to these authors, the reduced number of subjects tested \((n = 19)\) could be an explanation for this lack of relation. In addition, although they found a high ICC \((0.94)\), the CV was excessively high, which is a negative indicator for the reliability of the metrics and might have influenced the results. This problem is not apparent in the present study because the reliability of our results was much higher. Furthermore, Cordova and Armstrong (9) used different protocols to measure jump performance because they only

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**Table 2. Correlations (r) between countermovement jump (CMJ) height and selected kinematic variables.**

| Metric                          | CMJ 1, r  | CMJ 2, r  | CMJ 3, r  |
|---------------------------------|-----------|-----------|-----------|
| Eccentric time (ms)             | -0.335*   | -0.297*   | -0.328    |
| Concentric time (ms)            | -0.404†   | -0.457‡   | -0.436†   |
| Eccentric impulse (N/s)         | 0.280     | 0.412‡    | 0.384‡    |
| Transition impulse (N/s)        | 0.397‡    | 0.367‡    | 0.388‡    |
| Concentric impulse (N/s)        | 0.427‡    | 0.482‡    | 0.379‡    |
| Eccentric force (N)             | 0.671     | 0.340*    | 0.584‡    |
| Transition force (N)            | 0.768‡    | 0.741‡    | 0.792‡    |
| Concentric force (N)            | 0.701‡    | 0.799‡    | 0.825‡    |
| Eccentric peak power (W)        | 0.579‡    | 0.684‡    | 0.678‡    |
| Transition peak power (W)       | 0.423‡    | 0.510‡    | 0.660‡    |
| Concentric peak power (W)       | 0.812‡    | 0.839‡    | 0.851‡    |
| Eccentric average power (W)     | 0.604‡    | 0.582‡    | 0.684‡    |
| Transition average power (W)    | 0.614‡    | 0.600‡    | 0.754‡    |
| Concentric average power (W)    | 0.829‡    | 0.857‡    | 0.870‡    |
| Maximum negative velocity (m/s) | 0.572‡    | 0.542‡    | 0.649‡    |

Significance: *p < 0.05; †p < 0.01; ‡p < 0.001.
measured the jump with the right leg. Thus, other factors such as balance and protocol familiarization could have influenced the data. Finally, the impulse measured during the vertical jump was a poor reliability indicator (9).

According to several authors (1,2,14,15), power output generation is one of the key predictors of performance in distinct athletic movements. In this context, CMJ height has been shown to have important correlations with average and peak power during the concentric phase of the vertical jump. The present study found that the average power produced in CMJ is an important variable in predicting CMJ performance ($r = 0.81-0.85$, $p < 0.001$). These results agree with others previously published. Dowling and Vamos (10) observed a strong association ($r = 0.928$, $p > 0.01$) between CMJ height and peak power during the concentric phase of the jump. Ashley and Weiss (5) also found that peak power ($r = 0.80$, $p < 0.05$ to $r = 0.83$, $p < 0.01$) was the variable most associated with vertical performance, albeit for the squat jump. In addition to peak power, Aragón-Vargas and Gross (3, 4) detected an important relation to the average power produced. In addition, Harman et al. (12) found that peak power was significantly associated with CMJ height when subjects used the arms ($r = 0.88$, $p < 0.05$), whereas the average power had a smaller relation to the height of the same jump ($r = 0.54$, $p < 0.05$). These studies suggest clearly that the power produced in the vertical jump is a factor strongly predictive of height attainment in the CMJ. Nevertheless, these data were not the most significant aspects of the present or previously cited studies. In fact, peak power is directly dependent on velocity (power = force $\times$ velocity). The peak power produced during jumping performance is always attained when the velocity is close to maximum value during the concentric phase, and this maximum velocity is intimately related to the takeoff speed (takeoff speed always being somewhat lower than maximum velocity), which is well known to determine vertical jump height. Therefore, to state that the vertical jump depends directly on takeoff speed (by definition) is equivalent to stating that it depends directly on peak power. Nevertheless, the confirmation that peak power is an excellent predictor is important, and is more important if associated with other variables (10). Although these authors add that the relation between the peak of power and the jump height is uncertain, it remains true that the power reached during the concentric phase of the vertical jump is one of the best predictors of CMJ performance.

To date, and to the authors’ knowledge, only Dowling and Vamos (10) and the present study have investigated the relation between maximum negative velocity and jump performance. The results of these 2 investigations appear to indicate that maximum negative velocity can also be a good predictor of the CMJ performance. Both studies found a positive correlation, indicating that those subjects reaching a greater negative velocity will tend to jump higher. The relations found by us ($r = 0.54-0.65$, $p = 0.000$) are higher compared with those observed by Dowling and Vamos (10) ($r = -0.3$, $p > 0.01$). In our case, this relation is within a specific range of $-0.8$ m $\cdot$ s$^{-1}$ and $-2.2$ m $\cdot$ s$^{-1}$ that constitutes the margins of the values of velocity that were found. Thus, a tendency exists suggesting that the greater the velocity in the eccentric phase of the movement, the greater will be the height of the jump, provided that the velocities fall within the range indicated.

The present data contribute important knowledge to the determinant factors found in vertical jump performance that, to date, have not been analyzed in large samples of trained athletes. As predictors, it is important to observe high values of correlation between the force produced during the concentric and eccentric phases with the height of all the CMJ trials. Our study also confirms previous findings in which peak power was shown to be the best predictor of vertical jump height. Nevertheless, the moderate but significant value that accrued to negative velocity was perhaps more noticeable.

**Practical Applications**

Improvement in jumping ability is a major training goal for many sports, and CMJ is a well-recognized training exercise used to achieve this. In individual sports such as track and field, athletes must improve jump performance to achieve better personal best records, especially long and triple jump specialists. Nevertheless, a team sport athlete must jump higher than, and, moreover, faster than, his or her opponent. These findings should be interpreted with caution because correlations do not signify causation, so additional research is required to clarify whether improvements in upper-body strength, velocity, or power as a result of resistance or plyometric training will indeed improve jumping ability in trained track and field athletes.

Coaches often express the need to have access to an easily administered test that will allow assessment of the athlete without actually measuring the sport performance. This study represents one approach to assessing the physical state of elite track and field athletes that might satisfy this need.

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