POWER-TIME, FORCE-TIME, AND VELOCITY-TIME CURVE ANALYSIS OF THE COUNTERMOVEMENT JUMP: IMPACT OF TRAINING

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ABSTRACT

Cormie, P, McBride, JM, and McCaulley, GO. Power-time, force-time, and velocity-time curve analysis of the CMJ: impact of training. *J Strength Cond Res* 23(1): 177–186, 2009—The purpose of this investigation was to examine the impact of training on the power-, force-, and velocity-time curves of the countermovement jump (CMJ) through both cross-sectional and longitudinal comparisons. The most novel aspect of this study was the analysis of these curves for the entire movement at a sampling frequency of 386–506 Hz averaged across 30 subjects. Thirty subjects, all men, participated in this investigation and included 12 athletes and 18 untrained men. Two major comparisons were conducted: 1) an acute, cross-sectional examination comparing experienced jumpers (jump height > 0.50 m; $n = 12$ men's athletes) with nonjumpers (jump height < 0.50 m; $n = 14$ untrained men), and 2) a longitudinal examination comparing performance before and after 12 weeks of power training (training group $n = 10$ untrained men; control group $n = 8$ untrained men). Data obtained from the baseline testing session of 14 subjects involved in the longitudinal study were used for the cross-sectional examination to represent the nonjumper group. The cross-sectional examination revealed significant ($p \leq 0.05$) differences between jumpers and nonjumpers in peak performance variables (i.e., peak power, force, velocity, displacement) as well as over a range of time points throughout the power-, force-, velocity-, and displacement-time curves of the CMJ. Similar results were observed in the longitudinal examination, with power training eliciting significant changes to peak performance variables as well as significant changes to the power-, force-, velocity-, and displacement-time curves over a range of time points throughout the CMJ. This study illustrates that training status not only influences the peak performance variables of the countermovement jump but also impacts the shape of the power-, force-, velocity-, and displacement-time curves throughout the movement. Because analysis of peak performance variables offers little insight into how adaptations have occurred after training, examination of the changes to the power-, force-, velocity-, and/or displacement-time curves offers a simple yet powerful monitoring technique that practitioners can use to gain insight into the precise nature and timing of adaptations to training.

KEY WORDS power training, countermovement jump, stretch-shorten cycle, jump height

INTRODUCTION

A multitude of evidence exists documenting the influence of strength and power training on jumping performance. Much of this research has used peak and/or mean power, force, velocity, and displacement as variables indicative of physiological adaptations to a particular intervention (1,4,11,12,15,21,22,25,28). Although these variables are important markers of adaptation, they are limited in their ability to delineate the exact nature and timing of changes throughout the movement. Very little cross-sectional or longitudinal data exists concerning the influence of training on power, force, velocity, or displacement throughout the full course of a countermovement jump (CMJ). It is hypothesized that changes to peak and average performance measures result from variations in the shape of the power-time, force-time, and velocity-time curves.

Through both cross-sectional and longitudinal examinations, the influence of training on peak and average power output during jumping movements has been well established (1,4,11–13,21,22,25,28). Cross-sectional examinations have revealed higher peak power outputs during a variety of jumping movements in individuals with superior levels of lower-body strength (4,21,25). Furthermore, significant differences in peak power output have been shown to exist between elite athletes of equivalent strength who compete in different sports (i.e., Olympic lifting verses power lifting) (21). Cross-sectional evidence indicating that the ability to produce power varies according to specific training

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modalities has been paralleled by findings of numerous longitudinal examinations. Improvements in power output during the CMJ have occurred after training involving high movement velocities such as power or plyometric training (12,13,22,28). These improvements were coupled with changes in muscle activation patterns, leading to the suggestion that a variety of neuromuscular factors are involved with the production of power (22). Additionally, heavy resistance training (loads $\geq$ 80% of one-repetition maximum [1RM]) has also been shown to elicit significant improvements in power output as well as changes in muscle activation (2,15,22,28).

Well-trained strength-power athletes have the ability to generate significantly greater peak force outputs during jumping movements in comparison with untrained individuals (21). Furthermore, force output at the time that peak power occurred during a CMJ has been shown to be higher in strength-power athletes than in endurance-trained athletes (4). In contrast to the cross-sectional findings, McBride et al. (22) observed no improvement in peak force output during a CMJ with 30% of squat 1RM after an 8-week training program involving light-load, high-velocity jump squats (30% of 1RM). Few longitudinal power training studies have reported adaptations in peak force output during jumping movements, but mixed results have been documented involving peak force output during maximal isometric tests of the lower body. However, improvements in the rate of force development during both jumping and isometric tests after power training have been a common observation throughout the literature (10,11,14).

Both cross-sectional and longitudinal comparisons have demonstrated training-induced improvements in peak velocity and displacement during a variety of jumping movements. Superior peak velocities have been achieved by athletes in comparison with untrained individuals as well as by athletes involved in high-velocity training versus training involving lower movement velocities (21). Similarly, improvement in peak velocity during a CMJ occurred after power training programs that required athletes to achieve high movement velocities (i.e., light-load ballistic movements) (22). These outcomes have been supported by a multitude of investigations demonstrating improved CMJ displacement after various lower-body power, plyometric, and weight training programs (11–13,19,22,26,28).

The literature is fraught with evidence of training-induced improvements in peak performance variables, yet the sources of these adaptations remain unclear. Whereas changes in muscle activation and strength levels indicate both neuromuscular and structural adaptations to training, tracking changes in peak power, force, velocity, and displacement fails to delineate exactly how improvements in performance occur. Consequently, the manner in which such physiological adaptations influence performance remains unknown. Similarly, the investigation of these variables limits the identification of possible mechanical changes in technique and other biomechanical factors that may influence performance. In addition to variations in peak power output, the shape of the power-time curve during vertical jumping is hypothesized to differ between elite and nonathletes as well as before and after power training. After training, the gradient of the power-time curve during the concentric phase may increase as a result of improved acceleration throughout the movement. The source of this improved acceleration may be the ability of trained athletes to generate additional force at the start of the concentric phase, thus increasing the impulse, velocity, power, and displacement of the jump (3,18). These theoretical differences stem from the neuromuscular adaptations evident with prolonged strength-power training including increased cross-sectional area of type II fibers, selective motor unit recruitment, improved firing frequency, and synchronization (9,16,19,20,24). Because no previous publications have conducted temporal phase analyses of any explosive movements, these hypotheses are yet to be tested.

The purpose of this investigation was to examine the impact of training on the power-, force-, velocity-, and displacement-time curves of the CMJ through both cross-sectional and longitudinal comparisons. Temporal phase analyses of the power-, force-, velocity-, and displacement-time curves throughout the entire jump are theorized to provide novel insights into the nature of the adaptations to strength and power training. Additionally, these analyses may confer a deeper understanding of the biomechanical mechanisms involved with improving jumping performance. The use of averaged power-, force-, and velocity-time curves from 30 subjects sampled at a high resolution (sampling frequency ranged from 386 to 506 Hz across the curves) allowed the testing of these theories.

METHODS

Experimental Approach to the Problem

This investigation involved two subexaminations: 1) a cross-sectional examination of the impact of training on the power-, force-, velocity-, and displacement-time curves of a CMJ involving the comparison of experienced jumpers (max jump height $>$0.50 m; $n = 12$ athletes) and nonjumpers (max jump height $<$0.50 m; $n = 14$ untrained men), and 2) a longitudinal examination of the impact of training on the power-, force-, velocity-, and displacement-time curves of a CMJ after 12 weeks of lower-body power training ($n = 10$ untrained men for the experimental group and $n = 8$ untrained men for the control group). Data obtained from the baseline testing session of 14 subjects involved in the longitudinal study were used for the cross-sectional examination to represent the nonjumper group (i.e., 14 of the 18 men involved in the training study also participated in the acute, cross-sectional study).

Subjects

Thirty subjects, all men, participated in this investigation. The sample comprised 12 athletes competitive in Division I football (specifically, running backs and wide receivers) or track and field (specifically, sprinters and long jumpers) and 18 men not involved in any formal sports or resistance training. Subject characteristics broken down by comparison are displayed in Table 1 (control group used in longitudinal comparison characteristics: age: 20.2 ± 2.9 years; height: 175.7 ± 4.5 cm; body mass: 85.5 ± 24.0 kg; body fat: 15.7 ± 7.3%; squat 1RM: 116.3 ± 30.3 kg; squat 1RM–body mass ratio: 1.4 ± 0.3). The participants were notified about the potential risks involved and gave their written informed consent, approved by the institutional review board at Appalachian State University.

Procedures

Cross-Sectional Examination. Subjects completed a single testing session that commenced with the assessment of maximal dynamic strength in the squat. A 1RM was estimated for each subject based on body weight and training experience, with the subject then performing a series of warm-up sets and several maximal lift attempts until a 1RM was obtained (29). During a 20-minute recovery period, anthropometric measures were assessed (height, weight, body composition, and three-site skinfold: chest, abdomen, thigh). After the recovery period, vertical jump performance was assessed. Each participant set up for the CMJ in a standing position while holding an unweighted plastic barbell across the shoulders. After instruction, subjects initiated the CMJ via a downward countermovement to a visually monitored knee angle of approximately 90°. Participants were instructed to keep constant downward pressure on the barbell throughout the jump and were encouraged to reach a maximum jump height with every trial in an attempt to maximize power output (2). The bar was not to leave the shoulders of the subject. If these requirements were not met, the trial was repeated. Subjects completed a minimum of two trials, with subsequent trials required if performance was not consistent (peak power within 5% of a previous trial qualified as consistent). Adequate rest was given between all trials (3 minutes).

Longitudinal Examination. Subjects were randomly assigned to either a power training group ($n = 10$) or a control group ($n = 8$). All subjects underwent the testing protocol used for the cross-section examination before commencing training (baseline) and after 12 weeks (posttesting). The power training sessions involved a 5-minute bicycle warm-up followed by two sets of six jump squats at approximately 70% of maximum jump height. Subjects then performed seven sets of six maximal effort jump squats separated by 3-minute rests. Jump squats were performed at the load that maximized peak power output (body mass only; approximately 30% of maximal dynamic strength, or 0% of 1RM) (7,21,25). Subjects were instructed to perform each repetition as explosively as possible to maximize power output (2). Intensity was modified for each session so that an audible beep was heard by subjects during jumps that reached 98% of the maximal power output of their previous training or testing session. Subjects completed three training sessions during 14 days in the first 6 weeks and progressed to training twice per week after the sixth week, in adherence with the overload principle (23). As a limitation of the current investigation, it must be noted that this training program may not mimic those used on a daily basis by strength and conditioning coaches. The posttesting session was conducted 4–7 days after the previous training session. The control group was instructed not to make any changes to their current daily activity throughout the length of the study.

Data Collection Procedures. All testing was performed with the subjects standing on a force plate (BP6001200, AMTI, Watertown, Mass) while holding an unweighted (plastic) barbell across their shoulders. The right side of the barbell was attached to two linear position transducers (LPTs) (PT5A-150, Celesco Transducer Products, Chatsworth, Calif). The LPTs were located above-anterior and above-posterior to the subject and, when attached to the bar, resulted in the formation of a triangle, which allowed for the calculation of vertical and horizontal displacements (through

TABLE 1. Subject characteristics of experimental participants in the cross-sectional (jumpers $n = 12$; nonjumpers $n = 14$) and longitudinal examinations ($n = 10$).

	Cross-sectional		Longitudinal	
Subject characteristics	Jumpers (JH > 0.5 m)	Nonjumpers (JH < 0.5 m)	Baseline	Posttraining
Age (years)	21.2 ± 1.5	21.6 ± 2.8	22.1 ± 3.2	22.1 ± 3.2
Body mass (kg)	85.2 ± 14.8	79.4 ± 17.3	81.6 ± 18.8	80.9 ± 19.1
Height (cm)	176.9 ± 5.3	176.2 ± 9.1	176.7 ± 8.4	176.7 ± 8.4
Body fat (%)	10.3 ± 4.4*	16.2 ± 5.2	16.7 ± 8.1	15.7 ± 8.2
Squat 1RM (kg)	164.0 ± 26.8*	108.9 ± 22.1	107.5 ± 21.8	109.3 ± 16.3
Squat 1RM to body mass ratio	1.9 ± 0.2*	1.4 ± 0.3	1.4 ± 0.3	1.4 ± 0.3

*Significant difference ($p \leq 0.05$) between jumpers and nonjumpers.

trigonometry involving the measurement of displacement and known constants). The combined retraction tension of the LPTs was 16.4 N; this was accounted for in all calculations. Analog signals from the force place and LPTs were collected for every trial at 1000 Hz using a BNC-2010 interface box with an analog-to-digital card (NI PCI-6014, National Instruments, Austin, Tex). Custom programs designed using LabVIEW (Version 7.1, National Instruments) were used for recording and analyzing the data. This data collection methodology has been validated previously (6), and test-retest reliability for maximal peak power output in the jump squat was consistently $r \geq 0.95$ in our laboratory.

Data Analysis Procedures. Signals from the two LPTs and the force plate underwent rectangular smoothing with a moving average half-width of 12. From laboratory calibrations, the LPTs and force plate voltage outputs were converted into displacement and vertical ground reaction force, respectively. Vertical velocity was derived from the displacement and time data, and vertical ground reaction force was measured directly by the force plate. Power was calculated as the product of the vertical velocity and force data. Force and power were expressed relative to body mass to account for any differences in body mass between experimental groups. Variables were assessed in both the eccentric and concentric phases, which were defined as a) eccentric phase–the portion of the jump squat before takeoff in which the change in displacement is negative, and b) concentric phase–the portion of the jump squat before takeoff in which the change in displacement is positive. Peak power (PP), peak force (ConPF), peak velocity (PV), and peak displacement (PD) were determined as the maximal values achieved during the concentric phase of the jump. Peak force during the eccentric phase (EccPF) was determined as the maximal force value achieved during the eccentric phase of the jump.

Rate of force development (RFD) was assessed in both the eccentric and concentric phases as follows: a) eccentric RFD–from the initiation of the eccentric phase to the end of the eccentric phase (i.e., initiation of the countermovement to the end of the downward phase), and b) concentric RFD–from the initiation of the concentric phase to the point at which ConPF occurred. The rate of power development (RPD) was also assessed from the initiation of the concentric phase to PP. Acceleration of the system during the concentric phase of the movement was calculated using a second-order derivative of the displacement data. The analyses of these variables (RFD, RPD, and acceleration) were based on the raw curve of each subject and allowed for quantitative comparisons to be made between the gradients of the normalized force-time, power-time, and velocity-time curves, respectively. Intrasubject test-retest reliability for eccentric RFD, concentric RFD, RPD, and acceleration during the CMJ were consistently $r \geq 0.79$, $r \geq 0.97$, $r \geq 0.99$, and $r \geq 0.94$, respectively.

To test the possibility that training may influence the time at which peak power, force, and/or velocity were achieved, a series of coupling variables were assessed by overlaying the power-, force-, velocity-, and displacement-time curves and examining the time between peaks (Figure 1). Additionally, the force and velocity output at the time in which peak power occurred was also examined (i.e., force at PP, velocity at PP). Total work was calculated through integrating the power-time curve from the beginning of the countermovement, through the concentric phase, until the power output reached zero. Similarly, total power was determined by integrating the area under the force-velocity loop from the beginning of the countermovement, through the concentric phase, until the force output reached zero.

Temporal phase analyses of the jumps were conducted through the following process. The power-, force-, and velocity-time curves from all subjects were selected from the beginning of the eccentric phase, through the concentric phase, to the point at which each variable reached zero. The displacement-time curve was selected from the beginning of the eccentric phase up to peak displacement. Using a custom-designed LabVIEW program, the number of samples in each individual curve was then modified to equal 500 samples by changing the time delta (dt) between samples and resampling the signal (dt = number of samples in the original signal/500). The sampling frequency of the normalized signals was calculated according to the following equation:

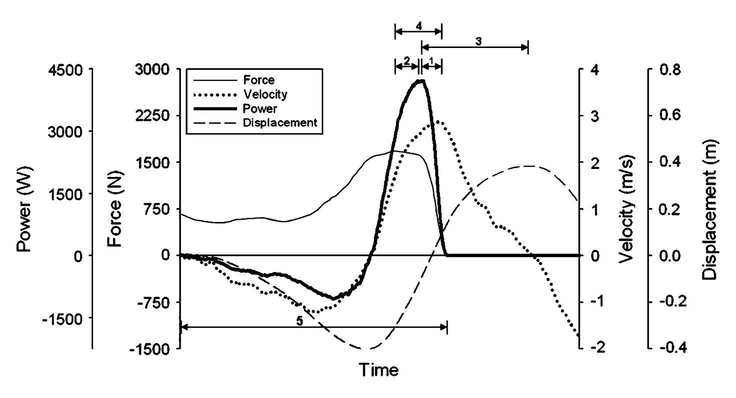

Figure 1. The power-, force-, velocity-, and displacement-time curves during a representative trial of a countermovement jump (CMJ). Coupling variables are indicated by the numbered arrows: 1 = time between peak power and peak velocity; 2 = time between peak power and peak force; 3 = time between peak power and peak displacement; 4 = time between peak force and peak velocity; 5 = time from beginning of movement to takeoff.

$$\text{Normalized sampling frequency (Hz)} = \frac{1\ \text{second}}{\left[\frac{(\text{number of samples in original signal})}{(\text{number of samples in normalized signal})}\right] \times [\text{seconds per sample}]}$$

Consequently, the sampling frequency of the modified signals was then equivalent to 500 ± 97, 500 ± 97, 386 ± 60, and 393 ± 64 Hz for the power-, force-, velocity-, and displacement-time curves, respectively. This resampling allowed for all power, force, velocity, or displacement curves to be expressed over equal periods of time (i.e., the 500 samples represented relative time [from 0 to 100%] taken to complete the jump). In other words, the various data sets are normalized to time so that data could be pooled. Each sample of the normalized power-, force-, velocity-, and displacement-time curves was then averaged across all subjects involved with that particular examination, resulting in averaged curves with high resolution (sampling frequency of 386–506 Hz). This allowed for comparisons between experimental groups at each time point throughout the movement. Intrasubject test-retest reliability for power-, force-, velocity-, and displacement-time curves during the CMJ were consistently $r \geq 0.94$, $r \geq 0.90$, $r \geq 0.89$, and $r \geq 0.92$, respectively.

Statistical Analyses

Independent-sample *t*-tests were used for comparisons between jumpers and nonjumpers. The general linear model with repeated-measures analysis of variance and Bonferroni post hoc tests were used to determine the impact of power training on jump performance variables and whether any differences existed between the power training and control groups. Intergroup differences throughout the power-, force-, velocity-, and displacement-time curves were assessed through a general linear model with repeated-measures analysis of variance. Bonferroni post hoc tests were used to determine the locations of any differences along the curves. The assumptions for linear statistics were met, and statistical significance for all analyses was defined by $p \leq 0.05$. All statistical analyses were performed using SPSS version 12.0 (SPSS Inc., Chicago, Ill).

RESULTS

Cross-Sectional Examination

Jumpers displayed significantly greater PP, ConPF, EccPF, PV, PD, RPD, acceleration, force at PP, and velocity at PP than nonjumpers (Table 2). Time between PP and PD was significantly longer for jumpers, with no difference existing between the other coupling variables (Table 2). Analysis of the power-, force-, velocity-, and displacement-time curves revealed significant differences between the jumpers and nonjumpers throughout the movement (Figure 2). Significant differences between jumpers and nonjumpers existed during the following phases of the CMJ in power from 90.6 to 99.8% of normalized time, force from 95.0 to 98.0% of normalized time, velocity from 77.0 to 78.0% and 85.8 to 92.2% of normalized time, and displacement from 85.4 to 100% of normalized time. Differences in training also affected the work conducted during the jump in that jumpers displayed significantly greater work than nonjumpers (Figure 3a, Table 2). Similarly, significantly more area under the force-velocity loop during the CMJ (i.e., total power) was observed in jumpers when compared with nonjumpers (Table 2).

Longitudinal Examination

No differences existed in any of the performance variables between the power training group and the control group at baseline. After training, PP, EccPF, PV, PD, concentric RFD, eccentric RFD, and velocity at PP improved significantly (Table 2). No differences existed between baseline and posttraining tests in the control group (control group data at baseline vs. posttesting: PP 4497 ± 888 vs. 4741 ± 1058 W [$p = 0.68$]; ConPF 1731 ± 390 vs. 1731 ± 395 N [$p = 0.90$]; PV 3.03 ± 0.24 vs. 3.02 ± 0.11$\text{m}\cdot\text{s}^{-1}$ [$p = 0.89$]; PD 0.42 ± 0.05 vs. 0.41 ± 0.05 m [$p = 0.67$]). Power training resulted in improvements throughout the power-, force-, velocity-, and displacement-time curves after power training (Figure 4). Significant differences between baseline and posttraining tests existed during the following phases of the CMJ in power from 29.2 to 54.6% and 60.4 to 97.4% of normalized time; force from 0.0 to 16.6%, 32.2 to 62.0%, and 70.8 to 81.4% of normalized time; velocity from 15.2 to 39.6% and 57.2 to 78.8% of normalized time; and displacement from 20.4 to 57.8% and 83.4 to 100% of normalized time. Similarly, the area under the force-velocity loop (i.e., total power) of the CMJ improved significantly from baseline to posttesting (Figure 3b, Table 2). However, no significant changes to the total work of the jump were observed after power training (Table 2).

DISCUSSION

On the basis of temporal phase analyses of the CMJ, it is evident that training not only influences peak performance variables but also elicits changes in the shape of the power-, force-, velocity-, and displacement-time curves throughout the entire movement. Using averaged curves with high resolution (386–506 Hz; $n = 30$), the current examination of power, force, and velocity output across the duration of the CMJ provides novel information concerning differences between well-trained athletes and novices. Furthermore, these analyses offer important insights into the physiological adaptations to power training and the biomechanical mechanisms involved with improvements in peak performance variables during the CMJ.

As expected, the cross-sectional examination revealed that jumpers displayed superior peak performance variables (i.e., PP, PF, PV, PD) in comparison with nonjumpers during the CMJ (4,21,25). The general shape of the

Table 2. The impact of training on the performance and coupling variables of a countermovement jump (CMJ).

Performance and coupling variables	Cross-sectional		Longitudinal	
	Jumpers (JH > 0.5 m)	Nonjumpers (JH < 0.5 m)	Baseline	Posttraining
Peak power (W/kg)	71.74 ± 10.69*	55.89 ± 7.96	57.71 ± 6.57	70.19 ± 11.46†
Peak concentric force (N/kg)	23.39 ± 2.95*	20.96 ± 1.73	20.46 ± 1.18	22.22 ± 3.01
Peak eccentric force (N/kg)	20.80 ± 4.01*	18.99 ± 1.80	18.98 ± 2.01	21.37 ± 3.57†
Peak velocity (m/s)	3.64 ± 0.26*	3.02 ± 0.30	3.14 ± 0.31	3.66 ± 0.34†
Peak displacement (m)	0.58 ± 0.05*	0.43 ± 0.04	0.45 ± 0.05	0.52 ± 0.08†
Concentric rate of force development (N/kg/s)	23.79 ± 2.43	25.34 ± 9.72	21.82 ± 10.03	42.21 ± 14.34†
Eccentric rate of force development (N/kg/s)	32.93 ± 16.02	32.61 ± 13.21	32.96 ± 14.83	55.36 ± 26.79†
Concentric rate of power development (W/kg/s)	348.08 ± 82.57*	248.70 ± 78.80	250.49 ± 61.69	265.38 ± 67.08
Acceleration (m/s^2)	13.67 ± 2.01*	10.65 ± 2.24	11.27 ± 1.96	12.35 ± 2.28
Force at peak power (N/kg)	20.80 ± 2.30	20.07 ± 1.96	19.65 ± 0.86	19.90 ± 2.00
Velocity at peak power (m/s)	3.31 ± 0.23*	2.78 ± 0.30	2.93 ± 0.30	3.51 ± 0.28†
Work (J/kg)	6.02 ± 1.14*	4.63 ± 0.71	4.67 ± 0.67	5.15 ± 1.24
Area under the force-velocity loop (W/kg)	93.61 ± 16.74*	68.79 ± 14.12	72.55 ± 13.04	93.81 ± 21.08†
Time from beginning of movement to takeoff (s)	0.98 ± 0.16	1.00 ± 0.17	1.01 ± 0.17	1.01 ± 0.15
Time between peak power and peak velocity (s)	0.05 ± 0.02	0.06 ± 0.02	0.05 ± 0.02	0.03 ± 0.03
Time between peak power and peak force (s)	−0.13 ± 0.12	−0.10 ± 0.14	−0.06 ± 0.10	−0.16 ± 0.17
Time between peak power and peak displacement (s)	0.37 ± 0.03*	0.33 ± 0.02	0.34 ± 0.02	0.36 ± 0.02
Time between peak force and peak velocity (s)	0.18 ± 0.12	0.15 ± 0.14	0.11 ± 0.10	0.19 ± 0.16

*Significant difference ($p \leq 0.05$) between jumpers and nonjumpers; †Significant improvement ($p \leq 0.05$) after 12 weeks of power training.

power-, force-, velocity-, and displacement-time curves were similar between the jumpers and nonjumpers; however, several important differences did exist. Jumpers were able to produce higher peak power outputs over the same period of time as nonjumpers by increasing the gradient of the power-time curve. This was reflected by the increased rate of power development exhibited by jumpers, which was 40.0% higher than the nonjumpers (Table 2). Similarly, the enhanced peak velocity was coupled with the increased gradient of the velocity-time curve, as highlighted by the jumpers displaying an acceleration rate that was 28.8% greater than that of nonjumpers (Table 2). The cause of the improved jump performance is theorized to stem from the ability of jumpers to accelerate their body mass to a greater extent than nonjumpers. This was because of the superior strength levels of the jumpers (squat 1RM–body weight ratio: jumpers = 1.93 ± 0.22; nonjumpers = 1.40 ± 0.27; $p = 0.00$ [21, 25]) and the fact that the body mass of the jumpers represented a smaller relative load (jumpers = 31.4% of maximal dynamic strength [MDS = 1RM + body mass − shank mass (6)]; nonjumpers = 39.1% of MDS). As a result of improved acceleration, jumpers were able to achieve greater peak eccentric force levels, which, in turn, allowed for superior force output at the beginning of, and throughout, the concentric phase of the jump (8,27). Consequentially, jumpers were able to attain greater vertical velocity during the concentric phase of the moment. As indicated by the force-velocity loops (Figure 3a), vertical velocity at takeoff was higher in jumpers, and thus, the athletes achieved greater CMJ displacement than their untrained counterparts (Table 2). Although the physiological mechanisms driving such changes were not directly measured by the current study, it is theorized that the observed improvements emerge from the neuromuscular adaptations to strength and power training. These adaptations have been well documented throughout the literature (i.e., increased muscle cross-sectional area, preferential hypertrophy of type II fibers, selective recruitment of

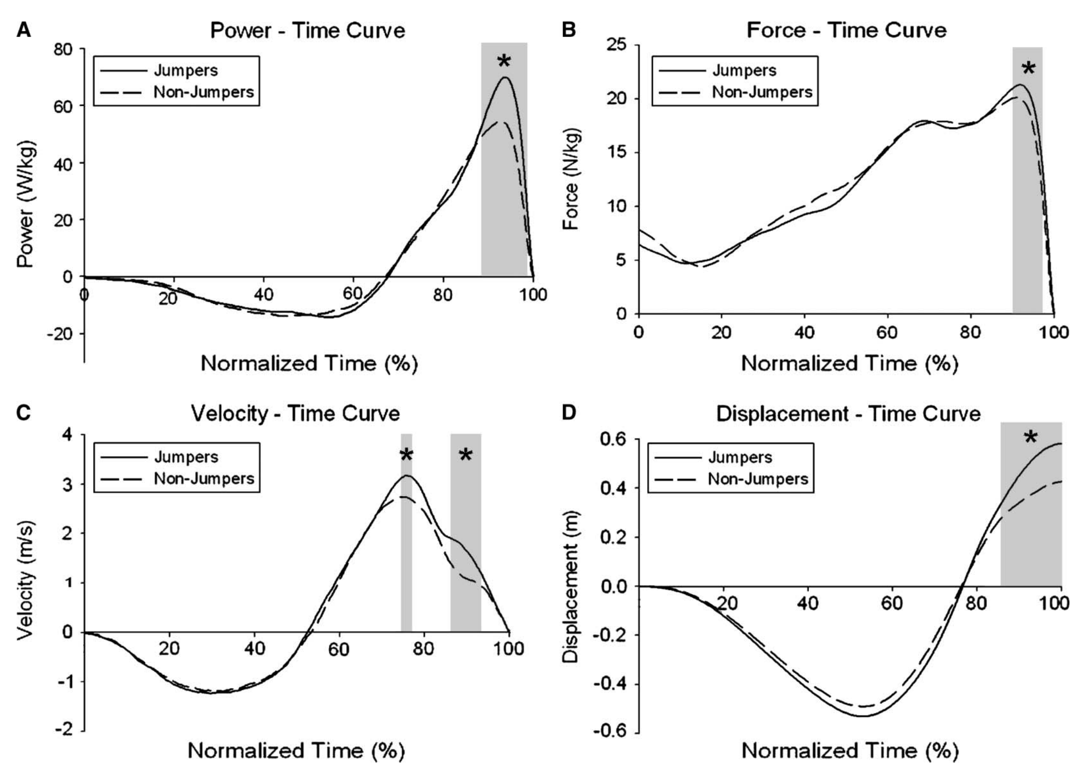

Figure 2. Comparison of the average (385–498 Hz; $n = 26$) power-time (A), force-time (B), velocity-time (C), and displacement-time (D) curves during a countermovement jump (CMJ) between jumpers (jump height > 0.50 m; $n = 12$) and nonjumpers (jump height ≤ 0.50 m; $n = 14$). *Significant difference ($p \leq 0.05$) between jumpers and nonjumpers in A) power from 90.6 to 99.8%, B) force from 95.0 to 98.0%, C) velocity from 77.0 to 78.0% and 85.8 to 92.2%, and D) displacement from 85.4 to 100%.

high-threshold motor units, increased firing frequency, and improved motor unit recruitment and synchronization) (5,9,16,19,20,24).

Twelve weeks of power training resulted in improvements in peak power, peak velocity, and peak displacement during the CMJ (Table 2). Remaining consistent with previous longitudinal studies, the low-load, high-movement-velocity training did not result in an improvement in peak force during the concentric phase of the jump (19,22). However, examination of power, force, and velocity output throughout the entire movement uncovered significant differences in the power-, force-, and velocity-time curves of the CMJ. After training, participants were able to generate greater power and velocity throughout the entire concentric phase of the CMJ (Figure 4). Interestingly, the shift in the concentric portion of the power- and velocity-time curves occurred in the absence of any changes to the gradients of the curves, highlighted by a lack of change in either the rate of power development or acceleration (Table 2). These observations were inconsistent with the cross-sectional analysis, and thus the sources of adaptation to the 12-week power training program are hypothesized to differ from the long-term adaptations evident in the jumpers. The most significant changes to the shape of the curves occurred primarily in the eccentric phase of the CMJ. After training, subjects changed the mechanics of their jumping technique by increasing the magnitude of their countermovement (i.e., lowered themselves much closer to the ground than they did during the pretraining test). This resulted in greater power and force unloading and increased negative velocities because the time spent in the eccentric phase remained consistent with the pretraining test. In addition, the shape of the force-time curve changed considerably with increased eccentric and concentric rates of force development and the establishment of a bimodal force tracing (i.e., a peak in force output during the eccentric phase followed by a drop-off in force during the transition between phases and a second peak during the concentric phase of the jump). In the same manner that CMJs elicit greater power, force, velocity, and displacement than static jumps, the cause of the improved performance after training was the generation of additional force at the start of the concentric phase (3,18,27). Elevated force levels during the eccentric phase allowed subjects to achieve higher acceleration rates at the beginning of, and throughout, the concentric phase of the jump (8,27). Consequentially, greater vertical velocity at takeoff was

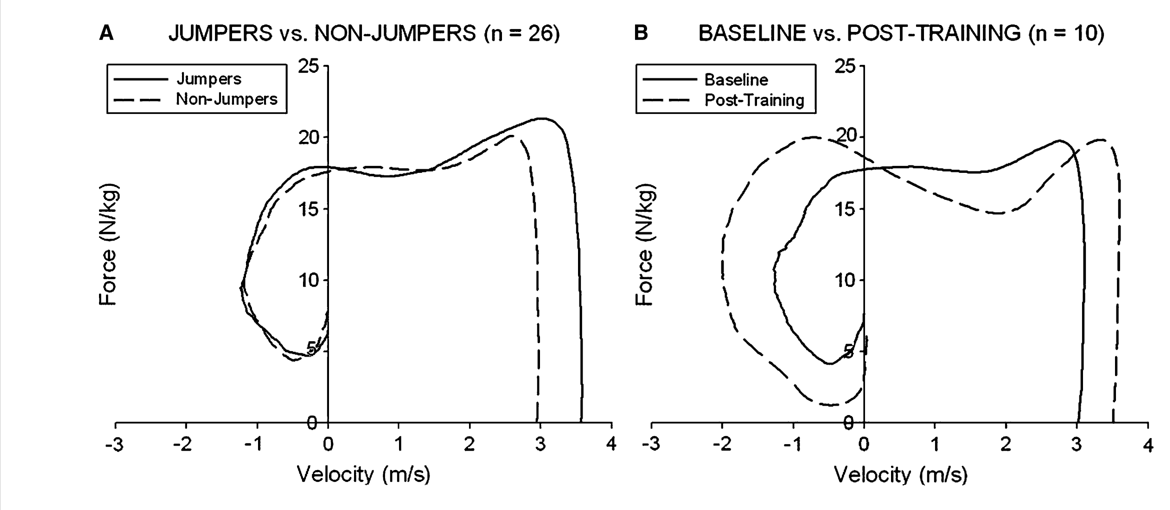

Figure 3. Comparison of the average (A: 385–498 Hz, $n = 26$; B: 390–506 Hz, $n = 10$) force-velocity loops of a countermovement jump (CMJ) between jumpers and nonjumpers (A), as well as before and after 12 weeks of power training (B). Values of the area under the force-velocity loop are displayed in Table 1 (A, jumpers displayed significantly [$p \leq 0.05$] greater area under the curve than nonjumpers; B, posttraining test displayed a significant [$p \leq 0.05$] improvement in area under the curve from baseline).

achieved during posttraining tests, which translated into improved CMJ displacement (Figure 3b, Table 2).

These results offer important insights into the mechanisms driving improvements in peak performance variables. Previously, it has been assumed that performance enhancement after training was primarily a result of physiological adaptations such as improvements in muscle activation (11,22,24). Yet, the current study indicates the possibility of mechanical changes in technique as another contributing factor to the improvements in peak performance variables. However, it cannot be ruled out that the use of audible biofeedback to monitor intensity throughout the 12 weeks of training may have influenced the observed technique changes. Regardless of the cause of the modified technique, the increased countermovement may have permitted subjects to generate higher force outputs through the optimization of stretch-shorten cycle mechanics (i.e., increasing the rate and magnitude of the stretch) (17), resulting in improved CMJ performance. Further study is required to delineate the precise mechanisms involved with changes in performance and alterations to jumping technique after lower-body power training.

The results of this study offer novel insights regarding the implications of training to improve jumping performance. Similar to previous findings, power training using the load that maximized power output caused improvements in peak power, peak velocity, and peak displacement but did not elicit any change in concentric peak force (15,19,22). However, the phase analysis of the force-time curve revealed that 12 weeks of power training elicited significant improvements in force output developed during the eccentric phase of the CMJ (Figure 4). Although the exact source of this adaptation cannot be clearly defined, it is proposed that changes in the shape of the force-time curve, which were not evident in examinations of peak performance variables, were the foundation of the increases in peak power, velocity, and displacement. These changes were comparable with the characteristics of the force-time curves of the jumpers and may have translated into improvements in rate of power development and acceleration if training were extended over a longer period of time. The major difference between the results of the trained jumpers and the power trained subjects was the considerable variation in strength levels. Because the system mass represented a lower relative intensity to the trained jumpers, the athletes were able to reach greater acceleration rates throughout the movement and thus, achieve a far superior rate of power development, peak power output, and greater total power (i.e., area under the force-velocity loop). If the jumpers underwent specific lower-body power training, it is hypothesized that the ability to generate high peak forces, coupled with improved force output throughout the movement (especially during the eccentric phase), would lead to even greater performance differences with the untrained subjects. Therefore, longitudinal examinations of the influence of power training on well-trained strength-power athletes involving phase analyses are required to identify the nature of adaptations that strong athletes display after power training.

The phase analysis of the jump squat revealed that the shape of the power-, force-, and velocity-time curves is affected by an individual's training status. Although differences in peak performance variables paralleled the findings of

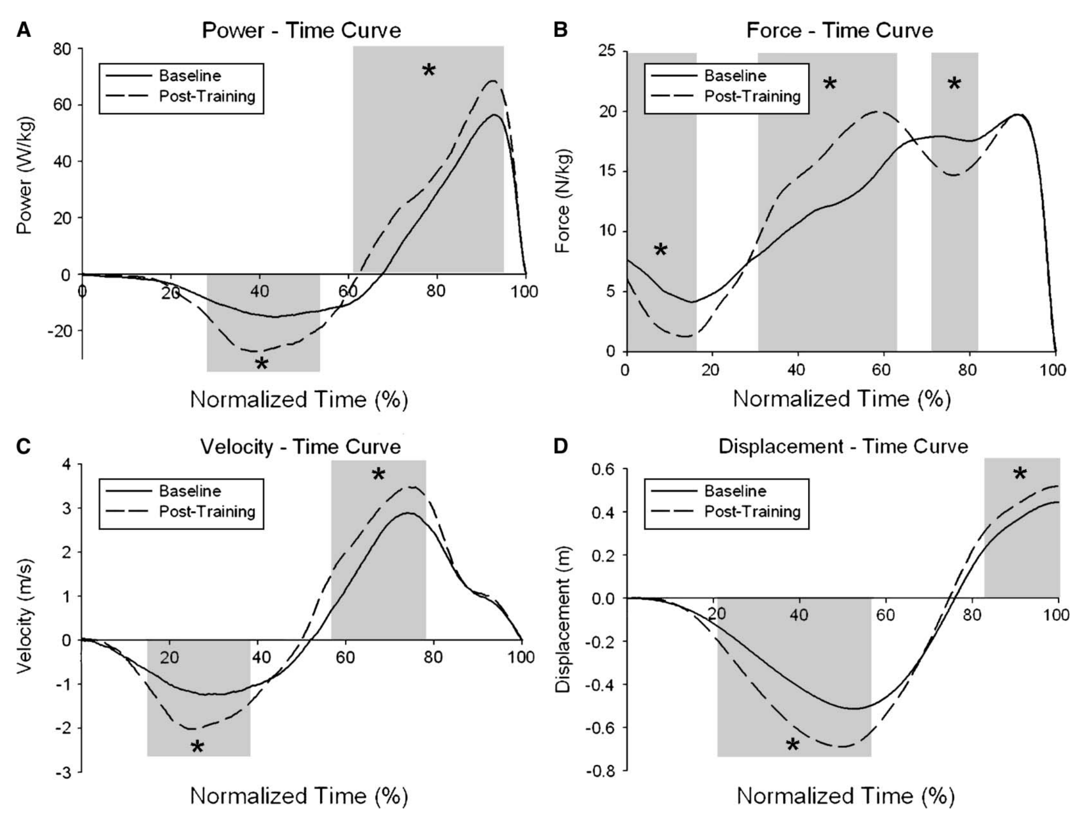

Figure 4. Comparison of the average (390–506 Hz; $n = 10$) power-time (A), force-time (B), velocity-time (C), and displacement-time (D) curves during a countermovement jump (CMJ) before and after 12 weeks of power training. *Significant difference ($p \leq 0.05$) between baseline and posttraining in A) power from 29.2 to 54.6% and 60.4 to 97.4%; B) force from 0.0 to 16.6%, 32.2 to 62.0%, and 70.8 to 81.4%; C) velocity from 15.2 to 39.6% and 57.2 to 78.8%; and D) displacement from 20.4 to 57.8% and 83.4 to 100%.

the phase analyses, such gross variables offer no indication of the precise timing and nature of adaptations to power training or how such adaptations affect the mechanics involved with improving vertical jumping. For this reason, future research should move beyond simply examining peak performance variables to investigating the features of the whole power-, force-, velocity-, and displacement-time curves during jumping movements. Furthermore, additional inspection of power, force, and velocity output throughout entire jumping movements is required to elucidate the specific areas that must be addressed during training to improve power production and jump performance.

PRACTICAL APPLICATIONS

Training status not only influences the peak performance variables of the CMJ (i.e., peak power, force, velocity, and displacement) but also impacts the shape of the power-, force-, velocity-, and displacement-time curves throughout the movement. Although the analysis of peak performance variables allows for the magnitude of improvement after training to be established, these variables offer little insight into what types of adaptations have occurred. The comparison of the full power-time, force-time, velocity-time, and/or displacement-time curves of a CMJ before and after a training intervention may help distinguish between physiological adaptations and mechanical changes to technique. Previously, it has been assumed that performance enhancement after power training was primarily a result of physiological adaptations (i.e., increased muscle activation) (11,22,24). Yet, the current study indicates the possibility of mechanical changes in technique as another contributing factor to the improvements in peak performance variables (i.e., increased depth of countermovement may result in the optimization of stretch-shorten cycle mechanics and lead to improved CMJ performance). The simplicity of the testing procedure involved with the analysis of these curves (i.e., it involves minimal time and equipment) makes it much more practical than other modes of mechanistic analyses (i.e., electromyographical and morphological analyses). Therefore, examination of the changes to the power-, force-, velocity-, and/or displacement-time curves of a CMJ may be a simple yet powerful monitoring technique that practitioners can use to gain insight into the precise nature and timing of adaptations to training.

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