IMPROVING VERTICAL JUMP PROFILES THROUGH PRESCRIBED MOVEMENT PLANS

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ABSTRACT

Mayberry, JK, Patterson, B, and Wagner, P. Improving vertical jump profiles through prescribed movement plans. *J Strength Cond Res* 32(6): 1619–1626, 2018—Developing practical, reliable, and valid methods for monitoring athlete wellness and injury risk is an important goal for trainers, athletes, and coaches. Previous studies have shown that the countermovement vertical jump (CMJ) test is both a reliable and valid metric for evaluating an athlete's condition. This study examines the effectiveness of prescribed workouts on improving the quality of movement during CMJ. The data set consists of 2,425 pairs of CMJ scans for high school, college, and professional athletes training at a privately owned facility. During each scan, a force plate recorded 3 ground reaction force (GRF) measurements known to impact CMJ performance: eccentric rate of force development (ERFD), average vertical concentric force (AVCF), and concentric vertical impulse (CVI). After an initial scan, coaches either assigned the athlete a specific 1- or 2-strength movement plan (treatment group) or instructed the athlete to choose their own workouts (control group) before returning for a follow-up scan. A multivariate analysis of covariance (MANCOVA) revealed significant differences in changes to GRF measurements between athletes in the 2 groups after adjusting for the covariates sex, sport, time between scans, and rounds of workout completed. A principal component analysis of GRF measurements further identified 4 primary groups of athlete needs and the results provide recommendations for effective workout plans targeting each group. In particular, split squats increase CVI and decrease ERFD/AVCF; deadlifts increase AVCF and decrease CVI; alternating squats/split squats increase ERFD/CVI and decrease AVCF; and alternating squats/deadlifts increase ERFD/AVCF and decrease CVI.

KEY WORDS force-plate testing, rate of force development, concentric vertical impulse, training plans

INTRODUCTION

Developing practical, reliable, and valid methods for monitoring athlete wellness and injury risk is an important goal for trainers, athletes, and coaches. The biometric revolution has created a wealth of quantitative data for use in this goal, but our understanding of the implications and proper uses of said data is still far from complete. Any new metric proposed to provide information about athlete conditioning should ideally address 3 issues (21,23):

- Is the metric reliable? (i.e., are the values it gives reproducible between tests of the same individual under the same conditions?)
- Is the metric valid? (i.e., is it able to identify "ill conditioned" athletes including those more susceptible to fatigue, at an increased risk of injury, or performance reduced ability to perform?)
- Is it correctable? (i.e., are there validated treatments for improving the metric?)

One promising set of metrics in this exploration center around kinetic and kinematic variables extracted from ground reaction forces (GRFs) during a countermovement vertical jump (CMJ) test. The CMJ test is among the most reliable and valid forms of jump tests for predicting athletic performance (17,20) and lifting ability (3,22). There has also been extensive research on improving vertical jump performance during CMJ including the effect of arm movement (9), warm-up protocols (2,12), stretching (1,24), vibration training (4), resistance training (13), muscle strength (25), and plyometric lifting (11,18). The relationship between specific GRF measurements and vertical jump performance was studied by Laffaye et al. (14) who calculated correlations between 5 force-time variables (eccentric rate of force development–ERFD, average vertical concentric force–AVCF, total time–T, eccentric time, and ratio of eccentric to total time) and vertical jump height (JH) during a CMJ test. They found that the 2 force variables (ERFD and AVCF) exhibit a strong positive correlation with JH, whereas the 3 remaining time variables exhibit weaker (but still significant) negative correlations. A follow-up study (15) suggested that these relationships, however, are not uniform across different sport and sex groups. Females, for example, demonstrate a stronger negative correlation between eccentric time and JH than

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Table 1. Summary statistics of body mass (kg) and jump height (m) for participating athletes based on sex.

Gender	Sample size	Mean mass	*SD* mass	Mean JH	*SD* JH
Female	2,749	64.54	8.949	0.349	0.056
Male	3,820	83.02	15.887	0.475	0.090

males, whereas males yield a stronger positive correlation between ERFD/AVCF and JH. Athletes involved with indoor sports (volleyball and basketball) rely more on time variables during a CMJ, whereas athletes involved in outdoor sports (football and baseball) have more force dominated profiles (high ERFD/AVCF). Together, these findings suggest that analyzing the nature and quality of movement during a CMJ may be as important as measuring JH alone.

This article will focus on a specific CMJ test procedure studied by Nibali et al. (21) in which an athlete's ERFD, AVCF, and concentric vertical impulse (CVI) are averaged across the 3 maximum vertical height CMJs in a sequence of 6, a procedure henceforth referred to as a CMJ scan. Eccentric rate of force development and AVCF come directly from the aforementioned studies (14,15), whereas CVI can be derived from the variables therein by the relationship

$$\mathrm{CVI} \approx \mathrm{AVCF} \times (\mathrm{T}-\mathrm{ECCT})$$

Nibali et al. (21) established the reliability of CMJ scans demonstrating that all 3 test measurements lack systematic error in repeated trials (i.e., there is no "learning effect"), exhibit uniformity in variance with respect to athlete abilities (homoscedasticity), and yield between-trial variances small enough to detect moderate, or in some cases, even the smallest "worthwhile" change in athletic performance. There is also a growing body of evidence to suggest that ERFD, AVCF, and CVI interact in nontrivial ways to predict athlete performance and injury risk. For example, a study of National Collegiate Athletic Association (NCAA) men's basketball players conducted by Fry et al. (7) showed that athletes with high AVCF coupled with low ERFD/CVI obtain more offensive rebounds and play more minutes than players with other scan profiles. These findings are consistent with an earlier study by Hoffman et al. (10), which demonstrated a positive correlation between peak power and JH in basketball players. Mayberry et al. (19) recently established a link between AVCF, ERFD, CVI, and ulnar collateral ligament injuries in baseball pitchers. In particular, pitchers with a strong imbalance between the impulse (CVI) and force (AVCF/ERFD) components of their jumps were more than 3 times as likely to incur an elbow injury as those with profiles that are more balanced. Together, these studies suggest that CMJ scans constitute both a reliable (Issue 1) and valid (Issue 2) form of athlete testing. The purpose of this study is to address Issue 3. More specifically, we aim to (a) describe how measurements from CMJ scans typically change over the course of short training periods (1–5 weeks) and (b) assess the impact of targeted strength movement plans on changes to CMJ scans. The hypothesis is that exercises that involve a movement held over a sustained period (e.g., split squats) will increase CVI, whereas exercises emphasizing movements that are more explosive (e.g., deadlifts) will influence AVCF. It is also hypothesized that load-bearing movements (e.g., front squats) will increase ERFD.

Previous studies have suggested that extensive power training can alter peak performance, force, and time variables obtained from CMJ (5) as well as both eccentric and concentric performances during jump squats (6). However, there has not to our knowledge been a detailed comparison of how different exercise regimes impact the force-time variables targeted by CMJ scans nor has there been a classification of how changes in these variables are typically correlated with one another after short training periods. This study seeks to expand our understanding of these factors and provide strength and conditioning coaches with suggestions for best practices in assigning exercises to improve specific aspects of athlete movement during CMJ.

Table 2. Frequency table stratified by sex, sport, and observational groups.*

	Baseball	Basketball	Football	Other	Soccer	Volleyball
C-Female	0	70	0	29	113	234
C-Male	424	59	64	53	13	7
T-Female	0	102	0	59	196	268
T-Male	524	49	76	60	24	1

*C = control; T = treatment; "Other" includes crew, field hockey, golf, ice hockey, lacrosse, rugby, snowboarding, softball, swimming, tennis, track and field, and water polo.

METHODS

Experimental Approaches to the Problem

An athlete management program at a privately run training facility (Sparta

Table 3. Summary of exercise plans included in the analysis.*

Plan	Count	Exercise(s)
0	1,066	None
A	290	Squat
B	223	Deadlift
C	122	Split squat
D	51	Squat; 1-leg squat
E	171	Squat; deadlift
F	101	Squat; split squat
G	110	Deadlift; 1-leg deadlift
H	62	Deadlift; side deadlift
I	88	Deadlift; split squat
J	51	Split Squat; 1-leg deadlift
K	57	Split squat; glute bridge
L	33	Squat; 1-leg squat; deadlift

*"Split Squat" refers to a rear foot elevated split squat or Bulgarian split squat. "Deadlift" refers to the conventional, straight bar form of the exercise. "Squat" refers to an Olympic style squat and may include both front and back derivatives of the exercise. All exercises were performed with a barbell unless the weights dropped below the minimum threshold of 20 kg at which point dumbbells or body mass were substituted.

Performance Science, Menlo Park, CA, USA) tracked CMJ scans and strength movements from athletes over a 4-year period from August 15, 2011 to July 11, 2015. The sample for this study consisted of athletes who completed 2 consecutive CMJ scans at the facility within a 1–5 week period. The "treatment" group (n = 1,359) consisted of athletes who performed at least 3 repetitions of a 1- or 2-movement plan in between scans, whereas the "control" group (n = 1,066) consisted of athletes who had no specified exercise plan in between successive scans. Change scores in CMJ measurements between scans were compared for the 2 groups after adjusting for several covariates including time between scans, rounds of exercise plan completed, sex, sport, and competitive level.

Table 4. Summary of principal component analysis components and correlations with changes in ground reaction force measurements.*

Component	*SD*	Prop. of var.	Corr ERFD	Corr AVCF	Corr CVI
PC1	1.488	0.738	−0.794	−0.915	0.864
PC2	0.735	0.180	−0.597	0.132	−0.409
PC3	0.496	0.082	−0.118	0.381	0.295

*PCi = ith principal component from PCA, i = 1, 2, 3; Prop. of Var. = proportion of variance explained by PC; Corr XXX = correlation between PC and CMJ scan variable XXX.

Subjects

The observational units for this study consisted of athletes competing in elite high school (n = 1,571), college (n = 393), or professional (n = 373) level sports (There were also 88 athletes of unknown competitive level). The data collection process was completed free of injuries and was conducted as part of the athletes routine testing using the Sparta software athlete management program. Participants (and parent or legal guardian for subjects younger than 18 years) provided signed consent before testing, data collection, and the publication of results as part of their agreement with Sparta Performance Science; as such, ethics approval for this study was not required. Data were de-identified and the age of participants was not recorded as a part of the study; however, athletes training at Sparta over the study period ranged in age from 15 to 30 years with an average age of approximately 18.7 (mean ± SD = 3.8 years).

The data collection process resulted in a sample size of 2,425 observations with a median length of time between successive scans of 21 days (Interquartile range = 12 days). Table 1 summarizes the body mass and JH for participating athletes. Table 2 further summarizes the breakdown of observations into the "control" and "treatment" groups based on the sex and sport of the participating athlete. Overall, 18 different sports were included with unbalanced sample sizes ranging from a maximum of 963 (Baseball) to a minimum of 1 (Field Hockey).

Procedures

Participants performed a series of 6 CMJs on a commercially available piezoelectric force plate with a sampling frequency of 1,000 Hz (9260AA6; Kistler Instruments, Winterthur, Switzerland). Numerical integration extracted 3 force-time variables (ERFD, AVCF, and CVI) from GRF data (16) during both eccentric and concentric phases of the jump–see Nibali et al. (21) for additional details of variable computations and definitions. There were 30 seconds allotted in between successive jumps, and measurements from the 3 jumps with maximal vertical height were averaged to obtain an overall score for ERFD, AVCF, and CVI during the scan. For comparisons across variables, scores were converted to normalized sex-specific T-scores using the formula:

$$T = 10 \times \left(\frac{\text{Score}-\text{Mean}_{\text{Gender}}}{SD_{\text{Gender}}}\right) + 50,$$

so that all 3 reported variables had a mean of 50 and an SD of 10. Athletes re-scanned at the facility after a period of 1–5 weeks to repeat the above process, and the

TABLE 5. Multivariate analysis of covariance results based on Pillai's trace.*†

Model term	DF	PILLAI	*F*	NUM DF	DEN DF	*p*
Intercept	1	0.000	0.024	2	2,220	0.977
ChangeDate	1	0.001	0.888	2	2,220	0.412
Rounds	1	0.001	1.003	2	2,220	0.367
Sex	1	0.000	0.164	2	2,220	0.849
Sport	5	0.006	1.302	10	4,442	0.223
Level	2	0.003	1.907	4	4,442	0.106
Plan	12	0.039	3.676	24	4,442	<0.001
Sex:plan	12	0.010	0.923	24	4,442	0.570
Level:plan	24	0.021	0.989	48	4,442	0.495
Sport:plan	57	0.048	0.948	114	4,442	0.638
Residuals	2,221					

*DF = degrees of freedom for term; PILLAI = value of Pillai's Trace; *F* = *F*-statistics associated with PILLAI; NUM DF = numerator DF from *F*-test; DEN DF = denominator DF.

†Plan was the only term yielding a highly significant *p*-value.

computed differences in T-scores for ERFD, AVCF, and CVI between successive scans (initial–final) were used as dependent variables in the analysis.

After the initial scan, a strength coach assigned the athlete either a specific workout plan (treatment group) or no specific plan (control group). Intensities (weight) prescribed to the athletes were based off percentages of athlete body mass and training level. Overall, tonnage (weight × reps × sets) was normalized so that athletes of the same training level completed the same relative tonnage (tonnage/weight) for all plans. Sparta software recorded primary exercise complexes completed by athletes and deemed an athlete "compliant" with an assigned plan if they logged at least 2 workouts consisting of the assigned plan in between successive scans and no other conflicting workouts during this time. The analysis excluded uncompliant observations, and the treatment group included only plans with at least 30 compliant observations; see Table 3 for a summary of plans meeting this requirement.

Statistical Analyses

Principal component analysis (PCA) was applied to the 3 force-time variables (change in ERFD, change in AVCF, and change in CVI). The percentage of explained variance determined the number of principal components retained for analysis based on a 90% threshold. Multivariate analysis of covariance (MANCOVA) was used to test for a significant difference in change components between independent scans after accounting for the number of days (changeDate) and the number of rounds (rounds) completed in between scans. Sex, sport, and competitive level were also included as blocking variables in the analysis. Pairwise-*t*-tests were performed to test for post hoc differences in component changes between the control group and the plan group to identify significant workouts. Bar charts were used to visualize comparisons. Statistical analysis was performed using *R: A language and environment for statistical computing* (R Core Team 2013. R Foundation for Statistical Computing. Vienna, Austria. URL http://www.R-project.

TABLE 6. Tests comparing athletes in the treatments and control groups.*

Plan	PC1 mean	PC1 *SEM*	PC1 *p*	PC2 mean	PC2 *SEM*	PC2 *p*
0	0.010	0.050	NA	0.018	0.001	NA
A	−0.038	0.082	0.623	0.038	0.002	0.684
B	−0.330	0.072	**0.002**	−0.131	0.003	**0.006**
C	0.676	0.183	<**0.001**	0.002	0.009	0.822
D	−0.064	0.160	0.724	0.075	0.010	0.587
E	−0.250	0.088	**0.032**	−0.070	0.004	0.144
F	−0.044	0.116	0.723	0.088	0.006	0.359
G	−0.031	0.104	0.781	−0.065	0.006	0.257
H	−0.352	0.125	**0.060**	0.040	0.010	0.824
I	0.118	0.129	0.506	0.083	0.007	0.423
J	1.038	0.274	<**0.001**	−0.065	0.015	0.431
K	0.320	0.160	0.121	−0.020	0.013	0.702
L	−0.434	0.217	**0.087**	−0.014	0.024	0.806

*PCi Mean = ith principal component mean, $i = 1, 2$; PCi *SEM* = standard error of the PCi mean; PCi *p*-value = adjusted *p*-value from a 2-sided *t*-test comparing the treatment group mean with the control group mean, $i = 1, 2$. Significant results are in bold (*p*-value <0.01 = highly significant, *p*-value between 0.01 and 0.1 = marginally significant); Plans A–L = treatment groups; Plan 0 = Control Group.

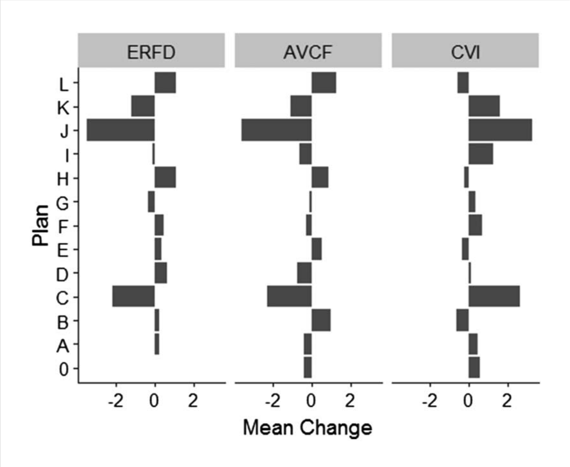

Figure 1. Comparison of mean T-score changes for athletes under different plans.

org/). Following the guidelines discussed in Gelman (8), results with a p values <0.01 were considered highly significant, whereas results with p values between 0.01 and 0.1 were considered marginally significant and reported for exploratory purposes.

RESULTS

Table 4 summarizes the principal components for changes in T scores. The first 2 components accounted for 91.5% of the variance in T-score changes and, hence, were the only ones retained for further analysis. The first principal component (PC1) scores positively correlated with CVI and negatively correlated with ERFD/AVCF. This implies that the primary changes in movement signatures were gains (losses) in CVI coupled with losses (gains) in ERFD/AVCF. In contrast, second principal component (PC2) scores positively correlated with changes in ERFD and CVI, but did not correlate with changes in AVCF. Therefore, the secondary component of T-score changes consisted of a simultaneous increase or decrease in CVI and ERFD.

Table 5 shows the results of the MANCOVA. Change in PC1 and PC2 components differed significantly between exercise plan groups after accounting for differences in changeDate and rounds. Interestingly, there were no significant differences in PC changes between sexes, sports, or competitive levels nor were there any significant interactions between these variables and plan assignments.

Table 6 lists the results of comparisons between the exercise plan groups and the control groups along with the corresponding mean values and standard errors for observations in each group. Three plans showed highly significant mean differences with the control group: plan B (lower PC1 and PC2), plan C (higher PC1), and plan J (higher PC1). Figure 1 compares the mean changes in CMJ variables from all plans, whereas Figure 2 further compares characteristics of plans with significant effects. Plan B yielded the highest mean gain in and greatest success rate at improving AVCF with a relatively neutral impact on ERFD and a negative impact on CVI. In contrast, plans C and J demonstrated a large gain in CVI coupled with losses in both ERFD and AVCF. There were also 3 plans yielding marginally significant effects. Athletes in plan E showed a significant drop in PC1 corresponding to slight gains in

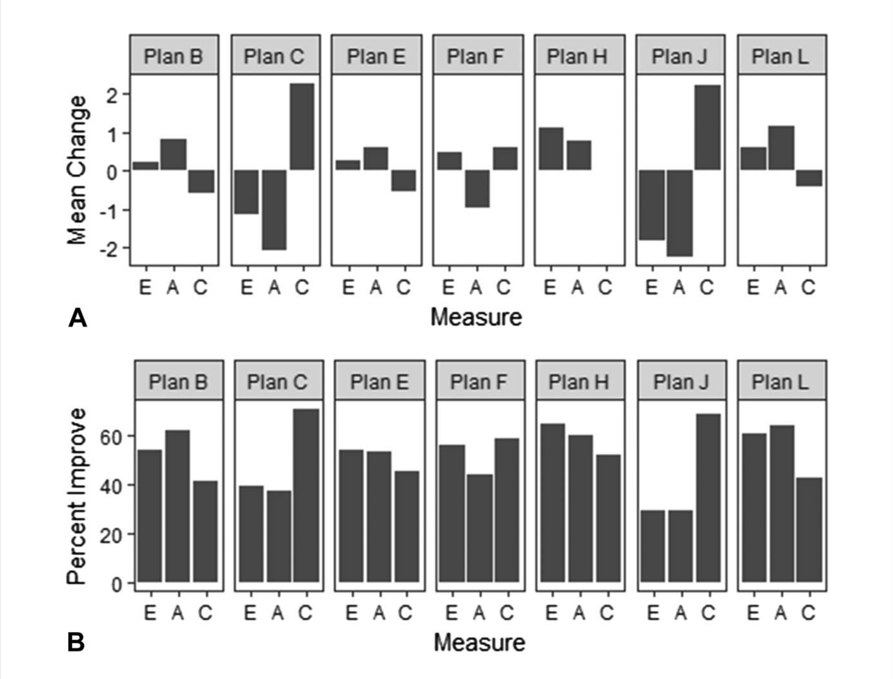

Figure 2. Comparison of T-score changes for athletes under different plans. A) Median changes in ERFD (E), AVCF (A), and CVI (C) for all athletes in the 4 observational groups. B) Percent of all athletes in the observational group who demonstrated a positive gain in the corresponding T-score. Note that bars with excessively low percentages are significant as well because athletes under these plans exhibited significant losses in the corresponding T-score.

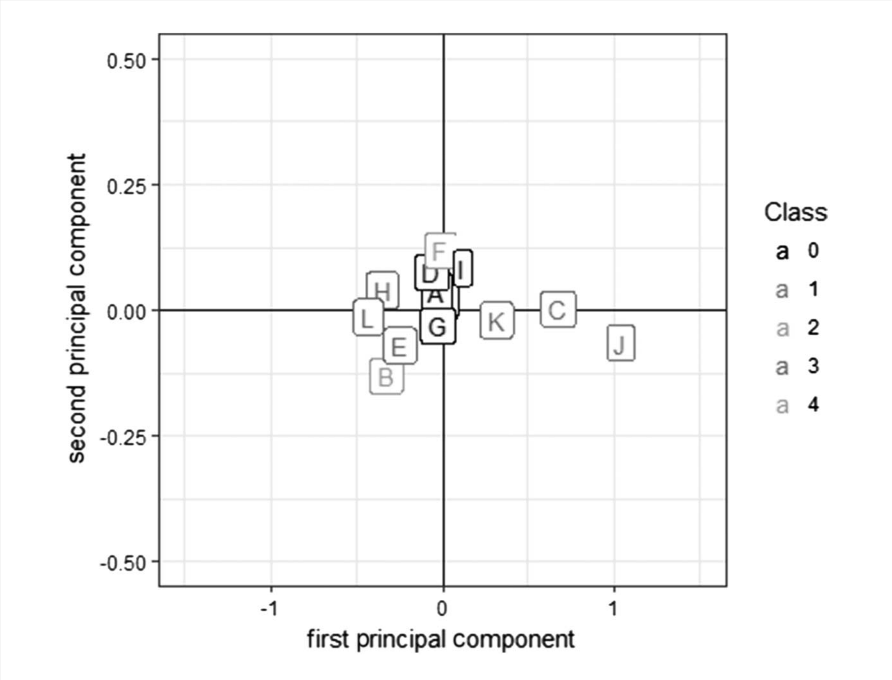

Figure 3. Mean principal component scores for movement plans along with hypothesized splitting into classes 1–4 (see Discussion).

ERFD/AVCF coupled with a loss in CVI. The improvement profiles for athletes on plans H and L were similar to athletes on plan E (gains in ERFD and AVCF and a drop in CVI), although the results were more variable.

Discussion

The analysis of over 2,000 athlete scans throughout a 4-year period shows that changes to GRF profiles during CMJ are strongly associated with different strength movement assignments. The resulting changes appear to be consistent across sexes, sports, and the level of competitiveness and robust over 1–5 week periods of testing. Two workouts significantly predict increases in CVI and decreases in ERFD/AVCF: plans C and J. Both plans involve split squats. Because CVI is a product of the average weight-normalized force during the concentric phase of CMJ and the amount of time this force is applied, we theorize that the split squat has a positive effect on improving CVI for 2 main reasons. First, it is a single-leg exercise and as such, inherently takes more time to complete than 2-legged squats because of the large balance component involved with performing the exercise. This has the effect of slowing an athlete down, increasing their potential to apply force over a longer period during CMJ. Second, split squats involve largely posterior chain hip dominant movements. Athletes who are able to achieve full extension of the hips should be able to increase the amount of time they push during the concentric phase of a jump, further increasing their CVI.

The analysis also shows that 2 plans significantly increase AVCF: plans B and E. Both plans involve deadlifts. Average vertical concentric force is the (weight normalized) average amount of force exerted during the entire concentric phase of CMJ. This value will often be lower if an athlete loses or leaks force as they transition from the eccentric to the concentric phase (amortization). We theorize that the deadlift has a positive effect on improving AVCF because of the large bracing component of the lift and the requirement of great trunk/torso stability needed to do the movement well.

Finally, 1 plan (plan E) significantly increases both ERFD and AVCF. Plan E involves an alternating pattern of squat and deadlift movements. ERFD is the average rate of force production measured during the eccentric phase of CMJ. We theorize that the addition of squats to a deadlift routine has a positive effect on improving ERFD largely because of the anterior chain strength and mobility required to do this movement well. Figure 2 shows that all plans which involved squats (plans A, D, E, F, and L) had a positive mean effect on ERFD further supporting this hypothesis, although the effect sizes of most of these plans were not large enough to show statistical significance in this study.

Based on a PCA of jump profile changes, we hypothesize 4 improvement classes for athletes undergoing CMJ testing:

- Plans which lead to gains in CVI coupled with losses in ERFD/AVCF (positive PC1 and negligible PC2)
- Plans which lead to gains in CVI and ERFD coupled with a loss in AVCF (positive PC2 and negligible PC1)
- Plans which lead to gains in ERFD and AVCF coupled with a loss in CVI (negative PC1 and negligible PC2)
- Plans which lead to gains in AVCF, losses in CVI, and negligible impact on ERFD (negative PC1 and PC2)

Figure 3 suggests a hypothetical splitting of exercise plans into these 4 categories and suggests the following prescriptive measures for strength and conditioning coaches:

- Splits athletes for athletes with low CVI and high ERFD/AVCF
- Alternating sequences of split and Olympic style squats for athletes with low CVI/ERFD

- Alternating sequences of deadlifts and Olympic style squats for athletes with low ERFD/AVCF
- Deadlifts for athletes with low AVCF and high CVI

One potential limitation of this study is the observational design. Data were gathered retroactively from a secure database, and coaches did not randomly assign athletes to treatment groups. In addition, this study does not look in detail at inter-sport differences in plan effects, although this would be an interesting direction for future research. Although there was no significant interaction between sport and plan assignment in the MANCOVA model, the unbalanced and sometimes small sample sizes for different sports in the data set obscure the interpretation of this result. Despite these limitations, the fact that this study applies to a large and diverse sample of real athletes adds to the novelty of the work. Performing controlled experimental studies on this population would be infeasible due to the restrictions placed on athletes by their coaches and sports.

Diagnostic metrics for strength and conditioning must pass all 3 phases of the validation process outlined in the introduction. A CMJ scan provides quantitative information through noninvasive methods and has been established as both a reliable and valid statistic for tracking athlete wellness and performance. This study further shows that deficiencies are correctable by prescribed movement plans, therefore, establishing CMJ scans as a promising candidate for monitoring athlete conditioning.

PRACTICAL APPLICATIONS

Force-plate testing of athletes is becoming increasingly common as the availability and cost of hardware and data acquisition software improve. This study seeks to improve practical applications of such testing by identifying key changes to vertical jump profiles under different strength movements in a large sample size, longitudinal study of competitive athletes. The findings suggest that athletes with identified deficiencies in eccentric rate of vertical force development (ERFD), AVCF, and CVI be subscribed Olympic style front and back squats, deadlifts, and split squats, respectively. Combinations of the above exercises assigned in alternating patterns can address multiple deficiencies simultaneously. It is possible to identify deficiencies in the 3 test variables based on individual athlete characteristics or sex/sport trends (15). This study supports the use of individual- or population-specific training based on objective, reliable, and valid measurements of force production.

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