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Velocity-Specific Relationships Among Eccentric and Concentric Force Velocity Profiles and Jumping Performance

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ABSTRACT

The purpose of this study is to determine the relationships among force velocity profiles during eccentric only movements (eFVP), concentric only movements (cFVP), and dynamic performance during a countermovement jump (CMJ), squat jump (SJ), and drop jump (DJ). Nineteen collegiate baseball players (1.85 ± 0.04 m, 86.4 ± 8.2 kg, 21.1 ± 1.8 years) from a single NCAA Division I team performed CMJ, SJ, and DJ, drop landings from varying heights, and hex bar jumps with varying weights. FVPs were created with a linear regression using the drop landings for eFVP and hex bar jumps for cFVP, which were used to calculate slopes and area under the entire FVP and velocity-specific regions. Correlations analyzed the results with bootstrapping for 95% confidence intervals. Area under eFVP correlated with cFVP at r=0.51 ($p<0.05$), cFVP slope presented strong correlations with CMJ height and DJ height while eFVP slopes did not relate to jumping performance or metrics. Area under the faster regions of cFVP and eFVP produced moderate and strong relationships to jumping performance. The area under the FVP, especially when separated into velocity-specific bands, may be a key metric which can audit or provide insight into velocity-based training program effectiveness and athlete comparisons.

Keywords: sports science, testing, athletes, ground reaction forces

INTRODUCTION

Concentric force velocity profiling (cFVP) of bilateral jumping movements has gained popularity in recent years as a method to assess athletic performance and guide training program optimization decisions using the slope of the cFVP[1–3]. But, recent evidence has demonstrated no relationship between cFVP slope and performance during jumping, sprinting, and change of direction movements in soccer and volleyball athletes[4,5]. These studies cast doubt on the utility of the cFVP slope derived from squat jumps to apply to dynamic lower body movements common in sport. Further, there are mixed reports on the effectiveness of the cFVP slope to guide velocity-specific training programs to attain optimal balance between strength and speed abilities[1,3,6–8]. In contrast, research on eccentric force velocity profiling (eFVP) during dynamic movements and its ability to guide eccentrically focused training for athletic performance is currently sparse. Knowledge of a cFVP might be leveraged to improve jump height or running speed while the eFVP might be leveraged to improve deceleration capacity related to change of direction, landing, and movements utilizing the stretch-shortening cycle. While previous studies have investigated eFVP using drop jumps[9] and drop landings[10], eFVP did not relate to relative back squat 1-repetition maximum (1RM) loads, jumping performance, or metrics associated with rate of force development during jumping[10]. The lack of correlation between eFVP and dynamic performance may be due to athletic capacity. Specifically, recreationally active participants may be less experienced with some of the jumping and landing test movements than competitive athletes. Another factor could be the mechanical and neuromuscular differences between eccentric only drop landings and jumping movements incorporating the stretch-shortening cycle (i.e. drop jumps, broad jump into vertical jumps, and countermovement jumps)[11–13]. The muscle regime (stretch-shortening cycle, eccentric only, or concentric only) used during testing is an important consideration for FVP application to sport. FVP is more commonly executed through eccentric or concentric only movements in isolation[1–3,10], which is computationally and logistically simpler but may reduce sport specificity since sport requires both eccentric and concentric movements. Conversely, FVP could be executed through stretch-shortening cycle movements like the drop jump or jump squat[9], which challenges methodological logistics and computations with potential to be more sport specific.

The field of research on dynamic FVP, in contrast to isokinetic FVP, is still young and requires further investigation into test parameters, limitations, and their velocity-specific relationships to dynamic sporting movements. Therefore, the purpose of this study is to determine the relationships among eFVP during eccentric only movements, cFVP during concentric only movements, and dynamic performance during a countermovement jump, squat jump, and drop jump in NCAA Division I student-athletes. We hypothesize significant correlations between eFVP and cFVP, in addition to muscle action specific relationships (eFVP to drop jump height and RSI, cFVP to squat jump height). A secondary purpose of the study is to identify relationships between velocity-specific regions of FVP and jumping performance metrics (e.g., jump height and reactive strength index). We hypothesize the faster cFVP and eFVP regions will exhibit stronger relationships with jumping performance metrics than the slower cFVP and eFVP regions.

METHODS

Experimental Approach to the Problem

Collegiate baseball players from a single NCAA Division I team performed jumping and landing exercises on a dual-force platform setup. All tests were completed in a single testing session. Jumping tests included a countermovement jump, squat jump, drop jump from 0.61 meters, weighted hex bar jumps with varying weights, and drop landings from varying heights. The cFVP used vertical ground reaction force (vGRF) data from hex bar jumps with 38, 52, 70, and 93 kg, while the eFVP used vGRF data from drop landings from 0.3, 0.61, 0.91, and 1.22 m.

Subjects

Nineteen collegiate baseball players (1.85 ± 0.04 m, 86.4 ± 8.2 kg, 21.1 ± 1.8 years) from a single NCAA Division I team participated in the study. Participants provided informed consent as part of a larger research collaboration with the athletic department approved by Creighton University's Institutional Review Board (#1121863-8). Participants wore athletic shoes for all tests (i.e., no specialty shoes). Participants were healthy at the time of testing, defined as able to train without restriction, and were free of any specific restrictions on participation made based on past injury.

Procedures

On the day of testing, participants performance a standardized warm-up of 2 sets of 10 bodyweight squats, 10 lunges on each leg, and 5 consecutive rebound jumps. Test instructions were provided verbally prior to data collection and included instruction for a countermovement jump, squat jump, drop jump, and modifications of the squat jump (weighted hex bar jump) and drop landings from varying heights. All tests were done on a dual-force platform setup (model 4060-07, Bertec, Columbus, Ohio) collecting GRF signals at 2000 Hz interfaced through motion capture software (Qualisys, IL, USA). Participants were allowed to rest ad libitum, which resulted in approximately 30-60 seconds between trials. First, participants performed 2 trials each of a countermovement jump, squat jump, and drop jump from 0.61 m (6 total trials). The countermovement and squat jumps were done with hands on the hips and instructed to "jump as quickly and high as possible". The drop jump allowed free hand movement and included instruction to "spend as little time on the ground as possible while jumping as high as possible". Next, participants performed 3 trials of a weighted hex bar jump with each of the following loads: 38, 52, 70, and 93 kg (12 total trials).

The hex bar jump was selected because it mimics the starting position of the squat jump and is not technically demanding. The loads were standardized for all participants, but the force production was normalized to participant mass during analysis. Participants started in a down position (i.e., bar in contact with floor) and were instructed to jump as high as possible. Lastly, participants performed 3 trials of drop landings from 0.3, 0.61, 0.91, and 1.22 m (12 total trials). Participants stepped off the box and were instructed to "land as quickly as possible in a safe landing position," which included clarification that "landing with your legs straight is not safe."

Data Analysis

All data analyses were performed using custom MATLAB scripts (MATLAB 2019a, MathWorks, Natick, MA). For all tests, raw vGRF signals were filtered with a 4th order Butterworth filter using a low pass cutoff frequency of 50 Hz and the vGRF were then summed.

Dependent variables from the drop jump were height and RSI. Dependent variables from the countermovement jump were height, modified RSI (RSImod), and eccentric RFD. Dependent variables from the squat jump were height, RSImod, and concentric RFD.

For the drop jump, initial impact, takeoff, and final impact timepoints were determined with a vGRF threshold of 20 N. Time in the air was used to calculate jump height instead of takeoff velocity because it provides a consistent method across all three jump tests:

$$\boldsymbol{Jump\ Height} = \frac{1}{2}g\left(\frac{\boldsymbol{time\ in\ air}}{2}\right)^2$$

Ground contact time was the time between initial impact and takeoff, and reactive strength index (RSI) was calculated as jump height divided by ground contact time.

During the countermovement jump, average eccentric rate of force development (RFD) during the countermovement jump was calculated as the difference between the first peak vGRF and minimum vGRF, divided by the change in time[14].

During the squat jump, average concentric RFD was calculated as the difference between the peak vGRF and bodyweight, divided by the time to peak vGRF.

During the hex bar jump (used to create the cFVP), the system weight was measured as the final 0.5 seconds of the trial when the participant was standing still holding the weight in hand. The cFVP was derived as a linear regression line fitted to the average vGRF relative to body mass and velocity during the hex bar jump, which were extracted from the time between initiation (when vGRF surpasses system weight) and peak vertical velocity. The area under the cFVP regression line was also calculated, from the velocity of 0 to the theoretical peak velocity when force is 0, in addition to the area between typical velocity ranges used in concentric velocity-based training programs: 0 – 0.5 m/s, 0.5 – 0.75 m/s, 0.75 – 1 m/s, 1 – 1.3 m/s, and >1.3 m/s.

During the drop landing (used to create the eFVP), the data array was flipped, which resulted in the signal resembling a squat jump (barker et al., 2022). Using this flipped vertical GRF signal, bodyweight was calculated as the average vertical GRF of the first 0.5 seconds (when participants were motionless in their final landing position)[10]. Acceleration was calculated using Newton's 2nd Law ($\Sigma F = ma$), and then time-integrated to attain velocity, using the trapezoidal method. Initial landing impact was determined with a threshold of 20 N to account for empty force plate noise while the end of the landing phase occurred when velocity reached 0[10,15]. The average vGRF relative to body mass and velocity were then calculated from impact to the end of the landing phase.

The average vGRF relative to body mass and velocity were then fit to a linear regression line to attain the eFVP. Since there are no velocity-based eccentric training methods reported in current literature, the velocity ranges for area under the eFVP are separated by 20% increments between 0 m/s and the fastest average velocity for each participant.

Statistical Analysis

Pearson product correlational analyses were performed among all dependent variables[16]. The FVP variables include slope, area under the FVP line, and area under the FVP line within velocity-specific ranges (5 cFVP ranges, 5 eFVP ranges). The jumping performance variables include CMJ height, CMJ RSImod, CMJ eccentric RFD, SJ height, SJ RSImod, SJ RFD, DJ height, and DJ RSI. Correlations were performed between eccentric and concentric FVP area, and then among all the FVP characteristics and all jumping performance variables. Bootstrapping was performed on the correlations to determine 95% confidence intervals. Percentile bootstrap was performed manually via resampling with replacement (tidyverse) using 1000 iterations[17].

RESULTS

The correlation between eFVP and cFVP areas was r = 0.51 ($p < .025$). Correlational results between FVP (slopes and areas) and jumping performance variables with 95% confidence intervals are displayed below (Tables 1-4). Descriptive statistics for single subject and group means are displayed in Table 5. cFVP and eFVP are displayed in Figure 1.

DISCUSSION

FVP has become a common assessment for athletic performance practitioners to administer individualized loading schemes in training programs to improve jump height or maximize power. Recent research from Samozino et al. has presented evidence to support an optimal cFVP slope to produce maximum squat jump height, from which an imbalance could dictate the partitioning of training volumes toward speed and strength[1,3,8]. These researchers

Table 1. FVP area correlation matrix to jump performance with lower and upper bound 95% confidence intervals. Correlations are bolded if the lower bound is above 0.

	eFVP Area	cFVP Area	eFVP + cFVP Area
CMJ Height	**0.522** **0.097, 0.840**	**0.620** **0.275, 0.834**	**0.656** **0.263, 0.889**
CMJ RSImod	0.392 -0.003, 0.756	**0.623** **0.153, 0.826**	**0.582** **0.120, 0.853**
CMJ eRFD	0.346 -0.076, 0.637	0.246 -0.237, 0.588	0.341 -0.121, 0.631
SJ Height	0.408 -0.305, 0.802	0.233 -0.426, 0.720	0.368 -0.489, 0.841
SJ RFD	-0.147 -0.558, 0.414	0.272 -0.335, 0.610	0.071 -0.406, 0.528
DJ Height	**0.578** **0.304, 0.811**	**0.672** **0.410, 0.830**	**0.718** **0.393, 0.890**
DJ RSI	**0.468** **0.062, 0.753**	0.447 -0.078, 0.750	**0.526** **0.110, 0.798**

Table 2. eFVP and cFVP slope correlations to jump performance with lower and upper bound 95% confidence intervals. Correlations are bolded if the lower bound is above 0.

	eFVP Slope	cFVP Slope
CMJ Height	0.222 -0.181, 0.678	0.387 -0.003, 0.633
CMJ RSImod	0.036 -0.433, 0.548	**0.460** **0.056, 0.702**
CMJ eRFD	0.138 -0.357, 0.6148	0.188 -0.208, 0.515
SJ Height	0.192 -0.400, 0.701	0.191 -0.364, 0.617
SJ RFD	-0.000 -0.317, 0.429	0.557 -0.059, 0.849
DJ Height	0.251 -0.037, 0.576	**0.570** **0.288, 0.761**
DJ RSI	0.122 -0.345, 0.539	0.150 -0.254, 0.520

Table 3. cFVP velocity-specific area correlations to jump performance with lower and upper bound 95% confidence intervals. Correlations are bolded if the lower bound is above 0.

	cFVP Area 0-0.5 m/s	cFVP Area 0.5-0.75 m/s	cFVP Area 0.75-1 m/s	cFVP Area 1-1.3 m/s	cFVP Area >1.3 m/s
CMJ Height	0.212 -0.189, 0.682	0.268 -0.076, 0.635	**0.639** **0.230, 0.820**	**0.606** **0.270, 0.746**	**0.537** **0.069, 0.800**
CMJ RSImod	0.132 -0.252, 0.587	0.164 -0.253, 0.512	**0.507** **0.097, 0.758**	**0.610** **0.346, 0.780**	**0.578** **0.153, 0.838**
CMJ eRFD	-0.027 -0.449, 0.362	0.033 -0.364, 0.382	-0.004 -0.458, 0.449	0.230 -0.270, 0.558	0.266 -0.202, 0.585
SJ Height	0.084 -0.373, 0.497	0.138 -0.266, 0.500	0.382 -0.260, 0.705	0.246 -0.328, 0.598	0.184 -0.579, 0.704
SJ RFD	-0.326 -0.606, 0.111	**-0.374** **-0.655, -0.002**	0.091 -0.396, 0.467	0.233 -0.218, 0.579	0.388 -0.272, 0.707
DJ Height	0.011 -0.425, 0.463	0.140 -0.295, 0.526	**0.577** **0.213, 0.739**	**0.645** **0.378, 0.753**	**0.654** **0.333, 0.862**
DJ RSI	0.317 -0.169, 0.706	0.196 -0.243, 0.672	0.457 -0.061, 0.796	0.465 -0.112, 0.773	0.349 -0.133, 0.640

Table 4. eFVP velocity-specific area correlations to jump performance with lower and upper bound 95% confidence intervals. Correlations are bolded if the lower bound is above 0.

	eFVP Area 0-20% m/s (Slowest)	eFVP Area 21-40% m/s	eFVP Area 41-60% m/s	eFVP Area 61-80% m/s	eFVP Area 81-100% m/s (Fastest)
CMJ Height	0.396 -0.034, 0.762	**0.452** **0.037, 0.828**	**0.522** **0.122, 0.823**	**0.587** **0.219, 0.873**	**0.582** **0.179, 0.858**
CMJ RSImod	0.219 -0.234, 0.685	0.291 -0.167, 0.738	0.392 -0.060, 0.740	**0.513** **0.101, 0.769**	**0.595** **0.100, 0.819**
CMJ eRFD	0.254 -0.145, 0.627	0.295 -0.108, 0.625	0.346 -0.027, 0.644	**0.396** **0.084, 0.662**	**0.402** **0.132, 0.708**
SJ Height	0.301 -0.552, 0.766	0.348 -0.470, 0.794	0.408 -0.351, 0.783	0.465 -0.117, 0.803	0.470 -0.107, 0.806
SJ RFD	-0.092 -0.473, 0.406	-0.116 -0.502, 0.363	-0.147 -0.573, 0.357	-0.184 -0.117, 0.284	-0.204 -0.605, 0.365
DJ Height	**0.435** **0.084, 0.658**	**0.498** **0.156, 0.716**	**0.578** **0.272, 0.787**	**0.653** **0.406, 0.859**	**0.651** **0.362, 0.877**
DJ RSI	0.293 -0.174, 0.657	0.367 -0.079, 0.680	**0.468** **0.041, 0.757**	**0.584** **0.199, 0.797**	**0.648** **0.318, 0.851**

Table 5. Single subject and group means of jumping performance.

Participant	CMJ Height	CMJ RSImod	CMJ eRFD	SJ Height	SJ RFD	DJ Height	DJ RSI
1	0.39	0.55	7287.53	0.38	9583.31	0.45	1.21
2	0.38	0.60	7965.59	0.37	2950.35	0.46	0.98
3	0.36	0.46	5444.61	0.35	4884.08	0.33	1.10
4	0.35	0.51	6051.19	0.30	4882.81	0.37	0.85
5	0.40	0.45	4377.66	0.38	9501.69	0.45	1.10
6	0.44	0.55	3778.58	0.42	8887.14	0.47	1.22
7	0.44	0.58	4379.70	0.40	8669.64	0.46	1.16
8	0.40	0.46	3305.65	0.41	6144.69	0.39	0.79
9	0.36	0.43	3127.87	0.33	9940.56	0.39	0.80
10	0.37	0.44	6571.65	0.37	6214.49	0.43	0.90
11	0.56	0.66	5579.85	0.51	2136.23	0.57	1.03
12	0.32	0.44	5358.31	0.35	6374.88	0.38	0.71
13	0.38	0.45	4647.99	0.34	3417.97	0.40	0.88
14	0.52	0.67	7892.47	0.47	4882.81	0.49	1.25
15	0.28	0.40	8683.45	0.26	3487.72	0.34	0.72
16	0.41	0.54	6221.89	0.40	9055.86	0.43	0.98
17	0.43	0.65	8592.97	0.36	8235.58	0.46	1.11
18	0.39	0.50	7189.14	0.29	8953.53	0.44	1.02
19	0.37	0.47	5989.44	0.39	2441.41	0.42	1.23
Mean	**0.40**	**0.52**	**5918.19**	**0.37**	**6349.72**	**0.43**	**1.00**
Standard Deviation	**0.06**	**0.08**	**1717.85**	**0.06**	**2694.11**	**0.06**	**0.18**

clearly state the concept of an optimal cFVP slope would only apply to the squat jump movement, and the optimization of the cFVP slope, or balancing of speed and strength qualities, would only improve squat jump height if power was maintained (i.e. an improvement in power could increase jump height regardless of cFVP slope)[1,3,8]. Thus, the proposal of an optimal slope may not apply to populations with the potential to meaningfully improve power, or whose performance may be based on more complex movements. Indeed, recent research reported no association between cFVP slopes and jumping performance in competitive female soccer players and young male volleyball players[4,5], in addition to ineffective outcomes from training programs individualized with cFVP slopes in national level team sport athletes and older men[6,7]. The results of our current study, which included both eFVP and cFVP, indicate the relationship was nonexistent between eFVP and cFVP slopes and CMJ, SJ, and DJ performance except for moderate and strong relationships between cFVP slope and CMJ RSImod and DJ height, respectively (table 2). To audit these relationships *post hoc*, we separated the FVP slopes into three tertiles- since a balanced or optimal FVP slope may occur around the median slopes- and the correlational results remained insignificant. However, the area under the eFVP and cFVP, which is the product of force and velocity and thus a representation of power, displayed moderate to strong relationships to CMJ height, CMJ RSImod, DJ height, DJ RSI, but not SJ height. These data suggest the current subject pool of NCAA Division I baseball players are not at a stage of development where the FVP slope is a relevant guide for training and should emphasize increasing the area under the FVP (increasing power) before training programs explore rebalancing or optimizing the FVP slope. Therefore, many athletes, even at "elite" or "national" levels of competition, are not likely to have reached their full potential for power production and may not benefit from slope optimization.

A second important result of the study was the velocity-specific areas under the eFVP and cFVP and their relationship to jumping performance. Concen-

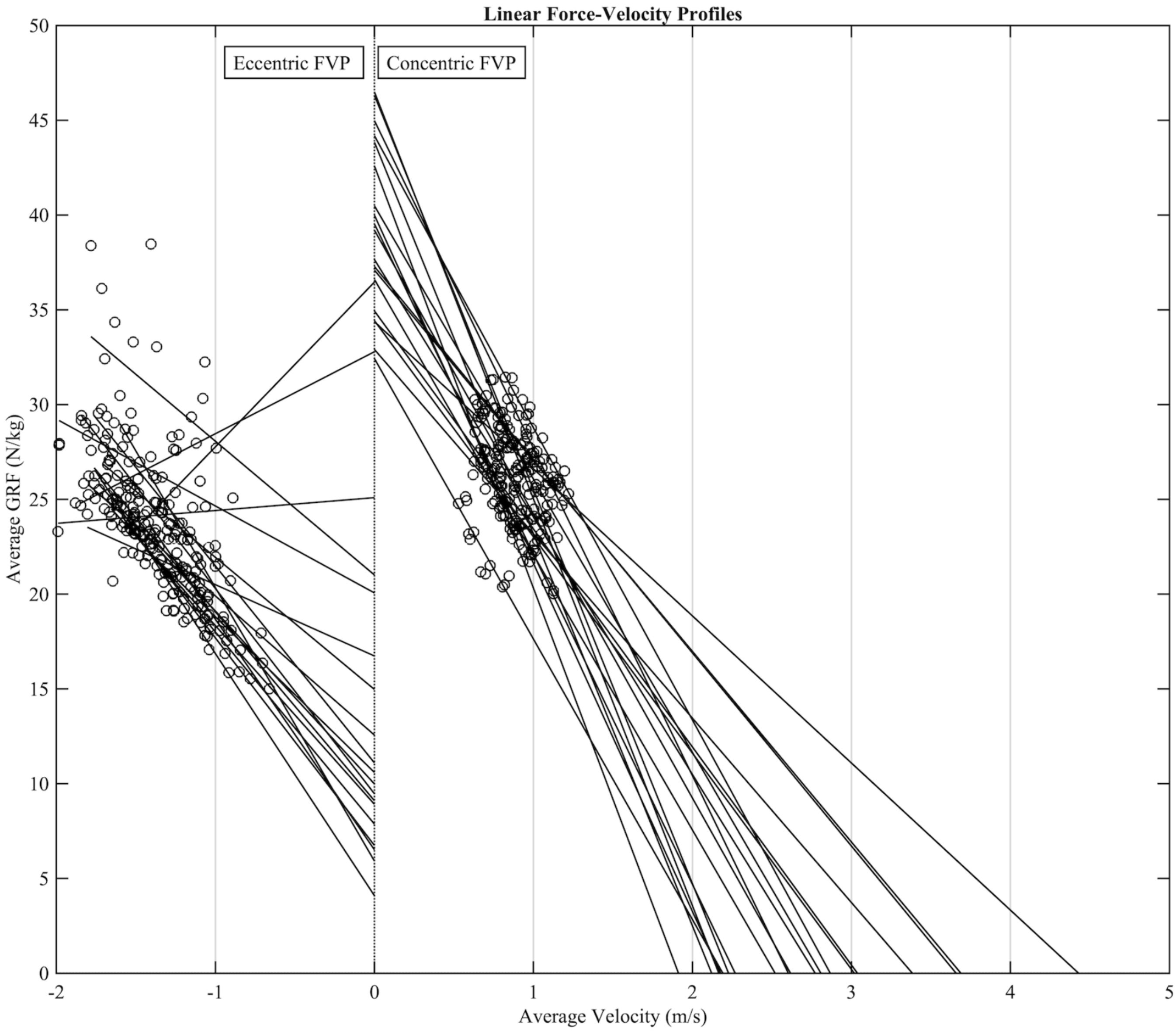

Figure 1. Single subject eccentric and concentric FVP side by side.

trically, we found no relationship between the slow velocity areas (0-0.5 m/s and 0.5-0.75 m/s) of cFVP and jumping performance, but strong relationships between fast velocity areas and jumping performance. We observed a similar pattern eccentrically where only the moderate to fast velocity areas of eFVP related strongly to jumping performance with exception of DJ height presenting moderate to strong relationships with all eccentric velocity-specific areas. These outcomes suggest power production during moderate and fast velocities is of greatest relevance for bodyweight jumping performance. However, the FVPs are linear regression lines with limitations that must be acknowledged and understood before practitioners can make effective and contextual use of an FVP.

The extrapolation of a regression line beyond actual data can present false improvements at the velocity and force intercepts. For example, if an athlete were to decrease performance during the slowest trials while maintaining performance in the fast and moderate speed trials, the FVP would display a decrease in force intercept, but also an increase in the velocity intercept despite no measurable changes in any of the fastest trials[18]. In the current study, only 3 hex bar jump trials across the entire subject pool were performed with an average velocity greater than 1.3 m/s. However, we observed strong relationships between cFVP area greater than 1.3 m/s and jumping performance. Because area under the cFVP beyond 1.3 m/s is predominantly hypothetical and can be increased by reductions in strength, researchers and practitioners must remain cautious to not overreact to cFVP results. A primary training goal should be to increase the area under the cFVP across all velocities for complete athletic development, even if those improvements lead to slope imbalances. In a hypothetical case, increasing area under the faster FVP regions may be challenging and require large training volumes for minimal improvements while increases in strength may be attainable with moderate training volumes. This hypothetical athlete would be measurably better by total area under the FVP with moderate strength improvements and speed maintenance rather than strength maintenance and minimal speed improvement. However, their linear cFVP would present a decrease in theoretical maximal velocity due to the increased strength and maintained speed qualities- a false negative because they did not *actually* get slower[18]!

The eFVP does not present a hypothetical constraint in the high velocity range because the 81-100% velocity window terminates at the fastest trial. However, the slow eccentric velocities do require consideration because the task of landing from 0.3 m is submaximal. Participants were encouraged to land as quickly as possible to elicit maximal effort, but the eFVP created from drop landings does not resemble the eFVP derived from classical isokinetic eccentric torque production at 60, 180, and 300 degrees/sec, for example. Thus, linear regression limitations may be similarly volatile and sensitive during slow eccentric velocities (drop landings) and fast concentric velocities (hex bar jumps), but for different reasons. If an athlete lands from the low box height (0.3m) softly with low average force, it could artificially steepen the eFVP slope and increase the high velocity eFVP area. In contrast, a stiff landing from the low box could artificially decrease or flatten the eFVP slope, thus artificially decreasing the high velocity eFVP area.

PRACTICAL APPLICATIONS

Strength coaches and sport scientists have always been interested in force-velocity relationships to optimize velocity-based training prescriptions and the assessment of athleticism. In part, the slope of the FVP has gained attention because practitioners receive a single value to direct training toward speed or strength training. However, emphasizing a singular slope value overlooks the primary objective of increasing the working effect, or power, of the *competition movement*. Further, the slope becomes important only when increasing power is not feasible, most often due to training plateaus or reaching a ceiling of athletic potential. The *competition movement* varies widely across sports and individual testing variability creates a critical limitation for the application of FVP to sport. The results of the current study suggest even competitive collegiate athletes have room to improve power, but also highlights the varied correlations among velocity-specific force production and three common jump tests. The CMJ, SJ, and DJ are useful for controlled laboratory tests, but remain elementary in comparison to complex sport and competition movements. A gross imbalance in FVP slope derived from a squat jump may be a consequence of optimizing performance for another sporting movement (e.g. sprinting, throwing, change of direction, weightlifting). Therefore, we advise strength coaches and sport scientists to explore the utility of FVP for their context and restrain from epitomizing an optimal FVP slope derived from squat jumps or drop landings. The area under the FVP, especially when separated into velocity-specific bands, may be a key metric which can audit or provide insight into velocity-based training program effectiveness and athlete comparisons across sports or different positions within the same sport. Fast eccentric and concentric force production, which were strongly related to CMJ and DJ performance, should be emphasized in research and training programs for jumping athletes.

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