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Force-Velocity Profiles in Collegiate American Football Players

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ABSTRACT

The application of force-velocity (FV) profiling in American football has yet to be explored. **Purpose:** To measure and compare FV profiles in collegiate American football players grouped by position, and to determine if FV profiles could predict countermovement jump (CMJ) height and sprinting performance. **Methods:** Horizontal and vertical FV profiles, CMJ and sprinting performance were assessed in 81 collegiate American football players. One-way ANOVAs were used to determine if significant differences in FV profiles existed between position groups (big: offensive/defensive lineman, big skill: linebacker, skill: quarterback). Correlation analyses were used to determine if performance measures (CMJ, sprints) were related to FV profiles (maximum force, F0, maximum velocity, V0, maximum power, Pmax). We hypothesized that 1) "big" athletes would have the highest F0, and 2) horizontal and vertical FV profiling metrics would correlate with sprinting performance and CMJ height, respectively. **Results:** "Big" athletes had the highest absolute F0 in the horizontal FV profiles but when normalized to body weight, they had the lowest F0 and 77% were classified as force-deficient. When accounting for body weight, vertical FV metrics explained 62.8% of the variance in CMJ height and horizontal FV metrics accounted for 85.0% of the variance in sprinting performance. **Conclusion:** Athletes' FV imbalance could not be predicted by their position. Vertical- and horizontal-related FV variables predicted performance metrics that were performed in the same plane, suggesting that FV profiling could be a useful performance assessment tool in American football.

Keywords: performance, athletic profiling, running speed, sprinting performance, muscular strength, jump height

INTRODUCTION

American football is an intermittent, high-intensity sport played in 3-5 second bursts with 20-40 seconds of rest between each play at the Division I level.[1] The athletic demands during these 3-5 seconds are position-specific, but all positions require speed, strength, and power.[2-4] These performance characteristics are interrelated, where power is the product of force and velocity and an optimal relationship between force and velocity exists.[5] An imbalance results when an athlete deviates from their individualized optimal force-velocity (FV) profile,[5-7] which is identified as velocity or force deficiency. Athletes can optimize maximal power output (Pmax) by either increasing force or increasing velocity without a decrease in the opposing metric.[2]

An athlete who can produce a sufficient amount of force, but lacks the ability to create force quickly would be classified as velocity-deficient. In contrast, an athlete who produces force quickly but is unable to produce high amounts of force, would be force-deficient. Thus, FV profiling is used to assess an individual's imbalance between force and velocity and in turn supports the development of training programs that are designed to correct the imbalance between force and velocity, thereby maximizing Pmax and athletic performance.[8,9]

FV profiling is a validated and objective approach that determines the relationship between an athlete's force- and velocity-producing capabilities in both horizontal and vertical planes of movement.[6-13] FV profiling has been used to characterize an athlete's ability to generate power and design optimized training to enhance athletic performance in sports such as soccer,[9] rugby,[9,11] and ice hockey.[12] Yet, to our knowledge, FV profiles have not been measured in American football athletes.

Strength and conditioning coaches generally rely on subjective observations of the athletes' pre-season fitness and previous playing experience to design a training regimen for the athletes.[14] Whereas, FV profiles could be used to quantify FV imbalances, providing an alternative, objective approach. Based on empirical evidence, American football coaches often assume that the "big" athletes can produce large force, so these athletes should focus on velocity training. Likewise, the smaller athletes are assumed to require strength training. Whether these assumptions are true is unknown. Therefore, we sought to use FV profiling to determine the maximal force (F0), maximal velocity (V0), and maximal power (Pmax) in both the vertical and horizontal planes of movement in collegiate American football players. The first purpose of this exploratory, cross-sectional study was to compare FV measures between position groups to determine if subjective observations could predict FV imbalances. We hypothesized that the "big" athletes of the offensive and defensive line would have the highest F0 in both the vertical and horizontal FV profiles, and thus their training program should focus on velocity development. We also hypothesized that the athletes in the "skills" group (i.e., quarterback, wide receiver, cornerback, safety) would have the highest vertical V0 and the resultant training program should focus on strength or force development.

Performance metrics such as sprint (flying-10) performance, vertical countermovement jump (CMJ) height, 1-repetition maximum (1-RM) power clean, and 1-RM back squat are used to assess athletic performance during the season. Since this study was designed to explore the application of FV profiling in football, we sought to understand the relationship between performance metrics and FV profiling variables. Thus, the second purpose of this study was to determine if horizontal and vertical FV profiling metrics correlate to American football performance metrics, and if FV profiling variables could explain the variance in performance metrics. We hypothesized that horizontal FV profiling metrics would correlate with flying-10 speed and vertical FV profiling variables would correlate with vertical countermovement jump (CMJ) height.

METHODS

Participants

This study incorporated a convenience sample of 81 Division 1 American football players 20.5±1.6 years (mean±SD). Participants were categorized into one of the following positional groups: 1) Big (offensive lineman and defensive line), 2) Big Skill (linebacker, tight end, running back), or 3) Skill (quarterback, wide receiver, cornerback, safety), or 4) Specialist (kicker, punter, long snapper). Table 1 shows the number of players allocated to each group with their average height and weight. Prior to the study, participants were deemed healthy by the university's sports medicine staff and all participants provided informed consent. All participants previously engaged in structured collegiate strength and conditioning protocols prior to study inclusion and had familiarity with the prescribed sprint and jumping protocols. This study was approved by the University's Institutional Review Board for Human Studies (IRB# 2022-00845).

Protocol

Anthropometric measurements were collected the week prior to performance testing. Body mass was measured with an analog scale (Toledo Scale Company, OH), and lower limb length (distance from the anterior superior iliac spine (ASIS) to toes with ankle plantarflexion with shoes), and initial hip height (distance from ASIS to the floor with knees

Table 1. Participant characteristics (mean ± SD).

	N	Age (years) (mean ± SD)	Weight (kg) (mean ± SD)	Height (cm) (mean ± SD)
Big	27	20.4 ± 1.8	124.6 ± 16.1	188.9 ± 6.5
Big Skill	21	20.6 ± 1.6	93.9 ± 10.3	179.7 ± 5.8
Skill	30	20.5 ± 1.5	80.4 ± 16.3	182.2 ± 5.5
Specialist	3	22 ± 0	94.4 ± 7.1	184.3 ± 12.1
Overall	81	20.5 ± 1.6	98.1 ± 23.8	183.8 ± 7.1

flexed 90° while seated on a plyometric box) were measured with a tape measure. Knee flexion at 90° was determined by aligning a square on the lateral side of the right knee joint so that the arms of the square aligned with the midline of the thigh and midline of the shin.

The first day of testing consisted of both horizontal and vertical FV profile testing. The second day of testing consisted of flying-10 sprints and 1-RM power clean testing. On the third day, participants performed the CMJ and 1-RM back squat. Participants were given 24-48 hours of rest between each testing day. Testing took place on a turf field and in a weight room at the same time of day and in similar environment conditions, in which participants were accustomed to sprinting and jumping training, respectively.

All participants began the session with a standardized dynamic warm-up prior to maximum velocity training days. Participants were given at least 5 minutes of rest after the warm-up prior to the sprint trial testing. FV profiling was conducted using methods described in previous studies.[5,14,15] Sprints were recorded on an Apple iPad camera (6th generation, Cupertino, CA, USA).[16] Speed sticks (tall vertical cones) were placed at 5 m, 10 m, 15 m, 20 m, 25 m, and 30 m distances and were used as markers to measure the time it took for the athlete to cover each 5 m distance (figure 1).

Participants started from a two-point, staggered stance and were instructed to self-select the lead foot. Verbal encouragement was given to all participants and they were instructed to run as fast as they could for the entire duration of the 30 m sprint. Video analysis was used to determine the split times for each 5 m distance based on when the participants' midline of the pelvis was in line with the speed stick. The video-based timer was initiated on the first propulsive movement and each 5 m split was determined and entered into the MySprint application, a validated iOS application (Pedro Jimenez Reyes, Madrid, Spain). These processes and prediction equations have been previously validated by Samozino and colleagues.[9,11,17] From these predictive equations, horizontal F0, horizontal V0, and FV imbalance (FVimb) were estimated by the MySprint application. An FVimb value <60, 60-90, >90-100, >110-140, or >140 indicated that the athlete scored in the category of high force deficit, low force deficit, well-balanced, low-velocity deficit, or high-velocity deficit, respectively.[6]

All athletes were given 20-25 minutes of rest time to transition from the sprint testing to the jump assessment. The vertical force-velocity profile assessment included a series of 10-15 unloaded and loaded squat jumps. Participants were verbally cued to squat to the plyometric box with 90° of knee flexion, hold this position for 2 seconds, and then jump as forcefully and quickly as possible. Participants were not allowed to use a countermovement and trials were visually confirmed to follow these guidelines. Jump height was measured using JustJump! mats (Probotics Inc., 8692 Esslinger Court, Huntsville, AL). Similar methods were used for each jump trial for both unloaded and loaded conditions. Any deviation

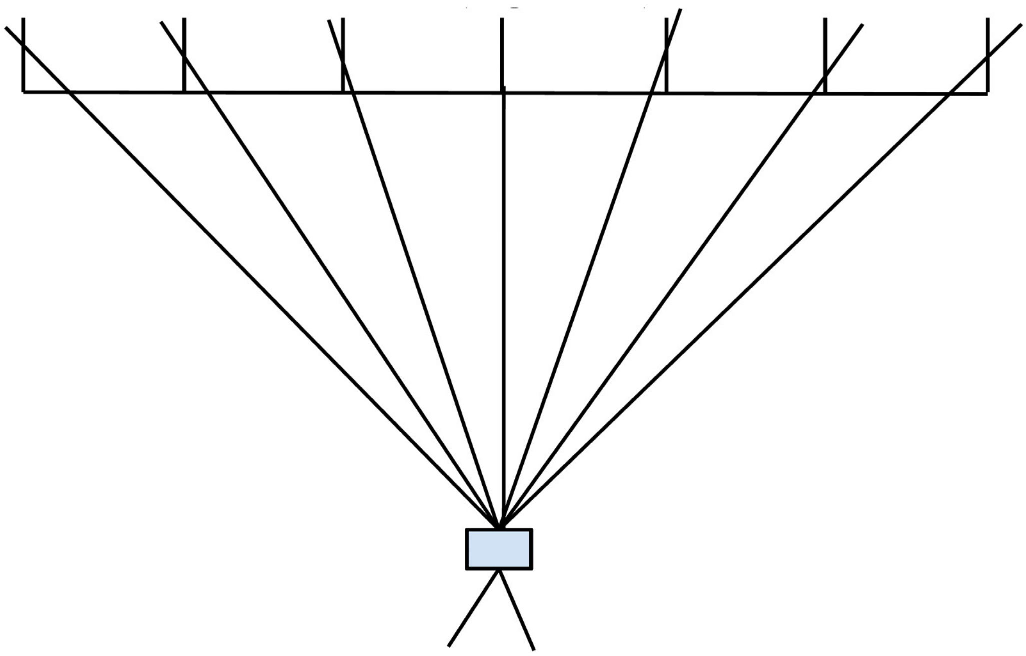

Figure 1. Set up of camera and markers for the 30 m sprint.

from this protocol required the participants to repeat the trial. To ensure consistency of body position, the unloaded squat jumps were performed with unweighted wooden dowels (0.2 kg, which was included in calculations). Participants were instructed to keep their hands on the dowel or bar throughout the entire trial. Jumps were tested unloaded and with 20 kg, 40 kg, 60 kg, and 80 kg of additional weight on the barbell. A minimum of two successful jumps were required at each load and 2-3 minutes of rest was given between each jump trial. The highest recorded jump height was used in the subsequent analyses. An open source spreadsheet (https://jbmorin.net/2017/10/01/a-spreadsheet-for-jump-force-velocity-power-profiling/), which is pre-populated with prediction equations, was used to determine vertical F0, vertical V0, and vertical Pmax.[5,6,13-15]

A standardized dynamic warm-up identical to the horizontal FV profile test day was used prior to flying-10 testing. Following the warm-up, participants were given 5-7 minutes of recovery, in which flying-10 instructions were given. All participants were familiar with flying-10 sprints but were reminded to build up to maximal running velocity during the initial 10 or 20 yards, and then maintain their maximal velocity through the end of the timing gates over the next 10 yards (Brower, Draper, UT). Three trials were collected and the best time was used in data analyses. Five recovery minutes were provided between trials. All "bigs" (offensive and defensive linemen) were given 10 yards to build up to their top sprinting speed, while all other positions were given 20 yards.

Participants had a minimum of 8 weeks of collegiate strength and conditioning training prior to the study, which included power clean training. Prior to their 1-RM attempt, participants completed 2 repetitions at 60% and 70% of their estimated 1-RM, and 1 repetition at their estimated 75%, 80%, 85%, and 90% 1-RM. Based on their attempt at 90% 1-RM, the administrator assigned the next weight by adding 5-10% to the last weight. Participants were given 3 attempts to achieve their 1-RM.

All participants were instructed to squat so that their hips dipped below their knees and the top of their thighs were parallel to the ground, which was visually confirmed by the administrator. Based on the previous weight lifted during their 8-week training period. Methods similar to the power clean method were used with the exception being 77%, 82%, 87%, and 92% 1-RM were used to build up to a 1-RM. Based on the load lifted at 92%-1RM, the administrator estimated an additional 8% weight for the final attempt. To ensure safety, one spotter stood behind the subject and two additional spotters were placed on either side of the athlete.

Statistical Analysis

The estimated sample size for multiple linear regression with 5 predictors (independent variables: clean 1-RM (kg), squat 1-RM (kg), CMJ (m), flying-10 (s), %IMB) was calculated using G*Power (Version 3.1.9.7). Previously reported data comparing position groups and physical performance characteristics report medium effect sizes.[18] Thus, considering a medium Cohen's f^2 effect size (0.15), with 5% type I error, 95% power, and 5 predictors, the estimated sample size was 74 participants.

Descriptive statistics were calculated for all measures. Normality was tested using the Shapiro-Wilk test. A one-way ANOVA and Tukey's post-hoc statistical analysis tests were performed to determine if FV profiling differences existed between positional groups. Since the specialist group only had 3 athletes, data from these athletes were not used in the ANOVA. In addition, the magnitude of group differences in horizontal and vertical FV profile metrics, F0, V0, and Pmax, were assessed using Cohen's d. Effect sizes (ES) of 0.2, 0.5, and 0.8 were deemed small, moderate, or large, respectively.[19]

Regression and correlation analyses were performed to determine if FV profile variables were related to football performance metrics. Pearson's correlation coefficients were calculated to examine the relationships between measures of horizontal and vertical F0, V0, and Pmax with performance measures (1-RM clean and back squat, flying-10, and CMJ). Pearson's r of 0.2-0.39, 0.4-0.59, 0.6-0.79, and > 0.8 were used to denote weak, moderate, strong, and very strong relationships, respectively.[19]

Multiple linear regression was also used to determine if vertical F0, vertical V0, vertical Pmax and %FVimb could predict CMJ with and without adjusting for body weight. A second multiple linear regression was used to determine if horizontal F0, horizontal V0 and horizontal Pmax could predict flying-10 performance with and without adjusting for body weight. A variance inflation factor (VIF) greater than 5 was used to identify multicollinearity.[20] Force

Table 2. Results and Effect Sizes from the Horizontal and Vertical Force-Velocity Profile

	Variable	BIG (n=27) (mean ± SD)	BIG SKILL (n=21) (mean ± SD)	SKILL (n=30) (mean ± SD)	SPEC (n=3) (mean ± SD)	Overall (n=82) (mean ± SD)	Effect Size (Cohen's d) BIG VS. BIG SKILL	BIG VS. SKILL	BIG SKILL VS. SKILL
Horizontal FV Profile	V0 (m/s)	8.6 ± 1.0	9.1 ± 0.9	9.3 ± 0.9	8.0 ± 0.4	9.0 ± 1.0	0.5	0.7	0.2
	F0 (N)	685.7 ± 188.8	610.3 ± 167.6	562.1 ± 96.6	579.9 ± 103.7	615.8 ± 157.7	0.4	0.8	0.4
	F(N/kg)	5.5 ± 1.3	6.6 ± 1.5	6.8 ± 1.1	6.1 ± 1.0	6.3 ± 1.4	0.8	1.1	0.2
	Pmax (W)	1434.6 ± 275.1	1364.4 ± 287.6	1288.5 ± 168.3	1153.4 ± 157.1	1351.9 ± 247.9	0.2	0.6	0.3
	P(W/kg)	11.6 ± 2.3	14.5 ± 2.5	15.7 ± 2.4	12.2 ± 1.5	13.9 ± 2.9	1.4	1.7	0.3
Vertical FV Profile	V0 (m/s)	3.9 ± 0.7	3.7 ± 0.7	3.0 ± 4.4	3.3 ± 0.2	3.8 ± 1.0	0.3	0.1	0.1
	F0 (N)	5240.4 ± 627.0	4968.5 ± 1047.6	4313.5 ± 634.9	4297.0 ± 113.0	4791.7 ± 848.3	0.3	1.5	0.8
	F(N/kg)	42.5 ± 5.9	52.9 ± 8.2	54.0 ± 8.3	45.8 ± 45.9	49.4 ± 8.9	1.5	1.6	0.1
	Pmax (W)	5032.9 ± 605.6	4541.5 ± 974.3	4005.9 ± 1027.1	3576.0 ± 213.2	4471.1 ± 979.3	0.6	1.2	0.5
	Pmax (W/kg)	40.8 ± 5.9	48.4 ± 8.6	48.3 ± 10.3	38.0 ± 2.4	45.0 ± 7.6	1.1	0.9	0.2
	%IMB	74.6 ± 21.9	96.2 ± 27.6	99.6 ± 29.0	95.3 ± 11.5	90.2 ± 27.9	0.9	1.0	0.1

Big: offensive and defensive lineman, Big Skill: linebacker, tight end, running back, Skill: quarterback, wide receiver, cornerback, safety, Specialist: kicker, punter, long snapper; F0: maximum theoretical force output; V0: maximum theoretical velocity output, Pmax: maximum power output, %IMB: imbalance between optimal FV profile and measured FV profile.

Table 3. Number of athletes (n) grouped by position and force-velocity profile.

	Force-deficient	Velocity-deficient	Well-balanced
Big (n=27)	21	2	4
Height (m)	1.9 ± 0.1	1.9 ± 0.1	1.9 ± 0.1
Weight (kg)	127.3 ± 15.0	112.0 ± 3.2	118.7 ± 4.0
Big Skill (n=21)	9	5	7
Height	1.8 ± 0.1	1.8 ± 0.04	1.8 ± 0.1
Weight (kg)	96.9 ± 13.2	91.0 ± 9.0	92.3 ± 3.7
Skill (n=30)	12	9	9
Height (m)	1.9 ± 0.04	1.8 ± 0.1	1.8 ± 0.04
Weight (kg)	88.1 ± 8.0	82.0 ± 8.3	76.6 ± 7.1
Specialist (n=3)	1	0	2
Height (m)	2.0	-	1.8 ± .0.2
Weight (kg)	102.5	-	90.3 ± 1.3

Height and weight are reported (means ± SD) except in cases where there are less than 2 subjects in each group. Big: offensive and defensive lineman, Big Skill: linebacker, tight end, running back, Skill: quarterback, wide receiver, cornerback, safety, Specialist: kicker, punter, long snapper.

and velocity are related to power, so multicollinearity would be expected. Since this exploratory study aimed to determine if the variance in CMJ and sprinting ability could be explained with FV profiling metrics, and the goal was not to develop prediction equations, all variables were kept in the multiple regression analysis regardless of the VIF. Statistical significance was set at $P<0.05$. Statistical analysis was performed using GraphPad Prism version 9.2 for MacOS (GraphPad Software, San Diego, California USA).

Table 3 shows the number of participants, height and mass in each position group, categorized by force-deficient, velocity-deficient, or well-balanced FV profiles. Within each position group, there was a mixture of force-deficient, velocity-deficient and well-balanced athletes.

Table 4 contains the one-way ANOVA results between position groups. There was a significant main effect of position for the horizontal variables, V0, absolute and relative F0, and relative Pmax ($P<0.05$), but not absolute Pmax ($P>0.05$). With regard to the vertical FV profile, there were significant differences between position groups in absolute and relative F0, and absolute and relative Pmax ($P<0.05$) but not V0 ($P>0.05$).

Tukey's post-hoc tests revealed significant differences in the horizontal FV profile between the Big and Skill position groups for the following variables: V0, absolute and relative F0 and relative Pmax ($P<0.05$). Also, significant differences were detected between the Big and Big Skill groups in relative F0 and relative Pmax ($P<0.05$). In the vertical FV profile, there were significant differences between the "Big" and "Skill" groups for all variables, i.e., absolute and relative F0, and absolute and relative Pmax ($P<0.05$). Similarly, there were significant differences between the "Big Skill" and "Skill" groups in absolute F0 ($P<0.05$).

Table 5 shows the Pearson coefficient analysis and simple linear regression results comparing the horizontal FV profiling variables and performance results. Table 6 shows the results of the correlation analysis and simple linear regression between the vertical FV profile and performance results.

Table 7 shows the multiple regression analysis results performed with (model 2) and without (model 1) controlling for body weight for the prediction of CMJ from the vertical FV profile. Model 1 shows that absolute F0, V0, Pmax and %FVimb in the vertical plane explained 33.4% of the variance in CMJ. In this model, all variables (absolute F0, absolute Pmax, percent FV imbalance) were significant predictors ($P<0.05$) with the exception of vertical V0 ($P=0.264$). While model 2, which accounts for body weight, shows that 62.8% of the variance in CMJ could be explained by the variables, only absolute Pmax and body weight remained significant predictors ($P<0.05$). Figure 2 illustrates normalized FV data.

Table 8 shows the multiple regression analysis results with (model 2) and without controlling for weight (model 1) in predicting flying-10 performance from the horizontal FV profile. Model 1 shows that 85.0% of the variance in flying-10 performance can be explained by absolute F0 and Pmax in the horizontal plane, but absolute V0 was not a significant predictor ($P=0.0545$). When accounting for body weight in model 2, body weight, horizontal absolute F0 and Pmax explained 85.0% of the variance in flying-10 performance ($P<0.05$), and absolute V0 remained a non-significant predictor ($P<0.05$).

DISCUSSION

The first aim of this study was to use horizontal and vertical FV profiling to compare F0, V0, and Pmax among position groups in collegiate American football players. To our surprise, the findings suggest that while the mean F0 for the "Bigs" group was the highest among all position groups for both horizontal and vertical FV profiles, i.e., 77% (21 of 27) of the "Bigs" were considered force-deficient relative to their velocity. This observation is important because we hypothesized that the "Bigs" would have the highest F0 in both the vertical and horizontal FV profiles and thus their resultant program should focus on velocity development. However, the results suggest that the "Bigs" would benefit most from force-focused training which would optimize their FV profile and lead to enhanced athletic performance.[5,6,10] Speculatively, this may be explained by the required need for these athletes to produce greater force to propel themselves when sprinting or jumping to overcome their larger body mass. The key finding from the present study is that the assumptions about an athlete's FV profile should not be made based on their position.

We also hypothesized that the "skills" athletes (i.e., quarterback, wide receiver, cornerback,

Table 4. One-way ANOVA analysis comparing position groups

	Main Effect of Position			Tukey's Post-hoc		
Horizontal FV Profile						
Dependent variable	**F**	**df**	***P* value**	**Comparison**	**Mean difference**	**P value**
V0 (m/s)	4.56	2, 75	0.014*			
				Big vs. Big Skill	-0.54	0.123
				Big vs. Skill	-0.73	0.012*
				Big Skill vs. Skill	-0.19	0.752
F0 (N)	4.78	2, 75	0.011*			
				Big vs. Big Skill	75.41	0.216
				Big vs. Skill	125.4	0.008*
				Big Skill vs. Skill	50	0.489
F0 (N/kg)	6.97	2, 75	0.002*			
				Big vs. Big Skill	-0.95	0.048*
				Big vs. Skill	-1.32	0.001*
				Big Skill vs. Skill	-0.37	0.614
Pmax (W)	2.57	2, 75	0.0836			
Pmax (W/kg)	21.5	2, 75	<0.0001*			
				Big vs. Big Skill	-2.89	0.0002*
				Big vs. Skill	-4.07	<0.0001*
				Big Skill vs. Skill	-1.18	0.197
V0 (m/s)	0.73	2, 75	0.483			
F0 (N)	11.05	2, 75	<0.0001*			
				Big vs. Big Skill	271.9	0.444
				Big vs. Skill	926.9	<0.0001*
				Big Skill vs. Skill	654.9	0.01*
F0 (N/kg)	18.39	2, 75	<0.0001*			
				Big vs. Big Skill	-10.3	<0.0001*
				Big vs. Skill	-11.4	<0.0001*
				Big Skill vs. Skill	-1.1	0.864
Pmax (W)	9.53	2, 75	0.0002*			
				Big vs. Big Skill	491.4	0.145
				Big vs. Skill	1027	0.0001*
				Big Skill vs. Skill	535.6	0.093
Pmax (W/kg)	6.74	2, 75	0.002*			
				Big vs. Big Skill	-7.5	0.009*
				Big vs. Skill	-7.4	0.005*
				Big Skill vs. Skill	0.14	0.998

*Each row contains results from individual one-way ANOVA. If there was a significant main effect, Tukey's post-hoc results are shown. V0: maximum theoretical velocity output, F0: maximum theoretical force output, Pmax: theoretical maximum power output, df: degrees of freedom. * P<0.05*

Table 5. Simple Linear Regression and Pearson Correlation Analysis Between Horizontal FV Profile and Performance Metrics.

	Variable	r	95% CI	R squared	*P* Value
V0 (m/s)	Clean 1-RM (kg)	0.10	-0.13 to 0.32	0.01	0.4044
	Squat 1-RM (kg)	-0.14	-0.36 to 0.09	0.02	0.2224
	CMJ (m)	0.58	0.41 to 0.71	0.33	<0.0001*
	Flying-10 (s)	-0.58	-0.71 to -0.41	0.34	<0.0001*
F0 (N)	Clean 1-RM (kg)	0.20	-0.03 to 0.41	0.04	0.0896
	Squat 1-RM (kg)	0.33	0.11 to 0.52	0.11	0.0035*
	CMJ (m)	-0.39	-0.56 to -0.19	0.15	0.0004*
	Flying-10 (s)	0.42	0.22 to 0.59	0.18	0.0001*
F0 (N/kg)	Clean 1-RM (kg)	-0.19	-0.41 to 0.04	0.04	0.1115
	Squat 1-RM (kg)	-0.19	-0.40 to 0.04	0.04	0.0982
	CMJ (m)	0.22	-0.002 to 0.42	0.05	0.0528
	Flying-10 (s)	-0.32	-0.50 to -0.10	0.10	0.0051*
Pmax (W)	Clean 1-RM (kg)	0.31	0.08 to 0.50	0.09	0.0084*
	Squat 1-RM (kg)	0.34	0.13 to 0.53	0.12	0.0024*
	CMJ (m)	-0.19	-0.39 to 0.03	0.04	0.0932
	Flying-10 (s)	0.21	-0.01 to 0.41	0.05	0.0586
Pmax (W/kg)	Clean 1-RM (kg)	-0.17	-0.39 to 0.07	0.03	0.1619
	Squat 1-RM (kg)	-0.32	-0.51 to -0.10	0.10	0.006*
	CMJ (m)	0.51	0.32 to 0.66	0.26	<0.0001*
	Flying-10 (s)	-0.62	-0.74 to -0.46	0.38	<0.0001*

F0: maximum force output; V0: maximum velocity output; Pmax: maximum power output; 1-RM: 1 repetition maximum; CMJ: countermovement jump; Flying-10: 10 yard split (seconds, s); %IMB: force-velocity imbalance from non-CMJ with 90° of knee flexion.

safety) would have the highest vertical V0 and the resultant training program should focus on force development. The skills athletes' mean vertical V0 was the highest of any position group, but the %FVimb was evenly distribute[d] among the players as they were a mixture of force-deficit, velocity-deficit, and well-balanced athletes.[14] The findings from the present study disprove our hypotheses, indicating coaches should not make assumptions about an athlete's capabilities based on their position as the "eye test" is not an accurate method for ascertaining an athletes' capabilities. Instead, FV profiling provides an objective method for determining an athlete's abilities.

We hypothesized that horizontal V0 would have a strong and positive correlation with flying-10 speed and that vertical F0 would have a strong and positive correlation with CMJ height. This hypothesis was correct as 62.8% and 85.0% of the variance in CMJ and flying-10 sprinting speed was explained by vertical and horizontal FV profiling metrics, respectively. Our data indicates that FV profiling measurements and performance metrics are highly related.

Understanding the determinants of CMJ could provide information on how to train for improvements in CMJ. In this model, multicollinearity was detected for F0, Pmax, and %FVimb, indicating that these independent variables are highly correlated with each other. This is not surprising as power is the product of force and velocity. Yet, V0 did not have a high VIF, suggesting that vertical V0 has little influence on vertical Pmax. Also, vertical V0 was not a significant predictor in either model that included and did not include body weight, which suggest that V0 has little impact on CMJ performance. When not accounting for body weight, vertical F0 and Pmax (variables that are related) were significant predictors, but when body weight was included in the model, only Pmax remained significant. This suggests that when body weight is considered, the ability to generate power (with maximal force production and minimal influence of maximal velocity) is the main factor that explains the variance in CMJ performance. The remaining variance is likely explained by the jumping proficiency (e.g., force orientation, neuromuscular coordination/recruitment). Nevertheless, in this model, Pmax and body weight were significant predictors, indicating that the ability to generate power relative to mass

Table 6. Simple Linear Regression and Pearson Correlation Analysis between Vertical FV Profile and Performance Metrics.

	Variable	r	95% confidence interval	R squared	*P* Value
V0 (m/s)	Clean 1-RM	0.00	-0.23 to 0.23	0.00001	0.9795
	Squat 1-RM	0.05	-0.18 to 0.27	0.002	0.6886
	CMJ	-0.11	-0.32 to 0.11	0.01	0.3347
	Flying-10	0.11	-0.17 to 0.32	0.01	0.3429
	%IMB	-0.37	-0.54 to -0.17	0.14	0.0006*
F0 (N)	Clean 1-RM	0.58	0.40 to 0.71	0.33	<0.0001*
	Squat 1-RM	0.58	0.41 to 0.71	0.34	<0.0001*
	CMJ	0.60	0.44 to 0.72	0.36	<0.0001*
	Flying-10	0.36	0.15 to 0.54	0.13	0.0011*
	%IMB	0.21	-0.007 to 0.41	0.04	0.0576
F0 (N/kg)	Clean 1-RM	0.08	-0.15 to 0.31	0.01	0.4878
	Squat 1-RM	-0.07	-0.29 to 0.17	0.00	0.5774
	CMJ	0.61	0.44 to 0.73	0.37	<0.0001*
	Flying-10	-0.62	-0.74 to -0.46	0.39	<0.0001*
	%IMB	0.71	0.58 to 0.80	0.51	<0.0001*
Pmax (W)	Clean 1-RM	0.41	0.20 to 0.59	0.17	0.0003*
	Squat 1-RM	0.52	0.33 to 0.67	0.27	<0.0001*
	CMJ	-0.11	-0.32 to 0.11	0.01	0.3336
	Flying-10	0.34	0.12 to 0.52	0.11	0.0026*
	%IMB	-0.61	-0.73 to -0.46	0.38	<0.0001*
Pmax (W/kg)	Clean 1-RM	0.18	-0.06 to 0.40	0.03	0.1409
	Squat 1-RM	0.05	-0.19 to 0.27	0.002	0.6985
	CMJ	0.70	0.56 to 0.80	0.49	<0.0001*
	Flying-10	-0.53	-0.68 to -0.35	0.28	<0.0001*
	%IMB	-0.10	-0.31 to 0.12	0.01	0.3797

*F0: maximum force output, V0: maximum velocity output, Pmax: maximum power output, 1-RM: 1 repetition maximum, CMJ: countermovement jump, Flying-10: 10-yard split (seconds, s); %IMB: force-velocity imbalance from non-CMJ with 90° of knee flexion. *P<0.05.*

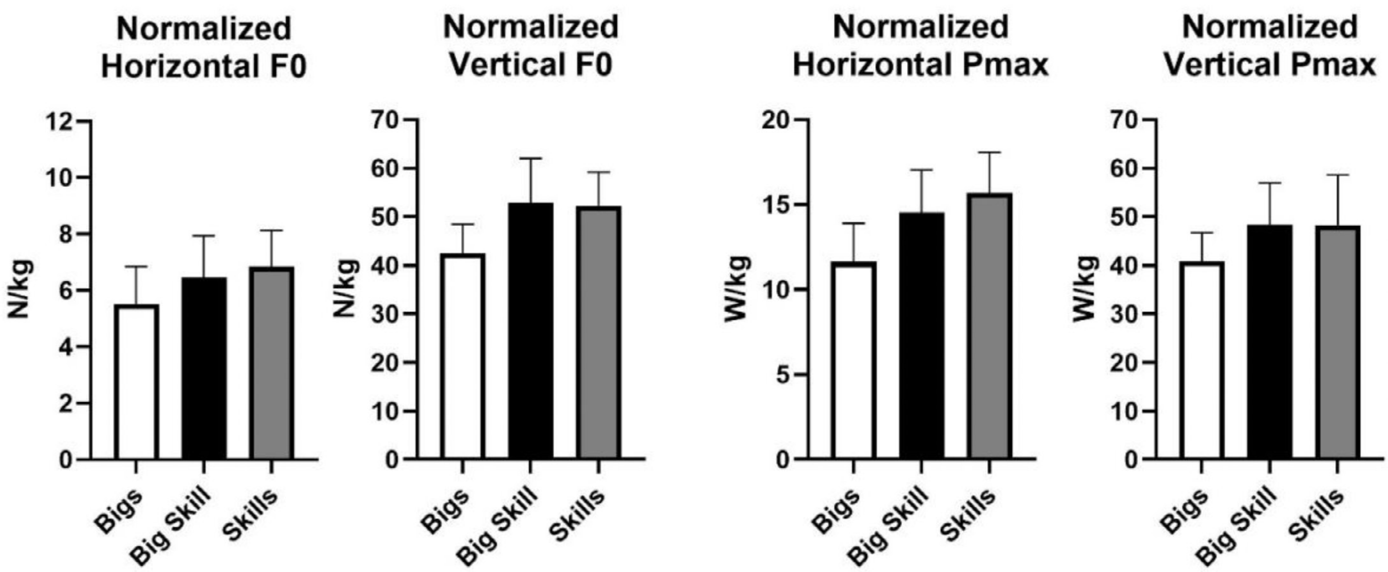

Figure 2. Normalized horizontal and vertical F0 and Pmax (mean ± SD) are shown for each group.

Table 7. Unadjusted and adjusted models using measures of Vertical F0, V0, Pmax, %IMB for determining CMJ.

Model	Variable	Estimate	Standard error	95% CI (asymptotic)	ltl	*P* value	VIF
Model 1 (R2 =0.334 ; SEE = 3.872)	Intercept	19.080	3.872	11.37 to 26.80	4.928	<0.0001*	
	Vertical F0 (N)	-0.004	0.001	-0.005462 to -0.002471	5.284	<0.0001*	2.734
	Vertical V0 (m/s)	-0.175	0.156	-0.4854 to 0.1350	1.125	0.264	1.217
	Vertical Pmax (W)	0.004	0.001	0.002211 to 0.005504	4.669	<0.0001*	4.267
	%IMB	0.144	0.026	0.09241 to 0.1964	5.532	<0.0001*	3.418
Model 2 (R2 = 0.628; SEE = 3.767)	Intercept	37.18	3.767	29.67 to 44.68	9.87	<0.0001*	
	Weight(lbs.)	-0.08151	0.01075	-0.1029 to -0.06010	7.586	<0.0001*	3.055
	Vertical F0 (N)	0.0005408	0.00082	-0.001093 to 0.002175	0.6595	0.5116	5.755
	Vertical V0 (m/s)	-0.09693	0.1177	-0.3314 to 0.1376	0.8238	0.4127	1.226
	Vertical Pmax (W)	0.001678	0.0006852	0.0003121 to 0.003043	2.448	0.0167*	5.177
	%IMB	0.009392	0.02652	-0.04346 to 0.06224	0.3542	0.7242	6.222

*Note: F0: maximum force output, V0: maximum velocity output, Pmax: maximum power output, 1-RM: 1 repetition-maximum, CMJ: countermovement jump, Flying-10: 10-yard split (seconds, s); %IMB: force-velocity imbalance from non-CMJ with 90° of knee flexion. *P < 0.05. SE: standard error, VIF: variable inflation factor, CI: confidence intervals.*

Table 8. Unadjusted and adjusted models using measures of F0, V0, and Pmax for determining Flying-10 Performance.

Model	Variable	Estimate	Standard error	95% CI (asymptotic)	ltl	*P* value	VIF
Model 1 (R2= 0.48; SEE = 0.29)	Intercept	0.6572	0.2902	0.07918 to 1.235	2.265	0.0264*	
	Horizontal F0 (N)	0.002061	0.0004698	0.001125 to 0.002997	4.387	<0.0001*	75.26
	Horizontal V (0)	0.0632	0.03237	-0.001263 to 0.1277	1.953	0.0545	11.91
	Pmax (Watts)	-0.001022	0.0002278	-0.001476 to -0.0005686	4.488	<0.0001*	44.24
Model 2 (R2 =0.85; SEE = 0.15)	Intercept	0.841	0.1578	0.5267 to 1.155	5.33	<0.0001*	
	Weight (lbs.)	0.001594	0.0001175	0.001360 to 0.001828	13.57	<0.0001*	1.481
	Horizontal F0 (N)	0.0007351	0.0002726	0.0001921 to 0.001278	2.697	0.0086*	86.37
	Horizontal V (0)	0.007049	0.01801	-0.02884 to 0.04293	0.3913	0.6967	12.57
	Pmax (Watts)	-0.0004451	0.0001305	-0.0007051 to -0.0001852	3.411	0.001*	49.5

*Note: F0: maximum force output; V0: maximum velocity output; Pmax: maximum power output; 1-RM=,1 repetition maximum; CMJ: countermovement jump; Flying-10: 10-yard split (seconds, s); %IMB: force-velocity imbalance from non-CMJ with 90° of knee flexion. * = P < 0.05, SE: standard error, VIF: variable inflation factor, CI: confidence intervals.*

should improve jump height, which has been routinely observed.[21]

In the multiple regression analysis for flying-10 performance, multicollinearity was found among F0, V0, and Pmax, which is not surprising because power is the product of force and velocity. Still, in both models with and without body weight, it is interesting that F0 and Pmax but not V0 were significant predictors. This is similar to the results of the multiple regression model for CMJ, where vertical V0 was not a significant predictor. It is intriguing that in the flying-10 regression model, horizontal F0 but not horizontal V0 was a significant predictor of flying-10 performance in both models (with and without body weight). These data suggest that the amount of force an athlete can generate in a horizontal plane is more important than his horizontal velocity, especially in the flying-10, which is highly dependent upon the athlete's acceleration during the short 10-yard distance.

FV profiling metrics explained 22% more variance in the flying-10 performance compared to the CMJ test. This difference may be explained by the fact that to be successful in the CMJ, power needs to be generated in the vertical plane against gravity but with sprinting, movement occurs in the horizontal direction. The difference in these movements and environmental conditions could explain why FV metrics of the horizontal performance measure account for greater variance than that of the vertical performance measure.

Evaluating the results of simple linear regression, our study shows a moderate, positive correlation between horizontal velocity and CMJ. This finding is in line with previous studies, which demonstrate that higher running velocities correlate with an elevated capacity to generate force in a short amount of time.[22-30] When considering body mass, a significant, positive correlation between horizontal relative F0 and flying-10 performance was observed, which is likely explained by the primary determinants of velocity (i.e., the magnitude of forces exerted onto the ground throughout foot-ground contact).[31,32] In other words, achieving higher running velocities necessitates the application of stronger support forces within shorter contact intervals.[30,32,33] We also observed a moderate, negative correlation between horizontal velocity and flying-10 speed, which was expected. Lastly, a small positive correlation between horizontal Pmax and squat 1-RM was observed in the present study. Comfort et al.[34] reported similar results, where relative squat strength yielded a stronger relationship with a 20-m sprint compared to absolute squat strength.[34] Vertical F0 had a positive correlation with back squat 1RM, clean 1-RM, and CMJ. All of these metrics are dependent on high force production, which has been observed in many studies, whereby increasing maximal force production improves squat 1-RM, clean 1-RM, and CMJ performance.[1,23,29,34-37] In summary, our findings suggest that results from both the vertical and horizontal FV profiles are related to sprinting performance. Therefore, performance coaches are encouraged to assess both vertical and horizontal profiles in the pursuit of peak athletic performance.

Of the standard performance measures utilized in this study, our findings suggest that vertical F0 explained 37% of the variance in CMJ, whereas vertical V0 explained 1% of CMJ variance. While previous work showed that the relationship between 1RM back squat and jump height was not consistently related to either F0 or V0, [5,23,26-28,34,35,38] the current study shows that vertical F0 has a stronger relationship than V0. Vertical F0 also accounted for 33-34% of both power clean 1-RM and back squat variance. This is also supported by previous studies and empirical evidence.[24,29,35,36,🗏✇] Together, these observations further highlight the value of FV profiling in collegiate American Football, indicating that performance in vertical FV profiling is related to traditional measures of vertical force and power production (CMJ, 1-RM power clean, and 1-RM back squat).

The primary limitation of this study was that vertical FV profiles were measured with electronic jump mats, where force plates would have been a more accurate measurement of FV profiles. Still, we followed Morin and Samozino's protocol for vertical FV profiles which has been previously validated. Another limitation was the reliance on the iOS app for the horizontal FV profile as the exact moment of initial propulsion of the sprint was subjective and was judged when the center midline of the hip aligned with the first speed-stick marker.

FUTURE RECOMMENDATIONS

FV profiling may be a useful tool for preparing American Football athletes for competition. Both horizontal and vertical F0 and V0 were significantly correlated with flying-10 speed, CMJ height, 1-RM power clean, and 1-RM back squat performance. The observed positive relationships between horizontal F0 and sprint performance and vertical F0 and CMJ provide practitioners with evidence that vertical- and horizontal-related FV variables indeed predict performance metrics that are performed in the same plane. As such, when training American Football athletes, we recommend that FV profiling be utilized within the training season to determine which characteristics (force or velocity) should receive the most focus, allowing for the optimization of power and enhanced athletic performance. The current study showed that it is feasible to conduct FV profiling in a large team within an organization with limited funding and staffing. Although more scientifically appropriate, the additional use of linear position transducers, force plates, timing gates, or motion analysis system could provide more information, it would require more resources. Still, the present study presents an alternative, practical, and efficient means of conducting FV profiling in large team sports that allows the strength and conditioning staff to make data-driven decisions about which training types and modalities should be used to improve performance.

CONFLICTS OF INTEREST

The authors declare no conflict of interest. The funders had no role in the study's design; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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ETHICAL APPROVAL

This study was approved by the University's Institutional Review Board for Human Studies (IRB# 2022-00845).c

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Conceptualization, PH, RI, TS, PY; methodology, PH, RI, TS, PY; investigation, PH, RI; resources, PH, RI; writing—original draft preparation, PH, RI: writing—review and editing, TS, PY, supervision, TS, PY; project administration, PH, RI. All authors have read and agreed to the published version of the manuscript.

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