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Original Article

Maturation-Dependent Variations in Force-Velocity Profiles and Relationship with Spike Jump Performance in Female Volleyball Players

İpek Akinci[1], İzzet İnce[2]

[1]Institute of Health Sciences, Ankara Yıldırım Beyazit University, Ankara, Türkiye;
[2]Department of Coaching Education, Faculty of Sports Sciences, Ankara Yıldırım Beyazit University, Ankara, Türkiye

Abstract

Objectives: This research explores the vertical force-velocity (FV) profiles of female volleyball players at different maturation stages and examines the correlation between these profiles and spike jump. **Methods**: Forty-two volleyball players (≥1 year training) were grouped by maturation stage—pre-PHV (n=9), mid-PHV (n=14), or post-PHV (n=19)—determined using anthropometric measurements (standing height, sitting height, leg length, and weight) and the Mirwald method to estimate maturity offset. FV profiles were assessed using Samozino's method with countermovement jumps under different loads. ANOVA with Bonferroni post-hoc tests analyzed group differences, while correlation analysis explored links between FV profiles and spike jump height (SJ). **Results**: Significant variances were observed among maturity groups concerning FV profile parameters, which included maximal force (F_0), maximal velocity (V_0), and maximal power (P_{max}) ($p<0.05$, $\eta^2=0.19$-0.69). Players at more advanced maturity stages demonstrated higher force parameters yet lower velocity values. Furthermore, only weak correlations emerged between spike jump height and parameters such as F_0 and P_{max} ($p<0.05$, $r=0.31$-0.39). **Conclusion**: Post-PHV female volleyball players exhibited greater force production, but lower velocity compared to pre- and mid-PHV players. The weak correlations between force-velocity profiles and spike jump height suggest that other factors may contribute to spike jump performance. Further research is needed to elucidate these determinants across different maturation stages.

Keywords: Force, Force-Velocity Profile, Maturity, Spike Jump, Velocity

Introduction

Volleyball is a team sport where players are required to perform various movements and respond quickly to constantly changing game situations[1]. Explosive movements, such as high vertical jumps and quick court coverage, are crucial and closely related to each other. The repetitive nature of sprints, jumps, and quick movements throughout a match places significant demands on the neuromuscular system[2,3]. One of the main problems and one of the main focal points of coaches or athletes is to optimize ballistic performance and to investigate its factors to determine which parameter is effective on the neuromuscular system and the mechanics required for technique. These parameters are force and velocity (FV)[4].

The FV relationship allows to characterize the mechanical ability of the musculoskeletal system to produce force, power, and speed. The evaluation of the linear FV relationship has been employed to delineate the maximal mechanical capabilities of the muscles engaged in generating a high level of force (as indicated by the theoretical maximal force F_0 (N)), achieving force at very high velocity (as indicated by the theoretical maximal velocity V_0 (m.s-1)), and attaining maximal power output (P_{max} (W)). In addition to these parameters, the linear FV relationship also provides information about the slope of the FV curve (FV_{slope} (N·s·m^{-1})) and the magnitude of

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Corresponding author: İpek Akinci, Institute of Health Sciences, Ankara Yıldırım Beyazit University, Ankara, Türkiye
E-mail: iakinci99@gmail.com
ORCID: 0009-0004-0862-793X

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the imbalance between actual and optimal FV profiles (FV_{imb}). The parameters derived from FV profiles are influenced by various factors, including morphological characteristics, neural mechanisms, muscle coordination, and the direction of force application (either vertical or horizontal)[5,6]. Parameters derived from the FV profiles parameters depend on numerous morphological factors, neural mechanisms, muscle coordination and the orientation of momentum (i.e., vertical or horizontal direction of force application)[7]. Maximal strength training increases the ability of muscles to produce force (and thus increases F_0), while training under high-velocity conditions (i.e. plyometric training) increases V_0 [8]. Vertical jump height is largely dependent on maximal power output[9]. However, by altering the slope of the FV relationship, jump performance can be improved regardless of changes in maximal power[10-12].

Athletic development generally precedes sport specialization. Therefore, specific measures are required to assess the physical fitness of young athletes, irrespective of their sport[13]. Biological maturation affects all body tissues, organs, and systems[14]. As children's biological age increases, so do their height and weight. This growth is followed by the maturation of the nervous, endocrine, muscular, and cardiovascular systems, which leads to changes in neuromuscular performance[15-17]. As muscles develop functionally, the rate of force production increases, allowing maturing athletes to outperform their later-maturing peers. In short, maturing athletes have better values than late maturing athletes due to increased muscle functional development[18]. It is crucial to identify gender-related physical and physiological differences resulting from maturation, as these, along with differences in strength, power, and coordination post-puberty, can help explain variations in performance among young athletes[17]. The fact that there are few studies in the literature explaining how the FV profile reflects and relates to athletic performance and sport-specific techniques, and that it is a new subject especially for volleyball, made us think that this study would be important. This study aimed to compare the mechanical FV parameters of volleyball players at different maturation stages and to examine their relationship with spike jump height.

Materials and Methods

Participants

This study included 42 female volleyball players, each with at least one year of training experience aged between 9 to 15 years, with an average chronological age, body height and body mass of 12.74±0.262 year, 175.97±1.458 cm and 49.95±1.638 kg, respectively. Anthropometric measurements and biological maturity status were determined for each participant using the Mirwald method. The FV profile was assessed using Samozino's method through both unloaded and loaded countermovement jumps. These athletes participated in volleyball training sessions for a minimum of 75 minutes, at least three times a week. For the purposes of this study, all participants were assessed for their distance from the peak height velocity (PHV) phase, a measure of biological maturation. Based on their maturation values, they were divided into three groups: pre-PHV (≤ -1; n= 9), mid-PHV (-1<PHV<1; n=14), and post-PHV (≥1; n=19).

Design and Procedures

A cross-sectional design was conducted with jumping performances. Countermovement jumps (CMJ) without load and with two different loads (25% (CMJ_{25}) and 50% (CMJ_{50}) of body mass)[18] and spike jump (SJ) with approach (without load) were conducted to identify the different components of the vertical FV profiles. Participants aged 10-11-12 years were included in the test on the first day and participants aged 13-14-15 years were included in the test on the second day. The athletes' name, birthday, year of birth year and training experience in volleyball were noted, then height, weight, leg length and sitting height measurements were completed. Invited in groups of 10 people, the participants were included in the test after completing their anthropometric measurements and warming up with a dynamic warm-up that they were accustomed to during the season. The warm-up consisted of low tempo running, lunges, side lunges, skips, side and cross jumps, and block jumps on the volleyball court and the whole warm-up lasted approximately 15 minutes. CMJ, CMJ_{25} and CMJ_{50} were used to calculate the FV profile. To minimize the impact of circadian rhythms on the performance of the volleyball players, all testing sessions were scheduled between 17:00 and 19:00, aligning with the typical hours of their regular volleyball training. This scheduling ensured that the athletes were tested at times consistent with their biological clocks. After the warm-up, each player performed two CMJs without external load and two spike jumps with an approach step. Additionally, two CMJs were performed with external loads of 25% and 50% of body mass, in randomized order. The highest recorded jump was used for statistical analysis.

Measures

Body mass (Tanita TBF 300, ABD), stature and sitting height (2-meter-long wall-mounted stadiometer, Mesilife, SW-G06B) were recorded. A 40 cm box was utilized for measuring participants' sitting height. Participants were seated on an elevation, ensuring a knee flexion angle of 90 degrees to form a complete angle, and their body height was calculated by subtracting the measured value from the elevation height, taking care to observe the specified knee flexion angle. Additionally, participants' leg length measurements were obtained by subtracting the calculated trunk length from the measured overall height. These parameters used to calculate maturity offset through an estimation of the time before, middle or after PHV, which also includes date of birth and the date of measurement. This method approximates the amount of time (in years) until, or since, an individual's predicted PHV indicating the maturity offset. Mirwald[19] equations differ according to gender. **Equation 1** used to determine the PHV for female participants.

Maturity Offset = *(0.0001882 × (Leg length) × (sitting height)) + (0.0022 × (chronological age) × (Leg length)) + (0.005841 × (chronological age) ×(sitting height)) − (0.002658 × (chronological age) × (body height)) + (0.07693 × (body mass) ÷ (height)) − 9.376*

Equation 1. Maturity Offset for female participant.

For jump measurements, Optojump Next (Microgate Next, Bolzano, Italy), consisting of two flat bars opposite each other equipped with optical sensors, was used. For CMJ with loads, a loads vest was used, and the weights was changed individually for each subject. The participants were asked to pass between the optical sensors before the jump to be made, and they were made to wait ready with their hands on their waist. The jump measurement was performed with the given command. The players were instructed to jump "as high as possible". In CMJ_{25} and CMJ_{50}, the weight was prepared in advance. In the spike jump height measurement with approach stepping, the children were asked to use the spike stepping technique learnt during training and matches. The athletes were made to stand a few steps behind the optical sensors, and on command, they were asked to step towards the optical sensors and perform their jumps. A 30 s rest was provided between each jump. Each jump was performed twice, and the highest jump was included in the statistical analysis. All participants completed the measurements in the same way. If the participants experienced an imbalance during the jump or pulled their knees to themselves, the measurement was considered invalid, and the jump was repeated. During each trial, the mean absolute force (*F*, expressed in Newtons) generated by the lower extremities during the push-off phase, along with the concomitant mean vertical velocity of the center of mass denoted as *v* (measured in meters per second), were ascertained utilizing the equations and methodological framework as proposed and substantiated by Samozino et al.[11,20]:

$$F = m \times g\left(\frac{h}{h_{pO}} + 1\right) \quad \textbf{Equation 2.}$$

$$v = \sqrt{\frac{g.h}{2}} \quad \textbf{Equation 3.}$$

$$P = m \times g\left(\frac{h}{h_{pO}} + 1\right) \times \sqrt{\frac{g.h}{2}} \quad \textbf{Equation 4.}$$

In these three equations "*m*" represents the total mass (body mass + additional load in kg), while the gravitational acceleration is denoted by "*g*" with a standardized value of 9.81 $m.s^{-2}$. The vertical displacement of the center of mass during push-off, indicative of the extension range of the lower limbs, is symbolized as "h_{po}" and measured in meters, while "*h*" signifies the jump height, also measured in meters. As the moving mass (body mass + additional mass) increases, there is a corresponding elevation in force and a simultaneous reduction in velocity. Modelled through a linear equation establishes the F-v relationship, from which extrapolation enables the derivation of maximal force (F_0, force-intercept) and velocity (V_0, velocity-intercept) values. FV_{slope} is calculated as the ratio of F_0 to V_0, while P_{max} is determined by the formula $P_{max}=F_0 \times V_0/4$. FV_{imb} is determined by the formula $FV_{imb}=100 \times |1-FV_{slope}/(FV_{slope}\ opt)|$.

Statistical Analyses

The normality of the data was assessed using the Kolmogorov-Smirnov test. Variables that met normality assumptions are presented as mean ± standard deviation ($\bar{X}$ ± SD) and 95% confidence intervals (95% CI). For variables that did not conform to normality, a natural logarithmic transformation (LN) was applied[21]. Differences in jump performance and FV profile parameters between groups were evaluated using one-way analysis of variance (ANOVA). Homogeneity of variance was tested using Levene's test. Post-hoc pairwise comparisons were performed using the Bonferroni correction. Effect sizes for the ANOVA were reported as partial eta squared (ηp^2), with thresholds defined as small (> 0.01), medium (≥ 0.06), and large (≥ 0.14). Pearson's Product-Moment Correlation Coefficient was used to assess relationships between spike jump performance and FV profile parameters. Correlations were classified based on the criteria set by Hopkins[22]: very weak (0.00-0.25), weak (0.26-0.49), moderate (0.50-0.69), high (0.70-0.89), and very high (0.90-1.00). Intraclass correlation coefficients (ICCs) were calculated between the first and second repetitions of CMJ, CMJ_{25}, and CMJ_{50}, using a two-way mixed-effects model with absolute agreement. ICCs were interpreted as follows: poor (≤ 0.49), moderate (0.50–0.74), good (0.75–0.89), and excellent (≥ 0.90) (Koo & Li, 2016). Statistical significance was set at $p < 0.05$

Results

Table 1 provides the descriptive statistics for the participants, including chronological age, maturity offset, body height, body mass, BMI, training age, fat percentage, fat mass, and muscle mass across the different PHV stages. Significant differences were observed in several FV parameters based on PHV stages.

Table 2 and Table 3 outline the comparisons: F_0 ($F(41,2) = 24.317$, $p < 0.001$, $\eta p^2 = 0.555$) demonstrated significant increases across PHV stages, with post-hoc comparisons revealing greater values in the post-PHV group (1740.90 ± 86.302 N) compared to the pre-PHV (858.33 ± 52.704 N) and mid-PHV groups (1233.36 ± 89.026 N). Significant differences were also observed in **relative F_0** (LN_F_{0rel}) ($F(41,2) = 3.658$, $p = 0.035$, $\eta p^2 = 0.158$), with higher values in the post-PHV group (30.04 ± 1.495 N/kg) than the pre-PHV group (23.02 ± 1.256 N/kg). **Velocity (V_0)** (LN_V_0) ($F(41,2) = 5.558$, $p = 0.008$, $\eta p^2 = 0.222$) and **relative power (P_{maxrel})** (LN_P_{maxrel}) ($F(41,2) = 3.929$, $p = 0.028$, $\eta p^2 = 0.168$) showed significant differences between pre- and post-PHV

Table 1. Descriptive statistics of volleyball players.

	Group	n	$\bar{x}$ (95%CI)	SD
Chronological Age (year)	**Pre-PHV**	9	10.00 (9.46 – 10.54)	0.236
	Mid-PHV	14	12.71 (12.44 – 12.98)	0.125
	Post-PHV	19	14.05 (13.58 – 14.43)	0.179
	∑	42	12.74 (12.21 – 13.27)	0.262
Maturity Offset (year)	**Pre-PHV**	9	-1.31 (-1.73 – -0.89)	0.180
	Mid-PHV	14	0.45 (0.22 – 0.68)	0.107
	Post-PHV	19	1.86 (1.66 – 2.06)	0.952
	∑	42	0.71 (0.30 – 1.12)	0.202
Body Height (cm)	**Pre-PHV**	9	145.39 (140.99 – 149.79)	1.907
	Mid-PHV	14	156.68 (153.55 – 159.81)	1.449
	Post-PHV	19	164.89 (161.97 – 167.80)	1.387
	∑	42	157.97 (155.03 – 160.92)	1.458
Body Mass (kg)	**Pre-PHV**	9	37.20 (34.52 – 39.88)	1.160
	Mid-PHV	14	46.78 (42.98 – 50.58)	1.759
	Post-PHV	19	58.31 (54.67 – 61.96)	1.733
	∑	42	49.95 (46.64 – 53.25)	1.638
BMI (kg/m²)	**Pre-PHV**	9	17.65 (16.16 – 19.14)	0.647
	Mid-PHV	14	19.08 (17.90 – 20.27)	0.549
	Post-PHV	19	21.45 (20.28 – 22.62)	0.557
	∑	42	19.85 (19.02 – 20.68)	0.411
Training Age (year)	**Pre-PHV**	9	1.94 (1.16 – 2.72)	0.334
	Mid-PHV	14	2.32 (1.74 – 2.91)	0.270
	Post-PHV	19	2.71 (1.83 – 3.59)	0.418
	∑	42	2.42 (1.97 – 2.86)	0.222
Fat Percentage (%)	**Pre-PHV**	9	20.29 (16.89 – 23.69)	1.437
	Mid-PHV	14	21.19 (18.11 – 24.26)	1.425
	Post-PHV	19	25.53 (23.11 – 27.96)	1.149
	∑	42	22.96 (21.26 – 24.67)	0.844
Fat Mass (kg)	**Pre-PHV**	9	7.66 (6.18 – 9.14)	0.627
	Mid-PHV	14	10.19 (7.91 – 12.45)	1.052
	Post-PHV	19	15.10 (12.83-17.37)	1.075
	∑	42	11.89 (10.31 – 13.47)	0.779
Muscle Mass (kg)	**Pre-PHV**	9	28.45 (26.18 – 30.71)	0.956
	Mid-PHV	14	34.71 (32.93 – 36.5)	0.825
	Post-PHV	19	40.76 (38.9 – 42.64)	0.886
	∑	42	36.18 (34.33 – 38.03)	0.915

n: Sample size; $\bar{X}$: mean; SD: Standard deviation; ∑: Sigma.

groups. Notably, **FV_{slope} (LN_FV_{slope})** ($F(41,2) = 5.074$, $p = 0.011$, $\eta p^2 = 0.206$) was significantly steeper in the post-PHV group (-9.00 ± 1.287 N.s.m^{-1}) compared to the pre-PHV group (-3.29 ± 1.435 N.s.m^{-1}). Significant differences in jump performance were also found: **CMJ_{50}** ($F(41,2) = 4.130$, $p = 0.024$, $\eta p^2 = 0.175$) was greater in the post-PHV group (11.95 ± 0.645 cm) than in the pre-PHV group (8.79 ± 0.532 cm). **Spike jump performance (SJ)** ($F(41,2) = 3.317$, $p = 0.047$, $\eta p^2 = 0.145$) was significantly greater in the mid-PHV group (30.27 ± 1.249 cm) compared to the pre-PHV group (25.73 ± 1.062 cm).

Figure 1 presents the correlation matrices between spike jump and FV parameters, showing no significant correlations between SJ and FV profile parameters across the pre-, mid-, and post-PHV groups ($p > 0.05$). Figure 2 provides the effect sizes (ηp^2) for spike jump and FV profile components across

Table 2. The results of comparison of the FV parameters and jump performances between maturity groups.

	Group	n	$\bar{X}$ (95%CI)	SD	$F_{(41,2)}$	p	ηp^2	Bonferroni
F_o (N)	Pre-PHV[1]	9	858.33 (736.80 – 779.86)	52.704	24.317	**<0.001*****	0.555	2>1
	Mid-PHV[2]	14	1233.36 (1041.03 – 1425.68)	89.026				3>1
	Post-PHV[3]	19	1740.90 (1559.58 – 1922.21)	86.302				3>2
LN_F_{Orel} (N/kg)	Pre-PHV[1]	9	23.02 (20.12 – 25.92)	1.256	3.658	**0.035***	0.158	3>1
	Mid-PHV[2]	14	26.63 (22.13 – 31.14)	2.083				
	Post-PHV[3]	19	30.04 (26.89 – 33.18)	1.495				
LN_V_o ($m.s^{-1}$)	Pre-PHV[1]	9	15.01 (7.30 – 22.71)	3.341	5.558	**0.008****	0.222	1>3
	Mid-PHV[2]	14	10.99 (5.92 – 16.07)	2.358				
	Post-PHV[3]	19	5.30 (2.96 – 7.65)	1.117				
LN_P_{max} (W)	Pre-PHV[1]	9	2981.11 (1630.11 – 4332.11)	585.86	1.432	0.251	0.068	
	Mid-PHV[2]	14	3067.28 (1883.66 – 4250.91)	547.88				
	Post-PHV[3]	19	2096.84 (1330.24 – 2863.44)	364.89				
LN_P_{maxrel} (W/kg)	Pre-PHV[1]	9	80.65 (42.03 – 119.28)	16.752	3.929	**0.028***	0.168	1>3
	Mid-PHV[2]	14	65.21 (40.42 – 90.00)	11.474				
	Post-PHV[3]	19	37.96 (22.06 – 53.85)	7.565				
LN_FV_{slope} ($N.s.m^{-1}$)	Pre-PHV[1]	9	-3.29 (-6.60 – 0.02)	1.435	5.074	**0.011***	0.206	1>3
	Mid-PHV[2]	14	-4.63 (-7.32 – -1.93	1.248				
	Post-PHV[3]	19	-9.00 (-11.71 – -6.30)	1.287				

n: Sample size; $\bar{X}$: mean; SD: Standard deviation; ηp^2: Partial eta square; F_o: Theoretical maximal force; LN_F_{Orel}: Natural logarithmic-transformed relative theoretical maximal force; LN_V_o: Natural logarithmic-transformed theoretical maximal velocity; LN_P_{max}: Natural logarithmic-transformed theoretical maximal power; LN_P_{max}rel: Natural logarithmic-transformed relative theoretical maximal power; LN_FV_{slope}: Slope of the FV relationship. *: p < 0.05; **: p < 0.01; ***: p < 0.001.

Table 3. The results of comparison of the FV parameters and jump performances between maturity groups.

	Group	n	$\bar{X}$ (95%CI)	SD	$F_{(41,2)}$	p	ηp^2	Bonferroni
$LN\_FV_{sloperel}$ ($N.s.m^{-1}.kg^{-1}$)	Pre- PHV[1]	9	-0.908 (-0.188 – -0.006)	0.042	1.129	0.334	0.055	
	Mid-PHV[2]	14	-0.108 (-0.185 – -0.030)	0.036				
	Post-PHV[3]	19	-0.153 (-0.198 – -0.109)	0.021				
LN_FV_{imb} (%)	Pre-PHV[1]	9	15.67 (-2.33 – -33.69)	7.807	5.296	**0.009****	0.214	3>1 3>2
	Mid-PHV[2]	14	21.93 (8.33 – -35.52)	6.293				
	Post-PHV[3]	19	48.95 (31.92 – 65.97)	8.104				
CMJ (cm)	Pre-PHV[1]	9	21.18 (18.78 – 23.57)	1.038	1.745	0.188	0.082	
	Mid-PHV[2]	14	24.27 (21.92 – 26.62)	1.089				
	Post-PHV[3]	19	23.01 (21.07 – 24.95)	0.925				
CMJ_{25} (cm)	Pre-PHV[1]	9	12.91 (11.54 – 14.28)	0.593	5.174	**0.010****	0.210	2>1 3>1
	Mid-PHV[2]	14	16.76 (14.99 – 18.53)	0.819				
	Post-PHV[3]	19	16.27 (14.66 – 17.87)	0.763				
CMJ_{50} (cm)	Pre-PHV[1]	9	8.79 (7.56 – 10.01)	0.532	4.130	**0.024***	0.175	3>1
	Mid-PHV[2]	14	10.07 (9.27 – 12.87)	0.835				
	Post-PHV[3]	19	11.95 (10.60 – 13.31)	0.645				
SJ (cm)	Pre-PHV[1]	9	25.73 (23.28 – 28.18)	1.062	3.317	**0.047***	0.145	2>1
	Mid-PHV[2]	14	30.27 (27.57 – 32.97)	1.249				
	Post-PHV[3]	19	29.51 (27.35 – 31.67)	1.028				

*n: Sample size; $\bar{X}$: mean; SD: Standard deviation; ηp^2: Partial eta square; $LN\_FV_{sloperel}$: Natural logarithmic-transformed relative slope of the FV relationship; LN_FV_{imb}: FV imbalance; CMJ: Countermovement jump height; CMJ_{25}: Countermovement jump height with %25 load of body mass; CMJ_{50}: Countermovement jump height with %50 load of body mass; SJ: Spike jump height. *: p < 0.05; **: p ≤ 0.01.*

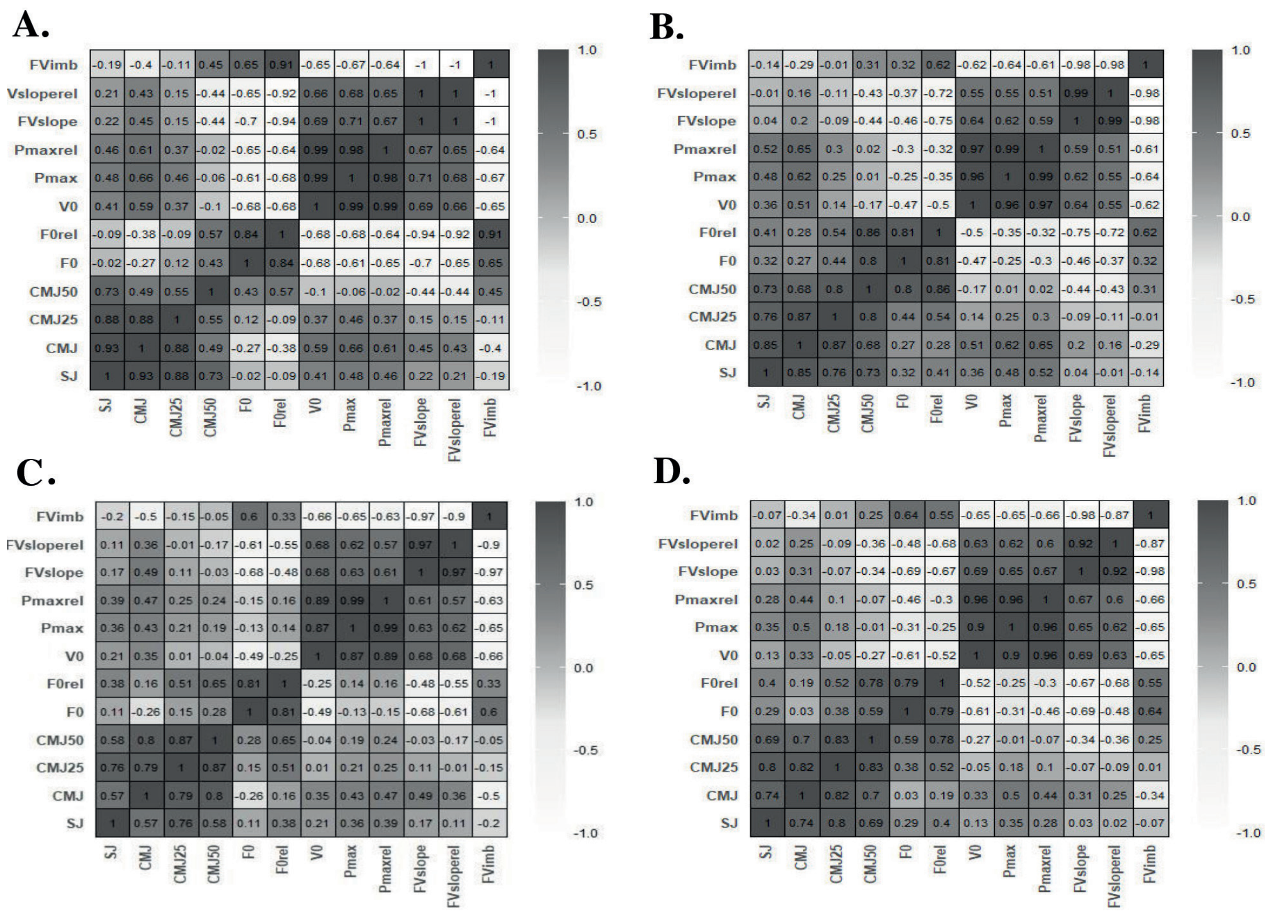

Figure 1. Correlation matrices of FV parameters and jump performances between maturity groups and all participants.

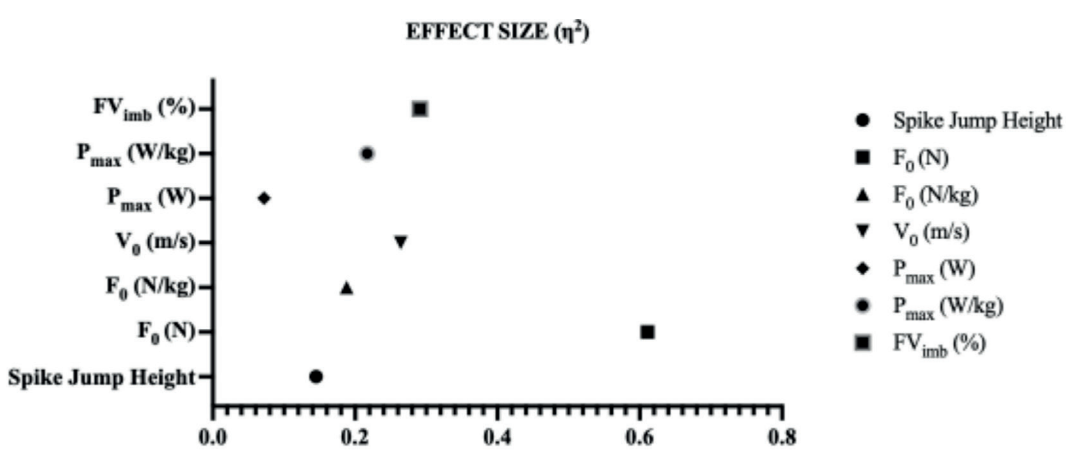

Figure 2. Plot of effect size partial eta squared (ηp²) for Spike Jump and parameters of FV profile of pre, mid and post PHV groups.

the three maturity groups, demonstrating large effect sizes for F_0 (ηp^2 = 0.555), V_0 (ηp^2 = 0.222), P_{maxrel} (ηp^2 = 0.168), and FV_{imb} (ηp^2 = 0.214), among others.

Discussion

The purpose of this study was to compare the mechanical force-velocity (FV) profiles of athletes with at least one year of volleyball training, categorized by their biological maturation status, and to examine the relationship between FV parameters and spike jump performance. While there are numerous studies exploring volleyball performance, research focusing specifically on the relationship between maturation periods and FV profiles is limited, particularly in young volleyball players. To date, the FV profile has not been extensively studied in this demographic. The key findings of this research indicate that there were significant relationships between vertical FV components such as F_0, V_0, P_{max}, FV_{slope}, FV_{imb}, and spike jump (SJ) performance.

Based on the results in Table 2 and Table 3, no significant differences were found in specific parameters such as LN_P_{max}, LN_$FV_{sloperel}$, and countermovement jump (CMJ) across different PHV stages, suggesting a consistent development of these performance metrics during maturation. However, a significant increase in F_0 was observed in the post-PHV stage, indicating an enhancement in maximal force capacities as athletes mature. This finding emphasizes the importance of taking maturation status into account when designing and evaluating strength training programs for young athletes. Meylan et al.'s study investigated the effects of movement-based strength training and weightlifting on young athletes at various maturation stages. Their study demonstrated that targeted training significantly improved force, velocity, and power, particularly in athletes at mid- and post-maturation stages. During the detraining phase, the pre-maturation group experienced the most pronounced loss, while the post-maturation group showed a decline in sprint performance, although all groups maintained or improved their jump distance[21]. A significant difference in F_0 was noted across PHV stages, with post-hoc comparisons showing that F_0 values were significantly higher in the post-PHV stage compared to both the mid- and pre-PHV stages. This suggests a marked increase in maximal force capacity as athletes mature, further underscoring the need to account for maturational status when assessing or designing strength training interventions for young athletes. Moreover, significant differences were observed in parameters such as LN_F_{0rel}, LN_V_0, LN_P_{max}rel, and LN_FV_{slope} across PHV stages, indicating that athletes demonstrate notable improvements in both force and velocity as they mature. Supporting these findings, Baena-Raya et al. observed in elite male volleyball players that vertical jump, sprint, and bench press performances were strongly correlated with spike and serve speeds. This underscores the critical role velocity plays in specific volleyball techniques and overall performance[22]. These studies show that velocity has a significant impact on specific techniques and therefore on performance.

Differences in CMJ_{50} and SJ performance were noted across PHV stages, with post-PHV and mid-PHV athletes outperforming their pre-PHV counterparts. Physical and physiological changes associated with biological maturation occur at varying rates during critical developmental periods. These findings underscore the progressive improvement in explosive power and static jump ability as athletes mature, highlighting the necessity of age- and maturity-specific training interventions to optimize performance development in young athletes. In their 2021[23], study on young football players, Fernandez-Galvan et al. examined both horizontal and vertical FV profiles, concluding that key mechanical determinants of sprint and jump performance, such as F_0, V_0, P_{max}, and FV_{slope}, should be defined based on specific age or maturation stages. While training can strengthen weaker FV profile components, the authors emphasize that some determinants, particularly V_0, may not increase as a result of maturation or age. In this study, a strong correlation was found between CMJ performance and maturity level, with very large correlation effects observed between jump F_0, P_{max} values, and maturity. These results indicate that more mature and older football players exhibit superior performance in these FV components. As young athletes mature, their force production capacity and neuromuscular structures also develop, which is a critical factor influencing the performance of athletes still in their developmental phase. Structuring training programs for young athletes based on their maturation status and incorporating these parameters in talent selection can be crucial for athletic success[24]. Some studies have shown that players with advanced maturation often outperform their later-maturing peers in tasks such as static strength, endurance, speed, agility, jumping, and throwing[25]. In addition, jumping F0 made a significant contribution to explaining the variability of maturation level and chronological age, and when evaluated together with the FV_{slope}, this result shows that it is the mechanical determinant of jumping performance that evolves the most throughout the development process of young football players. In this study, it is suggested that the running and jumping abilities of young football players should be monitored equally according to their chronological age or maturation values[23]. The FV_{imb} value represents the imbalance between an athlete's force and velocity capacities. A higher FV_{imb} value indicates a greater imbalance, while a lower value reflects a more balanced development of power generation. In this study, biologically immature participants exhibited lower FV_{imb} values. This could be attributed to the rapid developmental processes in children, where factors such as bone structure, muscle growth, and hormonal changes have not yet fully matured[26]. In the comparison of spike jump heights across PHV groups, a statistically significant difference was observed, particularly between the pre-PHV and mid-PHV groups. The spike in volleyball is a complex movement that relies not only on force and power but also on technical and coordination skills, both of which are critical to performance. In the light of all this information, it is understood that spike is an important performance parameter in volleyball, but it will not be enough to take into account only parameters such as force, velocity, power when evaluating.

Understanding the timing of optimal training stimuli during an athlete's developmental phase is critical for improving performance through effective and efficient training programs. It is important to note that this study did not include elite volleyball players or candidates for elite status. The participants were limited to young female volleyball players, and technical or coordination skills were not evaluated in this research. This is a study in which the participants consisted only of young girl volleyball players, technical or coordination skills were not taken into account. One of the most prominent limitations of this study is the relatively small sample size, which restricts the scope of the investigation. This limitation may reduce the generalizability of the findings and limit the breadth of interpretation. Future research should address this by incorporating a more diverse and comprehensive participant group to better understand developmental differences based on biological maturity and chronological age. Given that maturation is a dynamic process, future research might benefit from a longitudinal design to observe how FV profiles evolve within individuals as they mature. This study is the first to compare the FV profiles of volleyball players based on their maturation status and to examine the relationship between these profiles and spike jump performance. The findings, particularly the large effect sizes observed in many parameters, highlight the significant impact of maturation on key performance metrics. Regularly applying jumping tests to assess FV profiles could offer valuable insights for volleyball players. In this context, identifying specific jumping mechanical determinants, such as F_0, V_0, P_{max}, and FV_{slope}, at distinct ages or maturation stages may help strengthen weaker components of the FV profile throughout the training process.

Ethical approval

This research was conducted with approval from the Ankara Yıldırım Beyazıt University Health Sciences Ethics Committee (2022-1146), in accordance with the ethical standards outlined in the 1964 Declaration of Helsinki and its subsequent amendments.

Consent to participate

All participants, their families, and coaches were informed about the study beforehand, including the potential risks involved. Written informed consent was obtained from the parents or legal guardians of the participants.

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