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Sex-Specific Influence of Maturity Status on Jumping Performance in Adolescents: A Cross-Sectional Study

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Abstract

Background: The development of jumping performance during youth has received renewed interest, but fundamental questions remain regarding the influences of sex and maturity status on jumping ability. This study aimed to investigate how sex and maturity status affect jumping performance in adolescents.

Methods: Two hundred healthy adolescents participated: 86 males (age 15.8±1.7 years, body mass 53.96±10.0 kg, height 167±10.4 cm) and 114 females (age 16.25±1.8 years, body mass 53.3±7.5 kg, height 159±0.7 cm), aged 13-19 years. Participants were divided into three maturity groups according to their estimated peak height velocity (PHV): Pre-PHV (maturity offset ≤-0.5 years), Circa-PHV (maturity offset between -0.5 and 0.5 years), and post-PHV (maturity offset ≥0.5 years). Testing included vertical jumps (drop jump, countermovement jump) and horizontal jumps (horizontal jump test, five jump test).

Results: Post-PHV males performed significantly better than Circa-PHV and Pre-PHV males in drop jump ($p<0.001$; ES: 0.67-0.76), countermovement jump ($p<0.001$; ES: 0.67-0.81), horizontal jump test ($p<0.05$; ES: 0.16-0.63), and five jump test ($p<0.001$; ES: 0.28-0.55). No significant differences were observed across maturity groups in females. The sex-based comparison revealed significantly better performance in males than in females across all tests ($p < 0.001$). Significant positive correlations were observed between maturity offset and jumping performance in males ($r=0.60$-0.67, $p<0.01$), but no such relationships were found in females.

Conclusions: This study suggests that sex and maturation status are associated with distinct patterns of jumping performance development in

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adolescents, with distinct patterns between males and females. Maturation substantially impacts jumping ability in males but shows minimal effect in females. These findings suggest that the maturation schedule should be carefully considered when assessing jumping performance in adolescents, particularly in males during puberty. Physical education teachers and coaches should implement sex-specific and maturity-based approaches when designing training programs and evaluating jumping performance in youth.

Keywords: Development, Height, Horizontal jump, Neuromuscular, Plyometrics, Power, Puberty, Tanner, Vertical jump

1. Introduction

Human movements such as jumping require complex motor coordination between upper and lower body segments and are fundamental to numerous athletic activities[1,2]. Jumping, a key component of the stretch-shortening cycle (SSC), is among the most widely used methods for assessing lower-limb power and is essential for success in most sports [3,4]. The SSC is characterized by an eccentric "stretching" phase followed by a concentric "shortening" action, which enhances force production during dynamic movements [5]. Vertical jumping movements, including countermovement jumps (CMJ) and drop jumps (DJ), rely heavily on the SSC and are commonly used to assess lower-extremity skeletal muscle function in both research and practical settings [6,7].

Research has established that sex and maturity status significantly influence jumping performance during adolescence [8,9]. Males generally demonstrate greater jumping ability compared to females, attributed to differences in muscle volume, fiber composition, and neuromuscular coordination [10]. These sex-based differences become more pronounced during puberty due to hormonal changes that affect muscle development [11,12]. Regarding maturation, research indicates that jumping

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performance typically improves as adolescents progress through puberty, with notable increases occurring around peak height velocity (PHV) [7,13]. This improvement is linked to various physiological changes, including increased muscle cross-sectional area, enhanced neural drive, and improved musculotendinous stiffness [14,15]. However, the precise timing and magnitude of these performance changes appear to differ between males and females throughout the maturation process [16,17].

Despite considerable research on jumping performance in adolescents, significant gaps remain in our understanding of how sex and maturity status interact to influence SSC performance [18,19]. While previous studies have examined either sex differences or maturity effects independently, few have systematically investigated their combined influence across different jumping tasks [20,21]. Additionally, most research has focused on a single jump type rather than comparing performance across various jumping modalities that place different demands on the SSC (vertical vs. horizontal, single vs. multiple jumps)[22,23]. Furthermore, the relationship between maturity offset and jumping performance has not been thoroughly examined across maturity stages in both sexes, limiting our understanding of when and how performance adaptations occur during adolescent development [24,25].

Examining the interaction between sex and maturity status across different jump types is crucial because adolescents experience sex-specific neuromuscular and anthropometric adaptations during puberty. Previous research has shown that males typically develop greater muscle volume, more favorable muscle fiber composition, and enhanced neuromuscular coordination compared with females, particularly during the period of peak height velocity (PHV) [8,16]. These maturation-related changes influence the efficiency of the stretch-shortening cycle (SSC) and affect jumping performance differently between vertical and horizontal jump modalities [7,23]. Ignoring these sex-maturation interactions may lead to misinterpretation of performance trajectories or inappropriate evaluation standards during adolescence.

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From a practical standpoint, understanding how maturation affects SSC performance is essential for designing individualized plyometric training programs and for talent identification. Studies have highlighted that maturation substantially enhances neuromuscular structure and power output in males[15,20], whereas females may exhibit different or attenuated adaptations [23]. Coaches and practitioners should therefore integrate sex-specific maturation profiles into testing and training models to ensure that performance assessments are developmentally appropriate and do not disadvantage late-maturing individuals. This reinforces the importance of studying the combined effects of sex and maturity status on various jump types.

Thus, this study aimed to: (i) investigate the influence of sex and maturity status on jumping performance in adolescents; (ii) examine the differences in both vertical and horizontal jumping abilities across maturity groups (pre-PHV, Circa-PHV, and post-PHV) for males and females; and (iii) determine the relationship between maturity offset and various jumping performances for both sexes.

We hypothesized that both sex and maturity status would significantly affect jumping performance, with males demonstrating greater improvements in jumping performance across maturation than females. Specifically, we expected a strong positive association between maturity offset and jumping performance in males compared to females. The conceptual framework of these hypotheses is illustrated in Figure 1.

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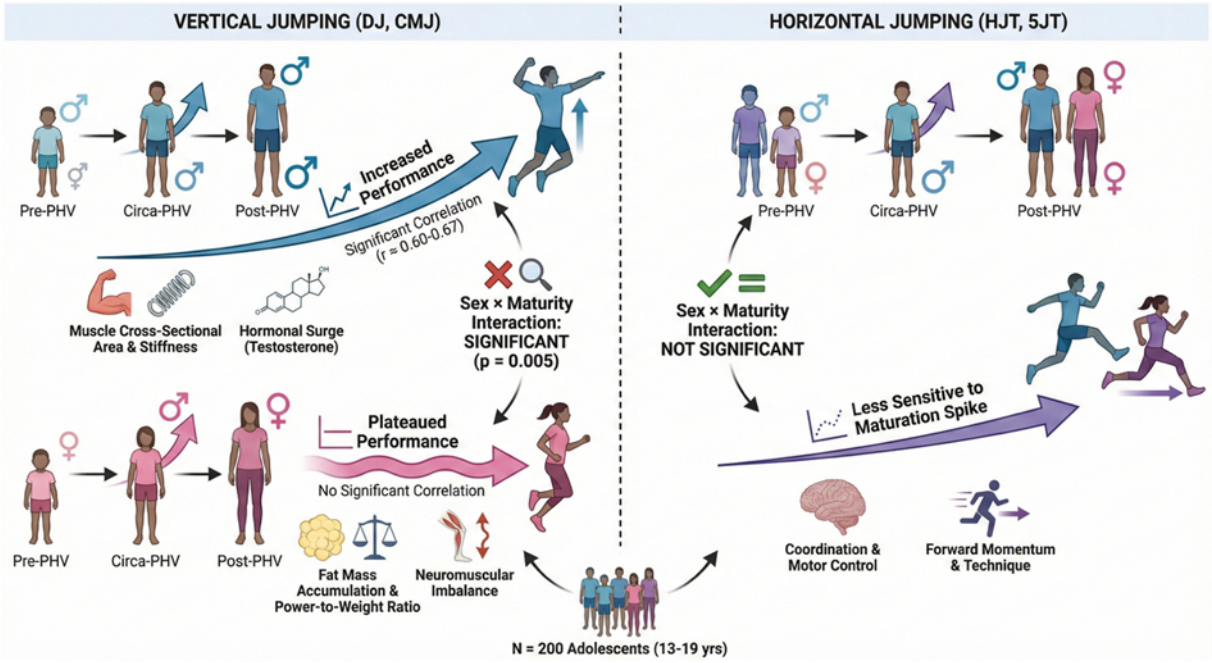

Figure 1: Sex-Specific Influence of Maturity Status on Vertical vs. Horizontal Jumping Performance in Adolescents

Abbreviations: CMJ: Countermovement Jump; DJ: Drop Jump; HJT: Horizontal Jump Test; N: Sample Size; p: Statistical Significance Value; PHV: Peak Height Velocity; r: Correlation Coefficient

2. Materials and methods

2.1. Study Design

This cross-sectional study investigated the influence of sex and biological maturity status on stretch-shortening cycle performance during jumping in adolescents. All testing protocols were completed over two weeks. During the first week, participants were familiarized with the testing procedures to minimize learning effects. The familiarization week consisted of two supervised sessions in which all participants were introduced to the jump techniques, test instructions, warm-up structure, and equipment (Optojump System). Each participant practiced all jump tasks: Countermovement Jump (CMJ), Drop Jump (DJ), Horizontal Jump Test (HJT), and Five Jump Test (5JT) to ensure proper understanding and to minimize technical variability during the testing week.

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Data collection was conducted during the second week. All tests were administered by the same experienced evaluators using standardized protocols and instruments. Physical assessments were performed during scheduled physical education sessions under consistent outdoor conditions. Before testing, participants completed a standardized 15-minute warm-up protocol consisting of jogging, dynamic stretching, and jump exercises supervised by an expert fitness coach. The overall experimental design, comprising participant recruitment, maturity stratification, and the randomized sequence of performance tests, is schematically illustrated **(Figure 2)**.

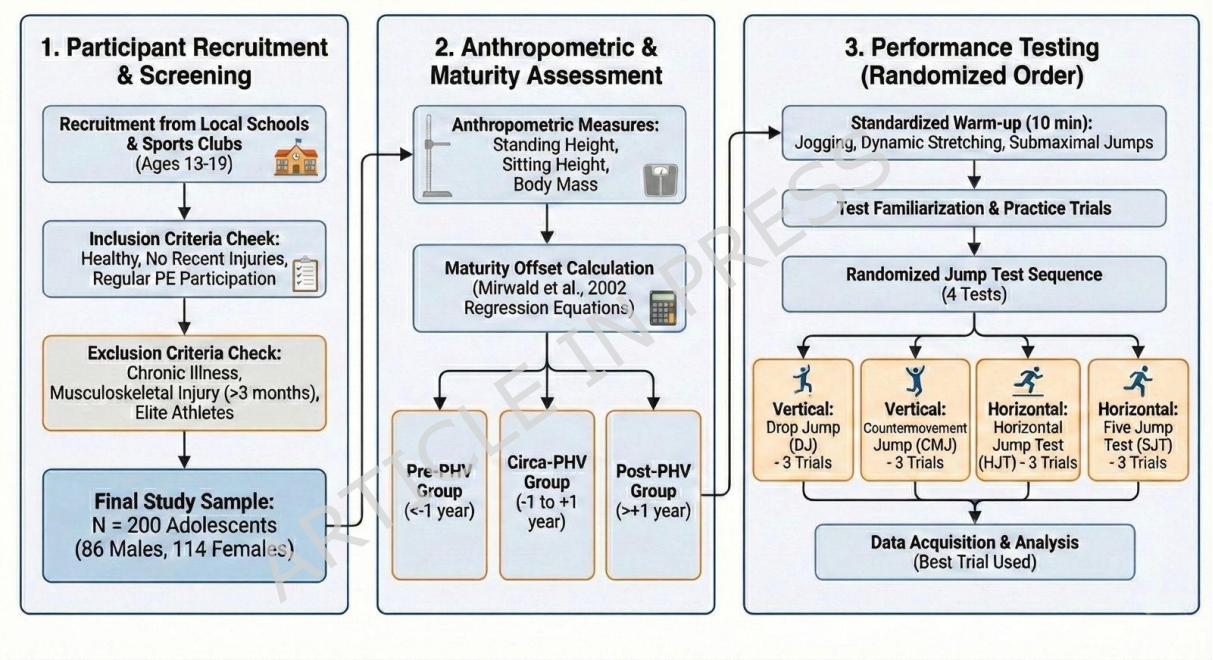

Figure 2. Study Protocol Flowchart

Abbreviations: 5JT: Five Jump Test; CMJ: Countermovement Jump; DJ: Drop Jump; HJT: Horizontal Jump Test; N: Sample Size; PE: Physical Education; PHV: Peak Height Velocity

2.2. Ethical approval and consent to participate

All procedures were conducted following the Declaration of Helsinki. Informed consent was obtained from all participants' parents or legal guardians. The study protocol was approved by the local research ethics

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committee of the High Institute of Sport and Physical Education of Kef, University of Jendouba (approval code: c11-2024, January 18, 2024). It also complied with the ethical and procedural requirements for conducting sports medicine and exercise science research [26].

2.3. Sample size calculation

The sample size was calculated according to the following equation[27] : $N = (Z\alpha/2)^2 \times s^2/\Delta^2$

Where:

- "s" is the standard deviation obtained from a previous study

- "Δ" is the desired precision (how close to the true mean)

- "Zα/2" is the normal deviate for a two-tailed alternative hypothesis at a level of significance

Based on previous research examining jumping performance in adolescents [28], countermovement jump height had a standard deviation (s) of approximately 4.5 cm. Setting the desired precision (Δ) at 1.2 cm and using a significance level of 5% (Zα/2 = 1.96), the calculation was as follows:

$N = (1.96)^2 \times (4.5)^2/(1.2)^2 = 54.0$

To account for potential subgroup analyses by sex and maturity status (3 maturity groups × 2 sexes) and to allow for approximately 15% potential dropouts, the target sample size was increased to 200 participants (86 males and 114 females). The sample size calculation was double-checked using ChatGPT-4, following Methnani et al.[29] guidelines, yielding the same result.

2.4. Participants

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Two hundred healthy adolescents participated in this study: 86 males (age 15.8 ± 1.7 years, body mass 54.0 ± 10.0 kg, height 167.0 ± 10.4 cm, estimated age at peak height velocity 16.2 ± 1.7 years) and 114 females (age 16.3 ± 1.8 years, body mass 53.3 ± 7.5 kg, height 159.0 ± 0.7 cm, estimated age at peak height velocity 13.7 ± 1.1 years). All participants were students who participated in two weekly sessions of physical education (2 hours per session), as specified in the Tunisian national curriculum guidelines [30]. None were involved in structured training programs outside of school. Participants were excluded if they reported any health concerns, diseases, or physical conditions that could affect physical activity. No injuries were reported during the study. All participants abstained from using screens (phones, tablets, computers, and televisions) for 24 hours prior to testing sessions to minimize potential effects of blue light on sleep quality and subsequent performance [31].

No standardized physical activity questionnaire was administered. Although all participants completed the same national physical education curriculum, individual differences in habitual physical activity or previous sport involvement could not be quantified. This constitutes a methodological limitation, as differences in activity levels may influence jumping performance and potentially contribute to sex-related differences.

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2.5. Maturity Assessment

Anthropometric measurements included body height, sitting height, and body mass. Body height was measured using a fixed stadiometer (±0.1 cm; Holtain Ltd., Crosswell, UK), sitting height with a purpose-built table (±0.1 cm; Holtain Ltd., Crosswell, UK), and body mass with a digital balance (±0.1 kg; ADE Electronic Column Scales, Hamburg, Germany). Lower limb length (cm) was calculated as the difference between standing height and sitting height. Body mass index (BMI) was calculated as body mass (kg) divided by the square of standing height (m) and reported in kg· m^2.

Biological maturity was assessed non-invasively by calculating maturity offset using gender-specific regression equations developed by Mirwald et

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al.[32]. These equations incorporate anthropometric measurements (body mass, standing height, and sitting height), chronological age, and sex to estimate the time relative to peak height velocity (PHV).

For boys, the equation was: Maturity Offset = -9.236 + 0.0002708 × (Leg Length × Sitting Height) + 0.001663 × (Age × Leg Length) + 0.007216 × (Age × Sitting Height) + 0.02292 × (Weight/Height ratio)

For girls, the equation was: Maturity Offset = -9.376 + 0.0001882 × (Leg Length × Sitting Height) + 0.0022 × (Age × Leg Length) + 0.005841 × (Age × Sitting Height) + 0.002658 × (Age × Weight) + 0.07693 × (Weight/Height ratio)

Based on the calculated maturity offset (MO), participants were classified into three groups:

- Pre-PHV: MO ≤ -0.5 years from PHV
- Circa-PHV: MO between -0.5 and 0.5 years from PHV
- Post-PHV: MO ≥ 0.5 years from PHV

This classification is widely used in research on youth maturation and follows the thresholds recommended by Mirwald et al.[32], who developed and validated the maturity offset prediction method.

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2.6. Performance Assessments

2.6.1. Horizontal Jump Test (HJT)

This test assessed horizontal jumping ability. Participants stood behind a marked line with feet hip-width apart. They performed a jump with an arm swing to achieve maximum horizontal distance while maintaining balance upon landing. Distance was measured from the take-off line to the nearest contact point at landing (heel position) using a tape measure. Three attempts were performed with 30-second rest intervals, and the best performance was recorded for analysis.

2.6.2. Five Jump Test (5JT)

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As described by Ramírez-Campillo et al.[33], participants began in a standing position with both feet flat on the ground and performed five consecutive forward jumps, alternating between left and right leg ground contacts. The total horizontal distance was measured to the nearest centimetres using a tape measure. Each participant performed two attempts with 5-minute rest intervals, and the best attempt was used for analysis.

2.6.3. Vertical Jump Tests

Vertical jump performance was assessed using drop jump (DJ) and countermovement jump (CMJ) tests. Jump height for both tests was measured using an infrared photocell timing system (Optojump System, Microgate SARL, Bolzano, Italy) connected to a digital computer. Flight times were recorded with 1/1000 s precision and automatically converted to jump height (cm) using the manufacturer's proprietary software based on the equation: $h = g \times t^2/8$, where h represents jump height, g is the acceleration due to gravity (9.81 $m \cdot s^{-2}$), and t is flight time.

For the drop jump (DJ), participants stood on a 40-cm-high box with slight knee flexion and their arms at their sides. The front of the feet extended slightly over the edge of the box. Upon an auditory signal, participants stepped forward off the box (without jumping) to the ground, allowing natural knee and hip flexion during landing. Immediately upon ground contact, participants performed a maximal vertical rebound jump without pausing, using an arm swing to maximize jump height, and landed on both feet simultaneously. The verbal instruction was to "jump as high as possible with minimal ground contact time." Each participant performed three trials with one-minute rest intervals between attempts, and the highest jump height (cm) was retained for analysis. Arm swing was permitted during the drop jump in accordance with previous youth SSC protocols [7,23]. While this increases ecological validity by reflecting natural reactive jumping patterns, it may add variability.

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For the countermovement jump (CMJ), participants began in an upright standing position with their hands on their hips to eliminate arm-swing contribution. They were instructed to rapidly flex their knees to approximately 90° (self-selected depth) and immediately transition into the concentric phase to jump as high as possible. Participants maintained their hands on their hips throughout the entire movement. Three trials were performed with one-minute rest intervals between attempts, and the highest jump height (cm) was used for subsequent analysis.

Moreover, for all jump tests, trials were discounted if the participant showed loss of balance upon landing, an evident technical error, failure to follow standardized instructions, or inconsistent take-off or landing patterns. Only technically valid trials were retained for analysis.

Statistical Analysis

Data are presented as mean ± standard deviation. Statistical analyses were performed using SPSS 22.0 (IBM Corp., Armonk, NY, USA). Data normality was confirmed using the Kolmogorov-Smirnov test, and sphericity was verified using Mauchly's test. The reliability of test measures was assessed using intraclass correlation coefficients (ICCs) and coefficients of variation (CVs), with corresponding 95% confidence intervals. ICCs were calculated using a two-way random effects model for absolute agreement with single measures [ICC(2,1)], following the guidelines of Koo and Li [34]. ICC values were interpreted as follows: <0.50 = poor, 0.50–0.74 = moderate, 0.75–0.89 = good, and ≥0.90 = excellent [34]. A two-way ANOVA with Sex × Maturation Offset interaction was used to analyze between-subgroup differences, with Bonferroni post-hoc tests for interpretation of significant effects. Differences between sexes were compared using independent samples t-tests. Effect sizes (ES) were calculated to estimate the magnitude of differences in tested variables and interpreted using the following thresholds: <0.20 (trivial), 0.20-0.59 (small), 0.60-1.19 (moderate), 1.20-1.99 (large), 2.0-3.99 (very large), and ≥4.0 (extremely large) [35]. Bivariate Pearson's correlation coefficients (r)

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were calculated to evaluate the relationships between maturity status and jumping performance. Correlations were classified as: <0.1 (trivial), 0.1-0.29 (small), 0.3-0.49 (moderate), 0.5-0.69 (large), 0.7-0.89 (very large), and 0.9-1.0 (nearly perfect) [36]. One-way ANOVA was used to obtain the ICC for repeated interval-scale measures [37]. Statistical significance was set at $p < 0.05$.

3. Results

Based on Table 1, Pre-PHV (pre-peak height velocity) participants exhibited significantly lower values for body height ($p < 0.001$; effect sizes: 1.5 and 2.4) and body mass ($p < 0.001$; effect sizes: 1.1 and 2.1), as well as a smaller maturity offset ($p < 0.001$; effect sizes: 2.8 and 4.7) when compared to both Circa-PHV and Post-PHV participants across both sexes. However, no statistically significant differences were observed between maturity groups regarding estimated age at peak height velocity (APHV).

Table 1: Descriptive characteristics of participants according to gender and maturity

	Males				Females			
	All (n=86)	**Pre-PHV (n=42)**	**Circa-PHV (n=17)**	**Post-PHV (n=27)**	**All (n=114)**	**Pre-PHV (n=14)**	**Circa-PHV (n=15)**	**Post-PHV (n=85)**
Chronological age (years)	15.8±1.7	15.3±1.6$^{\#\#\#}$	15.6±1.6*	16.8±1.5	16.2±1.8	12.5±0.7$^{\#\#\#}$	13.0±0.2$^{\#\#\#}$	16.5±1.5
Height (cm)	167±10.4	162±12.1$^{**\#\#\#}$	168±7.0$^{\#\#}$	172±5.8	159±0.06	152±0.05$^{\#}$	148±0.1$^{\#\#\#}$	160±0.05
Body mass (Kg)	53.9±10.06	50.2±9.9$^{*\#\#}$	55.1±8.6$^{\#}$	58.2±9.1	53.3±7.5	44.1±1.5$^{\#\#}$	43.6±1.0$^{\#\#\#}$	54.1±7.3
Limb length (cm)	90.9±11.9	94.0±14.0	89.2±10.08	87.1±7.9	80.9±11.7	85.5±12.0	73.0±19.1	81.0±11.4
BMI (kg/m^2)	19.1±2.4	18.5±2.0	19.2±2.9	19.6±2.5	20.8±2.5	18.9±1.2	19.9±2.8	20.9±2.5
APHV (years)	16.2±1.7	16.9±1.6	15.6±1.5	15.3±1.3	13.7±1.1	12.8±0.6	12.7±0.3	13.8±1.1
Maturity offset (years)	-0.3±1.5	-1.6±0.7$^{**\#\#\#}$	0.01±0.2$^{\#\#}$	1.4±0.8	2.4±1.1	-0.3±0.2$^{***\#\#}$	0.2±0.09$^{\#\#\#}$	2.7±0.9

Pre-PHV: pre-peak height velocity group; Circa-PHV: around peak height velocity group; post-PHV: post-peak height velocity group; APHV: Estimated age at peak height velocity. *Significantly different from the Circa-PHV group ($p < 0.05$). **Significantly different from the Circa-PHV group ($p < 0.001$). # significantly different from the post-PHV group ($p < 0.05$). # # significantly different from the post-PHV group ($p < 0.01$). # # # significantly different from the post-PHV group ($p < 0.001$).

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Table 2 presents the reliability data for the tests conducted in the present study. All tests demonstrated acceptable reliability, with CV values ranging from 1.1% to 7.9% and ICCs classified as good to excellent (0.824 to 0.990).

Table 2. Within-session reliability of jumping ability test measurements.

		ICC (95% CI)	CV (%) (95% CI)
		Vertical jump Performance	
DJ (cm)	Males	0.921(0.900–0.922)	7.36 (6.08–9.25)
	Females	0.920(0.918–0.921)	7.16 (6.04–8.99)
CMJ (cm)	Males	0.952(0.950–0.955)	5.84 (5.15–8.52)
	Females	0.954(0.952–0.954)	5.68 (5.10–8.49)
		Horizontal jump performance	
HJT(m)	Males	0.959(0.935-0.975)	5.1(3.90 - 6.29)
	Females	0.945(0.923-0.967)	4.1(3.90 - 4.29)
5JT(m)	Males	0.910(0.900–0.930)	7.89 (6.58–9.65)
	Females	0.900(0.900–0.910)	7.90 (6.95–9.75)

ICC = intraclass correlation coefficient; CV = coefficient of variation; CI = confident interval; DJ: drop jump; CMJ: countermovement jump; HTJ: Horizontal jump test 5JT: Five jump test

Table 3 shows the comparisons of the performance tests according to the maturational status. The between-group analysis revealed significant differences (p < 0.001 to 0.03) for males in all tests performed. The biological maturity-based comparison revealed no significant differences between the Pre-, Circa-, and Post-PHV sub-groups of females. However, a main difference was signaled by the ANOVA test between males in DJ [F (2.194) = 8.334; p<0.001], in CMJ [F (2.194) = 8.753; p<0.001], in HJ [F (2.194) = 3.983; p<0.005] and in 5JT [F (2.194) = 3.553; p<0.005].

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Generally, male performs better in horizontal jump (HJT; d =0.63; moderate effect sizes) and in FJT (d =0.55; small effect sizes) and in vertical jump (DJ ;d= 0.76; moderate effect sizes), in CMJ (d= 0.81; moderate effect sizes)). Post-hoc analyses revealed that compared to post-PHV, pre-PHV, and circa-PHV, males had significantly lower performance levels in all vertical jumps and ($p < 0.001$) in horizontal jumps ($p < 0.005$). However, no statistical differences were reported between female maturity sub-groups in jumping performance; post-PHV females reported higher horizontal jumping than pre- and circa-PHV. In contrast, circa-PHV females jump higher in CMJ and DJ longer than pre- and post-PHV.

Independent samples t-tests revealed significantly superior jumping performance in males compared to females across all tests: DJ (24.75 ± 3.48 cm vs. 16.58 ± 1.63cm; $p < 0.001$), CMJ (25.79 ± 3.48 cm vs. 18.52 ± 1.54 cm; $p < 0.001$), HJT (1.72 ± 0.21 m vs. 1.33 ± 0.17 m; $p < 0.001$), and 5JT (9.46± 1.08 m vs. 7.81 ± 0.80 m; $p < 0.001$).

Results revealed a significant main effect of sex in all jump performances ($p < 0.001$). In addition, two-way ANOVA showed a significant interaction (Sex × Maturational Groups) effect for vertical jumps (DJ and CMJ; $p = 0.005$) but not for horizontal jumps (HJT and 5JT; $p > 0.435$), as presented in Table 4.

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Table 3. Differences between maturational groups on jumping performance

		Maturational groups					**Effect size (90% IC)**		
Variables	**Sex**	Pre-PHV (n= 46)	Circa-PHV (n= 22)	Post-PHV (n=132)	F	P	Pre-PHV vs. Circa-PHV	Circa-PHV vs. Post-PHV	Pre-PHV vs. Post-PHV
DJ	**Male**	22.91±3.48###	23.28±3.54##	25.37±2.97	8.33	0<0.001	-0.11 (-0.98–0.77)	0.67 (-0.25–1.59)	0.76 (-0.01–1.52)
	Female	17.52±1.36	17.82±0.40	16.49±1.65	0.92	0.40	-0.36 (-0.90–0.18)	-0.83 (-1.13–0.53)	-0.63 (-0.94–0.33)
CMJ	**Male**	24.92±3.51###	25.35±3.61##	27.41±2.83	8.75	0<0.001	-0.12 (-1.01–0.76)	0.67 (-0.24–1.58)	0.81 (0.05–1.56)
	Female	19.26±1.23	19.97±0.43	18.43±1.55	0.98	0.37	-0.93	-0.10 (-1.58–0.61)	-0.56

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							(-1.43–0.43)		(-1.09–0.05)
HJT	**Male**	1.66±0.22 # # *	1.76±0.18	1.79±0.19	3.98	0.020	-0.49 (-0.54– -0.43)	0.16 (0.11–0.22)	0.63 (0.58–0.68)
	Female	1.29±0.11	1.24±0.07	1.33±0.17	0.56	0.57	0.63 (0.58–0.69)	0.54 (0.51–0.57)	0.24 (0.21–0.27)
FJT	**Male**	9.20±1.27 #	9.57±0.99	9.78±0.63	3.55	0.031	-0.34 (-1.61– -0.01)	0.28 (0.10–0.47)	0.55 (0.30–0.80)
	Female	7.54±0.72	7.06±0.54	7.85±0.80	1.65	0.19	0.87 (0.51–1.23)	1.01 (0.86–1.15)	0.39 (0.24–0.54)

F and P-values were obtained by two-way ANOVA (3 maturational groups). Pre-PHV: pre-peak height velocity group; Circa-PHV: around peak height velocity group; post-PHV: post-peak height velocity group; 90% IC: 90% interval confidence; DJ: Drop jump; CMJ: countermovement jump; HJT: Horizontal jump test; FJT: Five Jump Test. Different from the Circa-PHV group (*p < 0.05). Different from the Circa-PHV group (** p < 0.01). Different from the Circa-PHV group **(***p < 0.001). Different from the post-PHV group (**#**p < 0.05). Different from the post-PHV group (**# #**p < 0.01). Different from the post-PHV group **(# # #**p < 0.001).

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Table 4. Performance analysis of variance, two-way ANOVA, and (Sex x Maturational groups) interaction

	Sex Effect		**Maturational Groups Effect**		**Sex x Maturational groups Interaction Effect**	
Variables	F	p	F	p	F	p
DJ	107.24	<0.001	0.66	0.52	5.44	0.005
CMJ	113.63	<0.001	0.86	0.42	5.53	0.005
HJT	90.13	<0.001	1.80	0.17	0.60	0.548
5JT	76.96	<0.001	3.01	0.05	0.84	0.435

Results of the Pearson's correlation coefficient analyses of the maturity offset and horizontal jumping in both sex are depicted in Figure 3, between maturity offset and vertical jumping in Figure 4. Significant large correlation respectively with maturation and both VJ (r= 0.60; p<0.01) and

HJ(r= 0.67; p<0.01) for males. No significant correlations observed in the females.

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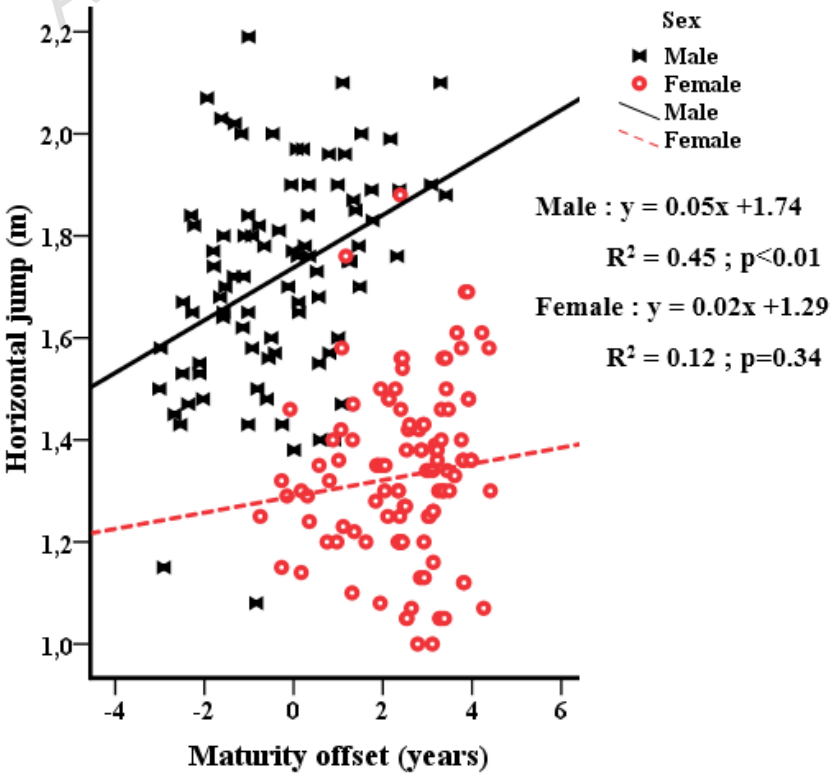

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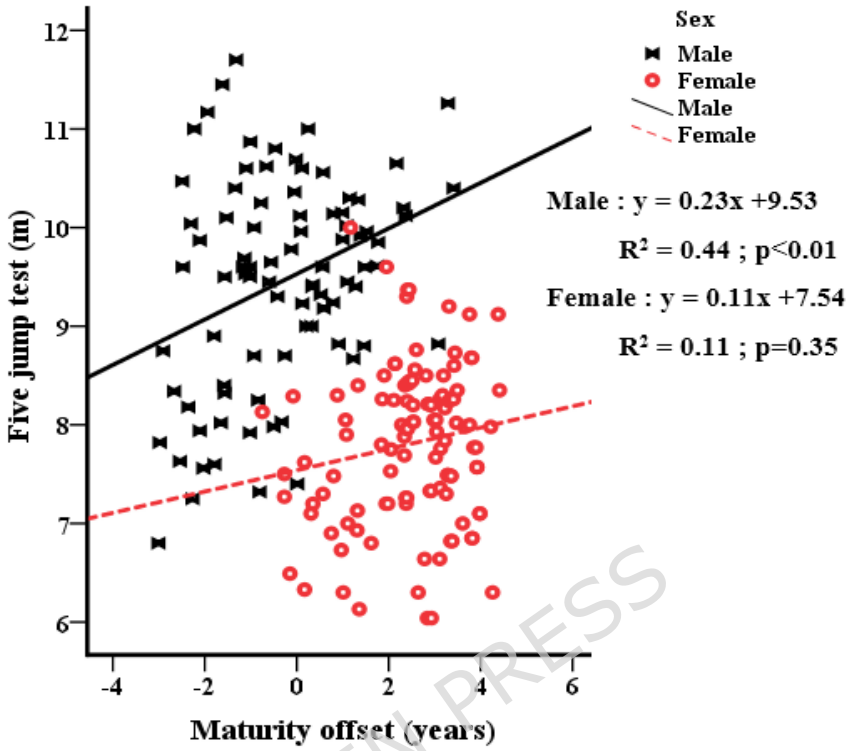

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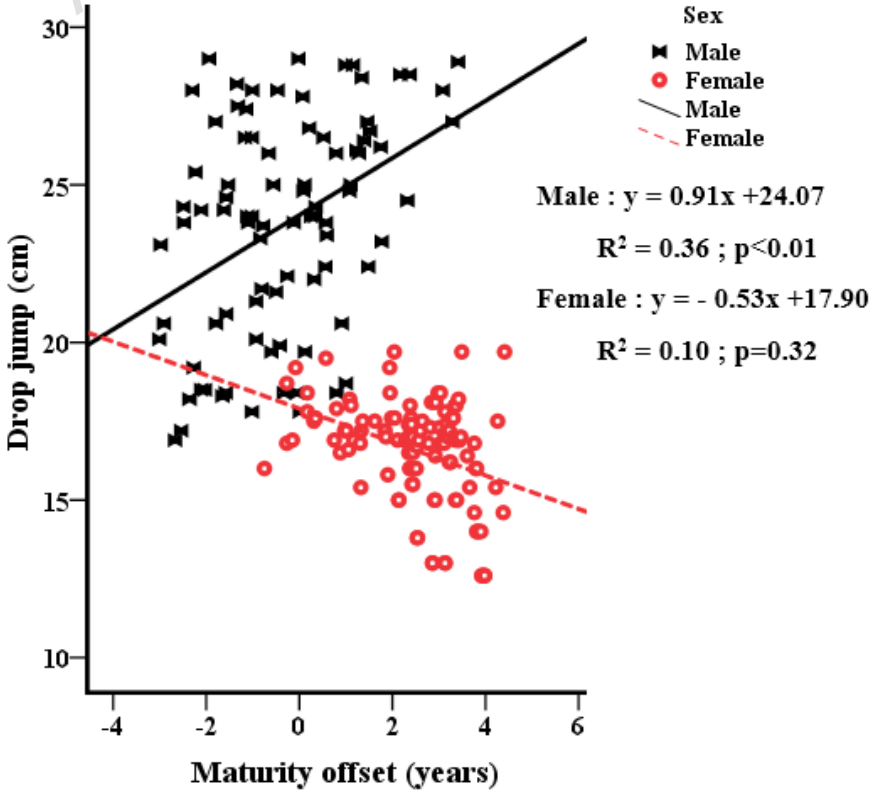

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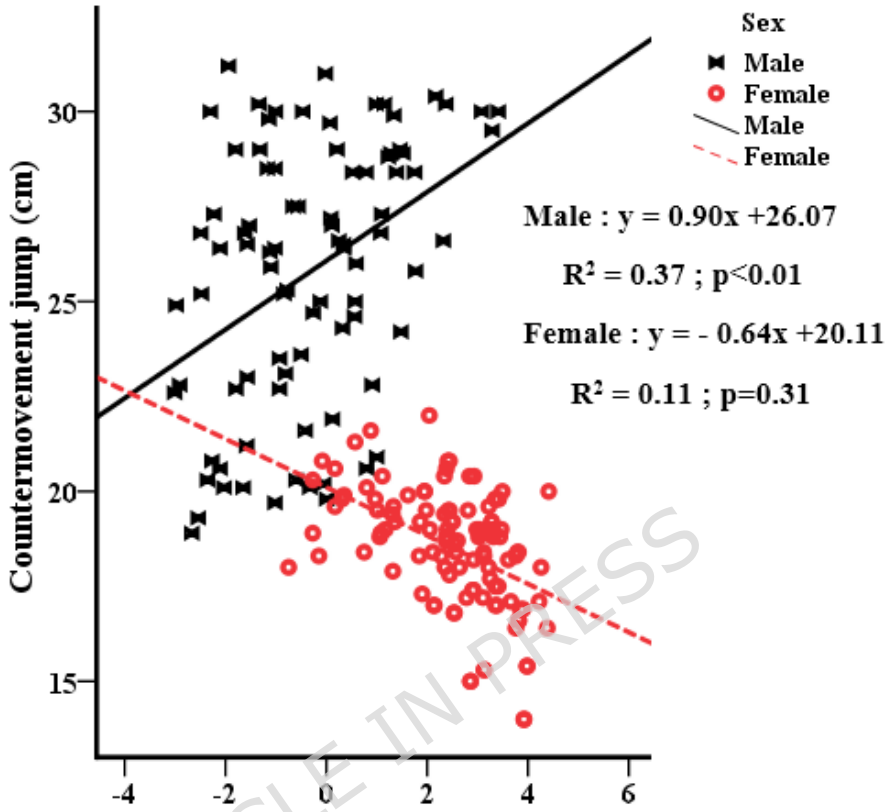

Figure 4. Relationship between maturity offset and vertical jumping performance in adolescent males and females: A. Drop jump, B.

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4. Discussion

This study aimed to investigate the influence of sex and maturity status on jumping performance in adolescents. Specifically, we examined differences in vertical and horizontal jumping abilities across maturity groups for both males and females and determined the relationship between maturity offset and jumping performance by sex. Our main findings revealed that: (1) males demonstrated superior jumping performance compared to females across all maturity groups; (2) maturity status significantly affected jumping performance in males but not in females; (3) post-PHV males performed significantly better than Pre-PHV and Circa-PHV males in all jump tests; and (4) significant positive

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correlations between maturity offset and jumping performance were observed in males but not in females.

The anthropometric results of our study showed that participants of younger biological age (pre-PHV) had significantly lower height and body mass than those of more advanced biological age (Circa-PHV and Post-PHV). Similar findings were reported by Ulbricht et al.[38], who found that Pre-PHV participants had approximately 7-12% lower body height and 18-30% lower body mass than Circa-PHV and Post-PHV groups. These differences in body structure are among the primary factors influencing physical performance outcomes during adolescence. The anthropometric changes associated with maturation are primarily driven by hormonal changes, particularly growth hormone and testosterone, which contribute to the development of muscle cross-sectional area and subsequent improvements in strength and power capabilities [20].

Our study demonstrated that male adolescents performed better across all jump tests, regardless of maturity status, than their female counterparts. These sex-based differences in jumping performance align with previous research by Focke et al.[8] and Bchini et al.16, who attributed these differences to physiological factors, including greater leg muscle volume, more favorable muscle fiber-type composition, and enhanced muscle power production in males. Ben Mansour et al.[22] further observed that males typically have higher absolute and relative power outputs (measured by body height or weight) than females. These sex-based performance differences likely stem from divergent endocrine profiles during puberty, with males exhibiting higher testosterone levels that enhance protein synthesis and muscle development [10]. Additionally, females typically experience greater fat mass accumulation during puberty, which may negatively impact the power-to-weight ratio and subsequently affect jumping performance [11,39]. Interestingly, sex differences in jumping performance were present even in pre-PHV participants, despite the absence of major hormonal or muscle-volume divergences. Several mechanisms may explain these early differences. Boys tend to exhibit slightly more favorable anthropometric proportions

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(e.g., lower-limb segment ratios), greater exposure to vigorous play and locomotor activities during childhood, and earlier development of neuromuscular coordination patterns associated with explosive movements[8,16]. These behavioral and biomechanical factors likely contribute to boys' superior pre-PHV jumping performance, independently of endocrine maturation.

A key finding of our study was that maturity status significantly influenced jumping performance in males but not in females. Post-PHV males displayed significantly better performance in vertical jumps (DJ, CMJ) and horizontal jumps (HJT, 5JT) compared to their Pre-PHV and Circa-PHV counterparts. This performance enhancement with maturation in males aligns with research by Edwards et al. [24], who noted that the PHV period corresponds with peak secretion of growth hormone and testosterone, facilitating muscle development and power production. The stretch-shortening cycle efficiency appears to improve considerably during male maturation, likely due to enhanced neuromuscular coordination, increased muscle stiffness, and improved motor unit recruitment patterns [7]. Interestingly, our female participants did not exhibit significant performance differences across maturity groups, with pre-PHV females performing similarly to, or better than, Post-PHV females in vertical jump tests. This finding supports research by Birat et al. [23], who suggested that imbalances between quadriceps and hamstrings that develop during the late Circa-PHV and early post-PHV period in females might negatively affect jumping performance. These results indicate that maturation-related performance adaptations follow different trajectories in males and females, necessitating sex-specific approaches to performance assessment and training during adolescence. It is also important to note that factors not controlled in this study- such as differences in habitual physical activity, arousal, motivation during testing, or menstrual cycle phase among females- may have contributed to performance variability. These contributors should be considered in future investigations to refine the interpretation of sex differences.

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Our analysis revealed a significant interaction effect between sex and maturity status for vertical jumping but not horizontal jumping performance. The absence of a Sex × Maturity interaction for horizontal jumps suggests that maturation may influence vertical and horizontal force-production mechanisms differently. Vertical SSC actions rely heavily on increases in musculotendinous stiffness, elastic energy storage, and reactive eccentric–concentric transfer, which are known to improve with male maturation[7,18]. Horizontal jumps, however, depend more on horizontal impulse, coordination between trunk–hip–knee flexion, and forward momentum, which may be less sensitive to biological maturation. This could explain why maturity modulated vertical but not horizontal jumping differently between sexes. This interaction suggests that the influence of maturation on vertical jumping ability differs substantially between males and females. Kumar et al.[18] similarly reported that maturation significantly improves jump-landing performance metrics in males, with older adolescents showing enhanced jump height and reactive strength. The observed sex-by-maturation interaction may be explained by differential adaptations in the stretch-shortening cycle mechanisms. Males appear to develop more efficient eccentric-to-concentric force transfer during maturation, possibly due to greater increases in tendon stiffness and neural adaptations that enhance the utilization of elastic energy[12]. The absence of this interaction effect for horizontal jumping suggests that the mechanisms underpinning horizontal force production may develop differently than those for vertical force production during adolescent maturation [33]. These findings highlight the importance of considering both sex and maturity status when evaluating and developing jumping abilities in adolescent populations.

The correlation analysis demonstrated significant positive associations between maturity offset and jumping performance (both vertical and horizontal) in males but not in females. This finding is consistent with research by R. Kite et al. [21], who reported that jumping performance in males strongly correlates with maturation status. The observed large correlations in males (r=0.60 for vertical jumps; r=0.67 for

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horizontal jumps) indicate that approximately 36-45% of the variance in male jumping performance can be explained by maturity status. This substantial relationship underscores the profound influence of biological maturation on power development in adolescent males. The absence of significant correlations in females suggests that other factors, such as technique, neuromuscular coordination, psychological factors, or training experience, may play more prominent roles in determining jumping performance in adolescent females [14]. These contrasting correlation patterns between sexes provide valuable insights for talent identification and development programs, suggesting that maturity-related assessments may have greater predictive value for performance potential in males than in females.

While our findings indicate limited maturation-related improvements among females, some studies have reported gains in lower-body power or SSC efficiency with maturation in female adolescents[17,23]. These inconsistencies highlight the complex, multidimensional nature of maturation effects in girls and underscore the need for longitudinal assessments.

Limitations

Our study has several limitations that should be acknowledged. Although the sample size was determined through appropriate power calculations, larger samples might provide more comprehensive insights into the relationship between maturity and jumping performance. Another limitation concerns the use of prediction equations for estimating maturity status. As noted by Kozieł and Malina[25] and Mirwald et al.[32], these equations rely on accurate anthropometric measurements, with potential errors in sitting height measurements that could significantly affect maturity offset calculations. Future research should consider employing multiple methods for maturity assessment to enhance reliability. Additionally, our cross-sectional design limits causal inferences regarding maturation and performance; longitudinal studies tracking individuals across developmental stages would provide more definitive evidence of developmental trajectories in jumping performance.

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Another limitation is the absence of a standardized physical activity questionnaire. Although participants followed the same educational program, individual differences in habitual physical activity or previous sport participation were not assessed and may have influenced sex-specific variations in jumping performance.

5. Conclusion

This study suggests that sex and maturation status are associated with distinct patterns of jumping performance development in adolescents, with distinct patterns between males and females. Post-PHV males performed significantly better in all jump tests compared to less mature males, while females showed minimal performance differences across maturity groups. Notably, maturity offset strongly correlated with jumping performance in males but not in females. These findings suggest that the maturation schedule should be carefully monitored when assessing anaerobic performance in adolescents, particularly in males. Physical education teachers and coaches should implement maturity-based rather than chronologically age-based approaches when designing training programs and evaluating jumping performance in youth. For female athletes, greater emphasis on neuromuscular training may be more beneficial than focusing on maturity status. These sex-specific developmental patterns highlight the importance of individualized approaches in youth physical development programs and talent identification protocols.

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Author contributions

SB: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. SA:
Conceptualization, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. I D: Conceptualization, Formal Analysis, Investigation,

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Methodology, Writing – original draft, Writing – review & editing. HIC: Conceptualization, Formal Analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. RT: Conceptualization, Investigation, Resources, Validation, Writing – review & editing. ZF: Conceptualization, Investigation, Methodology, Software, Supervision, Validation, Writing – original draft, Writing – review & editing. DM: Conceptualization, Investigation. Resources, Validation, Writing – review & editing. RIM: Conceptualization, Formal Analysis, Investigation, Methodology, Software, Supervision, Validation, Writing – review & editing. ABA: Conceptualization, Formal Analysis, Investigation, Project administration, Validation, Visualization, Writing – review & editing.

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Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author.

Declaration of competing interests

The authors declare no competing interests

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Ethics approval: The study was carried out by the Helsinki Declaration of Human Experiments. The local research ethics committee of the High Institute of Sport and Physical Education of Kef, University of Jendouba, approved the protocol with the code number c11-2024, which was authorized on January 18, 2024.

Declaration

In preparing this paper, the authors used the ChatGPT model 4 on November 15, 2024, to revise some passages of the manuscript, double-check for grammatical errors, and improve academic English. After using

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this tool, the authors reviewed and edited the content as necessary and assumed full responsibility for the publication [40,41].

Clinical Trial Number

Not applicable

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