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Maturity Affects Static Balance in Early Adolescent Boys and Girls Associated with Achilles Tendon Stiffness

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Abstract The purpose of this study was to investigate the effect of maturity status on static balance control in early adolescent boys and girls, with regards to Achilles tendon stiffness and plantar flexors force. Twenty boys and nineteen girls performed three balance tasks (two legs-eyes open, two legs-eyes closed, one leg stance) at 18 and 9 months before peak height velocity (PHV) and at PHV. We assessed the center of pressure (COP) displacements in anterior-posterior (AP) and medio-lateral (ML) directions and electromyographic (EMG) activity of medial gastrocnemius (MG) and tibialis anterior (TA) muscles and calculated the coactivation of these muscles. Additionally, we quantified Achilles tendon (AT) stiffness and plantar flexors force during an isometric contraction in the same time points. AT stiffness was related to increased TA activity during the three different balance tasks in boys, 18 and 9 months before PHV, whereas AT stiffness was related to increased co-activation in closed eyes task only 9 months before PHV in girls. Additionally, increased demands in ML direction balance control in the closed eyes task were related to increased plantar flexor muscles force in girls. These findings provide novel evidence that boys and girls employ different postural control patterns, related to AT stiffness, to maintain static balance across the adolescent growth spurt.

Keywords Adolescence, Balance Control, Achilles Tendon Stiffness, Plantar Flexors Force

1. Introduction

Adolescence marks a pivotal phase in human development characterized by substantial increases in body height and mass, accompanied by a corresponding surge in muscle force, thereby imposing pronounced mechanical loads on tendons [1, 2]. The Achilles tendon, in particular, undergoes discernible mechanical and morphological transformations during this period, coinciding with heightened tendon stiffness [3-5]. The onset of adolescence, marked by a rapid escalation in height known as Peak Height Velocity (PHV), significantly influences neuromuscular control and, consequently, motor development [6-8]. Motor development is intrinsically linked to balance, a fundamental component influenced by multifaceted sensorimotor and neural factors [9]. The central nervous system (CNS) integrates feedback from various sensory inputs to regulate balance [10]. While balance control appears to improve throughout adolescence, growth spurts occurring around the time of PHV have been associated with delayed progress in this regard [11, 12]. These growth-related periods coincide with the incomplete maturation of sensorimotor mechanisms, thereby amplifying the challenges posed by various motor control tasks [13]. Notably, during these phases, postural demands exacerbate adolescents' reliance on visual cues, compromising their ability to integrate proprioceptive inputs. Studies have indicated that, especially during static balance tasks, children and adolescents display a strong visual dependency, with the visual afferent system typically attaining adult levels at ages 15 to 16, and girls demonstrating earlier sensory system maturation [14-17]. This gender-based disparity in balance control during static tasks manifests across various age groups, as evidenced by recent research indicating superior balance control among girls compared to boys in the 9 months leading up to PHV. This superiority is linked to heightened ankle muscle co-activation, a strategic response aimed at minimizing center of pressure (COP) displacement [18]. Moreover, it is evident that the removal of visual feedback impairs balance control in both adolescents and adults [19]. However, the influence of sex-related differences in balance control, specifically the interplay between ankle muscle-tendon interactions during challenging balance tasks (e.g., the removal of visual feedback), remains inadequately explored.

In the context of quiet standing, balance is often likened to an inverted pendulum pivoted at the ankle joint, rendering ankle stiffness and ankle muscle activation pivotal factors in postural control [20, 21]. Particularly in growing children, where the center of mass is elevated, and the base of support is narrower, tendon stiffness emerges as a potential compensatory factor influencing balance control. Reduced tendon stiffness is associated with impaired motor coordination and balance control [22, 23]. Maturity appears to modulate the properties of adolescents' tendons due to the slower growth rate of muscles relative to bones, a phenomenon compounded by the strengthening of gastrocnemius muscle, which in turn affects Achilles tendon (AT) stiffness. Recent longitudinal data underscored a rapid surge in plantar flexor force among boys, compared to girls in the six months leading to PHV resulting in heightened AT stiffness around PHV [5]. Nonetheless, to the best of our knowledge, no longitudinal data exists regarding the association between balance control and ankle musculotendinous properties in adolescents of both genders around the time of PHV.

Regarding ankle muscle activation during quiet standing, preadolescents have exhibited elevated levels of Tibialis Anterior (TA) activity and increased ankle muscle co-activation during challenging balance tasks [24], a pattern that persists in late adolescents, particularly in the anterior-posterior (AP) sway direction [25]. In adults, studies have demonstrated that enhanced ankle muscle co-activation (e.g., TA/SOLEUS or TA/MG) serves as a strategic mechanism to enhance postural stability through heightened ankle stiffness [26-28]. This phenomenon suggests that joint stiffening may represent a mechanism for reducing COP displacement during demanding balance tasks. Furthermore, research has indicated the involvement of the medial gastrocnemius (MG) in lateral sway during unipedal stances [25], while passive muscle-tendon stiffness has been found to play a crucial role in minimizing the need for muscle activity during quiet standing [29]. Loram & Lakie [29] have even observed the absence of reflex activity in ankle muscles, underscoring the pivotal contribution of AT stiffness to stabilization. However, the function of these balance control strategies in adolescents before PHV remains unexplored.

It is widely acknowledged that intrinsic factors significantly impact postural balance, including maturation, which enhances postural function, and height, which exerts a negative influence on postural balance, along with neuromuscular and sensory characteristics [30]. However, the interactive effects of these parameters on balance control remain poorly understood. Consequently, this study aims to investigate longitudinal changes in AT stiffness and plantar flexor force in relation to muscle activation during various standing balance tasks in adolescent boys and girls. This investigation seeks to quantify the relationship between MG and TA activity during both simple and challenging balance tasks (e.g., one-leg stance and eyes-closed tasks) and AT stiffness and ankle muscle force. Our primary hypothesis posits that the maturation-induced increases in AT stiffness and force will correlate with heightened plantar flexor activity. Additionally, we anticipate differential adaptations in balance control between boys and girls around the time of PHV, particularly during challenging balance tasks. An in-depth comprehension of these interactions holds paramount importance for mitigating the risk of lower limb injuries and optimizing athletic development in adolescents during the PHV period.

2. Materials and Methods

2.1. Participants

A total of twenty male participants, with an average age of 12.5 years (± 0.29), and nineteen female participants, with an average age of 10.5 years (± 0.32), were included in this study. Detailed participant characteristics are presented in Table 1.

Table 1. Maturity stage based on anthropometric measurements of adolescent boys and girls at three different testing times

	TESTING TIME	-18mo_PHV	-9mo_PHV	0mo_PHV
BOYS (N=20)	Maturity Stage	-19,1 ±3,6	-9,72 ±4,7	-4 ±5,2
	Age (years)	12,5 ±0,3	13,1 ±0,3	13,8 ±0,3
	Body mass (kg)	46,6 ±6,7	51 ±6	56,5 ±8
	Height (cm)	153,7 ±3,3	159,5 ±4	164,4 ±4
GIRLS (N=19)	Maturity stage	-16,2 ±4,6	-7,9 ±5,4	-2,2 ±3,6
	Age (years)	10,6 ±0,3	11,2 ±0,2	11,9 ±0,2
	Body mass (kg)	34,3 ±6,4	37,4 ±7,5	40,9 ±8
	Height (cm)	143,4 ±5,5	148,4 ±5,6	152,1 ±5

None of the enrolled participants had a history of musculoskeletal injuries. Informed consent was obtained from parents or legal guardians, in accordance with the Educational Policy Institute (ERC-009/2020) guidelines of Aristotle University, adhering to the ethical principles outlined in the Declaration of Helsinki. Peak height velocity (PHV) occurs approximately two years earlier in girls compared to boys, initiating at around 10.5 years of age. Accordingly, we estimated the maturity offset, representing the time relative to PHV, using a sex-specific multiple regression equation. This equation was based on several anthropometric parameters for each participant, including body mass, standing and sitting height, lower limb length, and chronological age [31].

2.2. Overall Study Procedures

All participants followed a standardized protocol, commencing with balance measurements, followed by a 10-minute rest period, and ending with Achilles tendon measurements. Prior to the entire protocol, participants underwent a 10-minute warm-up session, which included 7 minutes of jogging at an intensity sufficient to elevate heart rate(HR) to 50-60% range of HRmax and 3 minutes of lower-limb stretching exercises targeting all lower-limb joints.

2.2.1. Balance Measurements

Three balance assessments were conducted in a sequential manner, involving three distinct tasks:

1. Postural balance task with participants standing on both legs with their eyes open.
2. Postural balance task with participants standing on both legs with their eyes closed.
3. Postural balance task with participants standing on their right leg with their eyes open.

Previous research has established that the center of pressure (COP) does not exhibit significant differences between dominant and non-dominant limbs [32]. Consequently, the right leg was randomly chosen for all participants. Each child received two familiarization trials before each task. During the balance measurements, participants were instructed to maintain maximal stability throughout the trials with their hands placed on their hips. In conditions involving open eyes, participants focused on a single point located 2 meters in front of them at eye level. The duration of both legs' postural balance tasks was set at 30 seconds, while the single-leg postural balance task was performed for 10 seconds, as this duration has been reported as reliable for assessing single-leg balance in children [14]. During these tasks, the swinging leg was flexed at a 90 °angle at the hip and knee joints. Center of pressure (COP) displacement in the anterior/posterior (A/P) and medio/lateral (M/L) directions was determined from ground reaction forces recorded during each balance task. Force signals were processed through an 8-channel charge amplifier (Kistler 9281CA, 5233A2, output range: ±5V) with built-in filter bridges (frequency response>7 kHz) and digitally sampled via an A/D card (1 kHz). The instantaneous COP (ay, ax) position was calculated using established equations, incorporating ground reaction forces and moments:

$$a_x=(F_x * a_{z0} - M_y)/F_z$$

$$a_y=(F_y * a_{z0} - M_x)/F_z$$

where a_{z0} is the distance between the base and the surface of the plate. Postural sway was quantified by computing the standard deviation (COPsd) of COP oscillations along the AP and ML directions. The standard deviation represents the root mean square amplitude of the COP displacement, providing a measure of average displacement around the mean COP [32].

2.2.2. EMG Measurements

Muscle activity of the medial gastrocnemius (MG) and tibialis anterior (TA) of the right leg was assessed using bipolar surface EMG electrodes (Motion Control, IOMED Inc., voltage range: 64–612 V). These electrodes were interfaced with a 16-channel analog amplifier (sampling frequency 1 kHz, CMRR 100 dB at 50/60 Hz, bandwidth 8.5 kHz, gain 400). The skin preparation and sensor placement adhered to the guidelines of the SENIAM project (Surface Electromyography for the Non-Invasive Assessment of Muscles; http://www.seniam.org). All signals were synchronized and digitized using the Biopac MP150 unit (Biopac Systems Inc., CA, USA) at a sampling frequency of 1 kHz with 16-bit resolution. The EMG raw data underwent full-wave rectification and low-pass filtering at 6 Hz to yield linear envelopes for each muscle EMG.

Root Mean Square (RMS) values obtained during the balance tasks were normalized (normEMG) with respect to maximal values achieved during maximal voluntary ankle plantar flexion contractions (MVC). Subjects performed isometric MVC tests (~5 seconds) following the standing balance assessments. These tests were conducted on a dynamometer (AMTI BIOVEC SYSTEM, OR6-6, USA) with a 70^0 trunk flexion, full knee extension, and a neutral foot position identical to that during the balance tasks. Coactivation between the TA and MG muscles was quantified using the following equation: (normEMG of TA / normEMG of MG) x 100 = coactivation index (CI) [33, 34].

2.2.3. Achilles Tendon Measurements

Each participant was positioned in a prone posture with their knee fully extended on a dynamometer bench (Cybex Humac Norm, CSMI, MA, USA). The right foot was set at a 90-degree angle relative to the tibia, ensuring a fully extended knee, and securely placed on the dynamometer's footplate [35-38]. Torque measurements were taken at the neutral position (0 degrees). The experimental setup and procedure closely followed previously published methods [39]. The perpendicular distance from the center of rotation to the line of Achilles tendon (AT) action was referred to as the AT moment arm (MA). This was computed using the excursion method [40, 41], as described in a prior study [5]. To determine the moment arm, a third-order polynomial equation was fitted to describe the relationship between angular position and AT elongation. The first derivative of this polynomial equation was then calculated to obtain the slope of the curve, which represents the moment arm. During the measurements, we observed some foot displacement from the initial position and changes in ankle joint angle. To account for these changes, we used a method as previously detailed [42, 5] to detect potential heel movement during muscle contraction. Any additional displacement at the musculotendinous junction (MTJ) was subtracted from the recorded elongation (ΔL) to correct for the influence of ankle joint rotation. The force exerted by the tendon was estimated using the formula: $F = M / d$, where F represents the tendon force, M stands for the plantarflexion moment, and d denotes the length of the AT moment arm. The antagonistic moment generated by the tibialis anterior (TA) was calculated using a method outlined in a previous study [43]. The maximal plantar flexor moment was adjusted by incorporating the antagonistic moment values. The plantar flexor moment was derived by adding the resultant joint moment to the antagonistic moment. Stiffness (k) in units of N/mm was determined as the slope of the linear segment in the force (F) – elongation (ΔL) relationship. To construct the F–ΔL relationship, data from the force-time calculations and data from the MTJ position – time relationship were merged for each ramped isometric plantarflexion in all measurements. Subsequently, muscle force (N) and MTJ length change (mm) data were synchronized, and the slope of the F–ΔL relationship was calculated using the formula: $k = dF / dL$ [44, 4].

2.3. Statistics

We initiated our analysis by assessing the normal distribution of the dataset through the application of the Kolmogorov–Smirnov test. Our study's dependent variables (DVs) encompassed AP COP, ML COP, MG activity, TA activity, and CI. To comprehensively explore the variations in these DVs across different maturity stages and within individuals, we employed a linear mixed model (LMM), recognized for its suitability in handling longitudinal data. In our investigation, sex served as a two-level predictor, effectively functioning as a fixed factor for all dependent variables. Furthermore, we conducted separate simple linear regression analyses for males and females at distinct maturation stages, specifically -18 mo_ PHV, -9 mo_ PHV, and 0 mo_ PHV. These analyses aimed to elucidate the relationships between the DVs and explanatory factors, namely peak force and AT stiffness. All analyses were carried out using SPSS 26.0 Statistical Package (SPSS Inc, Chicago, IL), and the predetermined significance threshold was set at $p < 0.05$.

3. Results

A significant sex by maturation interaction effect (b = 0.0015, 95% CI 0.0003-0.0027, p = 0.013) was found for the ML COP in the right leg (RL) balance task. Specifically, boys exhibited higher ML COP values compared to girls -9 mo_ PHV, with a subsequent significant decrease by PHV, resulting in convergence with girls' performance (Figure 1). Boys' ML and AP COP in one leg stance (p=.005 and p=.004 respectively) was greater than girls' -9 mo_ PHV (Figure 1 A-B). In terms of force, boys consistently demonstrated higher values across all stages (b = 1099.31, 95% CI 697-1501.64, $p < 0.001$), with a notable sharp increase observed from -18 mo_ PHV. Additionally, AT stiffness was greater in boys compared to girls from -9 mo_ PHV to 0 mo_ PHV (b = 123.89, 95% CI 38.1-209.65, p = 0.005). Notably, the rate of increase in AT stiffness was greater (p=0.015) in boys (-18 to -9 mo_ PHV) than in girls (-9mo to 0mo_ PHV) (Figure 2). Regression analysis revealed significant relationships at different time points in girls as compared to boys. Specifically, during the two-leg with eyes closed balance task, girls showed a significant increase in ML-COP in response to peak force (F(1,7) = 11.70, p = 0.011) and a significant increase in coactivation

(F(1,7) = 9.75, p = 0.017) and a decrease in MG activity (F(1,7) = 7.38, p = 0.030) in response to AT stiffness at -9 mo_ PHV. Conversely, boys showed a significant increase in TA activity, during two –leg open eyes balance task, -18 mo _ PHV in response to AT stiffness (F(1,8) = 5.37, p = 0.049) and a significant increase in TA activity during two-leg closed eyes balance task (F(1,7) = 6.68, p = 0.036) and the right leg eyes open balance task (F(1,7) = 5.63, p = 0.049) in response to AT stiffness, -9 mo_ PHV (Table 2).

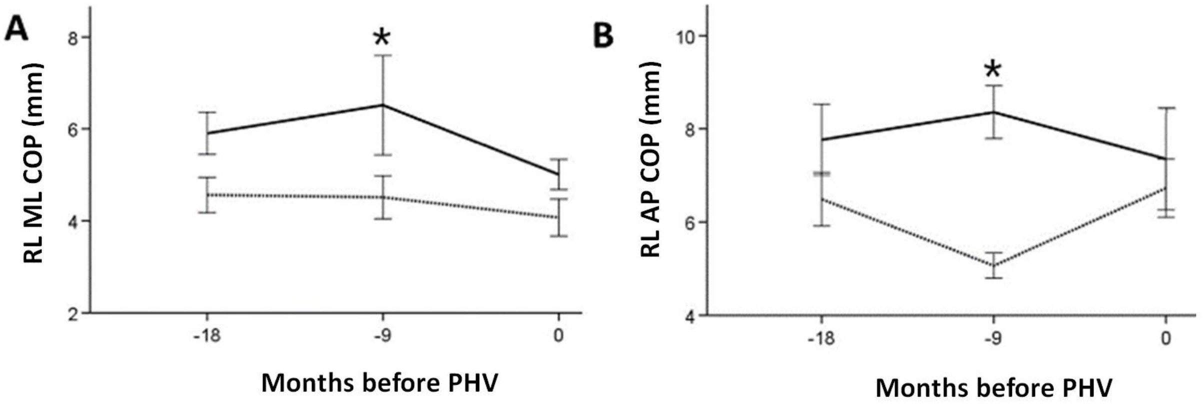

Figure 1. Changes in COP std in right leg (RL) balance task, in mediolateral (ML) (A) and anterior-posterior (AP) (B) direction, for boys (solid line) and girls (dashed line). Data are presented as Means ± Standard error. Significant sex by maturation interaction exists, with boys exhibiting higher ML and AP std COP, -9 mo_ PHV (p<0.05)

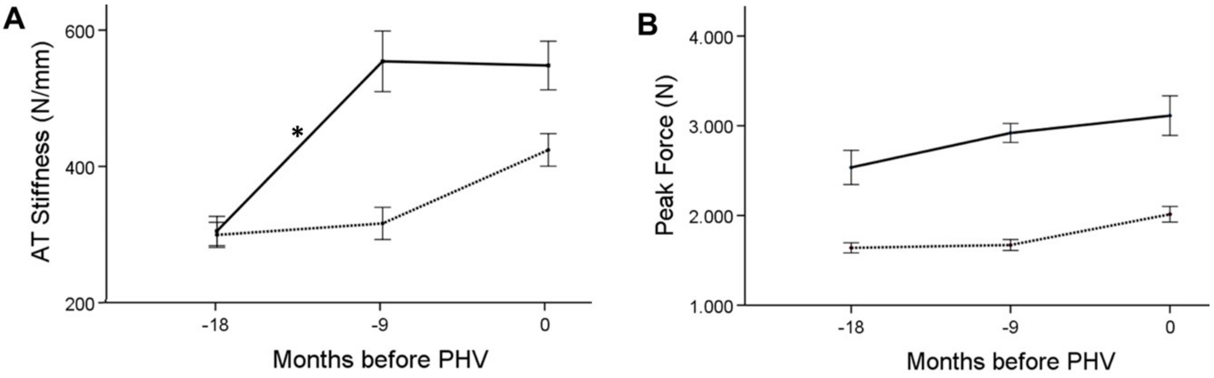

Figure 2. Changes in AT stiffness (A) and peak ankle muscles force (B) with maturity for boys (solid line) and girls (dashed line). Data are presented as Means ± Standard error. Significant rate of increase in AT stiffness exists between boys and girls (p=0.015)

Table 2. Fitted regression equations describing the relationship between independent variables (IV) and depended variables (DV) for which there was a statistical significance. Balance tasks: open eyes (OE), closed eyes (CE), right leg stance (RL)

DV (y)	SEX	IV (x)	MATURATION	EQUATION	R^2
ML COP (CE)	**GIRLS**	Peak force	9 months before PHV	y = 0.0002x - 0.006	0.64
MG activity (CE)		AT stiffness		y = -0.0860x + 64.219	0.52
Coactivation (CE)		AT stiffness		y = 0.3620x + 64.771	0.59
TA activity (OE)	**BOYS**	AT stiffness	18 months before PHV	y = 0.2200x - 21.000	0.41
TA activity (CE)		AT stiffness	9 months before PHV	y = 0.0650x + 15.598	0.50
TA activity (RL)		AT stiffness		y = 0.0400x + 3.245	0.45

4. Discussion

In this study, we delved into the intricate relationship between Achilles tendon (AT) stiffness, ankle muscle force, and their impact on the performance of static balance tasks, encompassing both easy and challenging conditions such as one-leg tasks and tasks with closed eyes. Our investigation involved adolescent boys and girls at three distinct time points within the 18 months preceding peak height velocity (PHV). Our findings shed light on the differing mechanisms employed by early adolescent boys and girls to regulate static balance, characterized by distinct neural patterns and musculotendinous interactions. Specifically, we observed that 9 months before PHV, during the closed eyes balance task, there was an association between increased demands in balance control in the ML direction and heightened force production, while higher AT stiffness correlated with higher co-activation of the tibialis anterior (TA) and medial gastrocnemius (MG) muscles in girls. Conversely, in boys, AT stiffness correlated positively with TA activity during open eyes (OE), closed eyes (CE) and right leg (RL) standing balance tasks, 18 and 9 months before PHV. These disparities highlight the asynchronous maturation processes in boys and girls, with the most pronounced differences emerging in CE and RL balance tasks approximately 9 months before PHV.

Notably, our data collectively suggest a consistent increase in AT stiffness within the 18 months leading up to PHV. Of particular interest is the explosive growth in AT stiffness observed in boys during the transition from 18 to 9 months before PHV, followed by a plateau phase. In contrast, girls displayed a gradual, more linear increase in AT stiffness throughout their maturation process. Recent findings are in agreement with our observations, suggesting that the greater AT stiffness observed in boys compared to girls, 6 months before PHV, is attributable to enhanced force development in the plantar flexors [5]. These findings resonate with cross-sectional studies conducted on young adults, which consistently reveal lower patellar tendon stiffness in women compared to men [45, 46]. However, discrepancies exist in studies involving children [4] and adults [3], where no significant sex differences in AT stiffness were observed, even after a six-month retest in adolescents [23]. Such discrepancies may be attributed to the robust statistical analysis, such as linear mixed modeling (LMM), employed in our study, effectively minimizing the influence of between-subject variability and revealing sex differences more clearly. In terms of balance control, our results unveiled divergent maturation processes around PHV for boys and girls. Specifically, boys exhibited greater center of pressure (COP) excursions, particularly during challenging balance tasks involving right leg stance, in both the ML and AP directions, approximately 9 months before PHV. This time point marked the most significant disparity, as girls demonstrated improvements in their balance control in both directions [18]. This aligns with other research that underscores how differences in balance control between boys and girls, aged 9-12 years, become more pronounced as the difficulty of the balance task escalates [47]. Consequently, our study investigated the relationship between AT stiffness, plantar flexor force, and balance control ability, particularly 9 months before PHV, during OE, CE and RL standing balance tasks.

Our findings revealed a positive association between AT stiffness and plantar flexor co-activation, specifically in girls, during the closed eyes static balance task. This positive relationship aligns with the findings of Gebel et al. [25], who postulated that increased co-activation serves as a strategy to maintain postural stability, primarily during the most challenging static balance tasks. They argued that heightened postural demands lead to increased cortical control. In this context, previous studies have demonstrated that heightened postural demands result in increased cortical excitability, reflecting a mechanism for controlling long latency reflexes during postural tasks [48]. Simultaneously, a shift from ankle to hip strategies has been observed with higher activation levels during quiet stance [49], with the loading mechanism of hip control influencing sway in the ML direction [50]. In light of our findings in girls, we posit that increased postural control demands during closed eyes tasks not only induce greater ankle muscle force production but may also trigger demands for hip muscle force. Future studies could explore the contributions of hip muscles (e.g., quadriceps, sartorius) to balance control during adolescence. Concerning visual feedback, previous reviews have concluded that during pubertal growth, new postural challenges hinder adolescents' ability to integrate proprioceptive inputs, leading to an increased reliance on visual cues [13]. In conclusion, we observe an earlier maturation of neuromuscular control, primarily driven by central regulation, in early adolescent girls who appear to rely more on visual cues during their growth spurt.

Furthermore, we identified a positive association between Achilles tendon (AT) stiffness and tibialis anterior (TA) activity in boys, both 18 and 9 months before peak height velocity (PHV), across 3 levels of balance task difficulty. As previously indicated, the ankle muscles, particularly the TA, play a pivotal role in maintaining static balance control [25, 24, 51]. Specifically, TA activity contributes to correcting tilting movements, primarily in the AP direction, aimed at restoring balance [52]. However, this strategy has been linked to neuromuscular deficits in children and older adults when performing both simple and challenging balance tasks. Grosset et al. [53] attributed increased TA activity in children to their inability to fully activate their muscles, recruiting fewer motor units, while Lamberts et al. [54] attributed it to lower musculoarticular stiffness Conversely, higher activity in antagonist muscles has been explained as impaired proprioceptive information or limited force capacity in older adults [24]. These findings further underscore the weaker maturation of muscle coordination observed in boys approximately 9 months before PHV, which corresponds with diminished balance control during one-leg tasks [18]. Additionally, the abrupt increase in AT stiffness from 18 to 9 months before PHV in boys may disrupt neural adaptability in conjunction with their growth spurt. Hence, it appears that peripheral adaptations in boys, such as the explosive increase in AT stiffness from 18 to 9 months before PHV, trigger compensatory mechanisms (e.g., TA activity) to maintain balance control during challenging tasks. These findings broaden our understanding of the influence of AT stiffness and ankle muscle force on static balance across different stages of biological maturity.

Nevertheless, this study has certain limitations. Firstly, although our results suggest a strong association between AT stiffness and plantar flexor muscle activity during standing balance, we did not investigate the role of the soleus muscle, despite its recognized importance in balance control. Secondly, future studies should explore hip muscle activity during standing balance, particularly as the complexity of balance tasks increases. Thirdly, during the 18-month period, there were changes in body mass and height between boys and girls, so we didn’t have a homogeneous sample, since a different body mass and height indicated that during balancing tasks, the inverted pendulum system of boys and girls was not operating in similar conditions.

5. Conclusions

Our study provides novel evidence that early adolescent boys and girls employ distinct strategies to successfully execute static balance tasks. Boys appear to adopt a peripheral mechanism characterized by high AT stiffness and increased TA activity, while girls exhibit a central balance regulation with a more compliant AT and elevated co-activation of plantar flexors. The relationships we observed between AT stiffness, MG and TA activity, and balance control underscore the substantial contributions of both the Achilles tendon and plantar flexor muscles to balance performance during this developmental stage. Given that girls exhibit fewer COP excursions than boys approximately 9 months before PHV, we infer that balance control during this period is primarily reliant on central rather than peripheral systems. Our findings have practical implications for educators, coaches and researchers who aim to tailor tasks based on the maturity and gender of their subjects.

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Conflict of Interest

The authors have no conflicts of interest to disclose.

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