International Journal of Strength and Conditioning

https://doi.org/10.47206/ijsc.v5i1.366

Force-Velocity Profiling among Different Maturational Stages in Young Soccer Players: A Cross-Sectional Study

Leon Niederdraeing[1, 2]* and Karen Zentgraf[2]

[1]Eintracht Frankfurt, Germany, [2]Movement Science and Training in Sports, Institute for Sports Sciences, Goethe University Frankfurt, Germany

*Corresponding author: leon.nieder@web.de

ABSTRACT

Speed is a key component of football performance. An individualized approach may be necessary to achieve optimal speed development. Force-velocity profiling breaks down linear sprint performance into force, velocity, and mechanical effectiveness on an individual basis. In young footballers, these factors are related to maturation and have a strong influence on physical performance. The aim of this study is to investigate horizontal force-velocity profiling at different stages of maturation.

As an indicator of maturity, the age of peak height velocity (APHV) of 85 young soccer players (age: M = 15.7, ± 1.63 years) was determined using the Mirwald formula. According to temporal distance from their individual estimated APHV, players were divided into four groups (mid-peak-height-velocity (PHV, N = 26); 1-2y-post-PHV (N = 21); 2-3y-post-PHV (N = 21); >3y-post-PHV (N = 17)). 30-meter sprint performance including five split times was measured with timing gates in all athletes. These splits were used to calculate an individual horizontal force-velocity profile with its components maximum theoretical force (F_H0), velocity (V_H0), and power (P_{max}). These profiles also included peak ratio of force (RF_{max}), actual relationship of maximum force and velocity (FV slope), as well as the theoretically optimal relationship of maximum force/velocity (FV_{opt}).

APHV-based group differences were found for F_H0, V_H0 and P_{max}, RF_{max}, and the difference between FV slope and FVopt. Values of absolute F_H0, V_H0, RF_{max} and P_{max} were increasing with maturation. In all groups, a lack of velocity in relation to force production of 24% ($p < .001$, $d = 1.15$) was detected, with the largest deficit at mid-PHV (M = 35.74 ± 21.73%) and the smallest deficit at >3ypost-PHV (M = 15.90 ± 20.15%).

The current finding of a velocity deficit in 30m-sprint performance of young soccer players suggests a need for velocity-oriented training - pronounced around APHV.

INTRODUCTION

Striving for top performance is an integral part of competitive sport. Athletic abilities, especially speed, play a key role in optimizing performance in soccer (Haugen et al., 2014a). This is, in part, due to the fact that many goals in soccer are scored following a sprint (Faude et al., 2012). Simultaneously, it has been shown that the overall ball speed of passes, the amount of high-speed running (5.5 – 7m.s^{-1}) and sprint distance (>7m.s^{-1}) per match have increased over the last decades (Wallace et al., 2014; Lago-Penas et al., 2022; Barnes et al., 2014). Consequently, linear speed and acceleration have been associated with youth players progressing to the first team and young players being selected for youth academies (Leyhr et al., 2018; Meylan et al., 2010).

When assessing athletic abilities in youth sports development, it is proposed that performance should be related to biological maturation rather than chronological age (Malina et al., 2004; Baxter-Jones, 2007; Lames et al., 2008). It is well known that physical development and athletic abilities change rapidly with maturation (Malina et al., 2004; Meyers et al., 2016), particularly around age at peak height velocity (APHV). This may be due to growth-related changes in the neuromuscular system and in muscle and tendon properties (Radnor et al., 2018; Radnor et al., 2020). Based on this, APHV should be determined to assess physical performance in an age-appropriate manner (Ferrauti et al., 2020).

Force-velocity profiling (FVP) is a method that describes the relationship between force and velocity for muscular contraction during a given motor task and relates to the capacities of the neuromuscular system (Cormie et al., 2011). FVP has been used to examine athletic performance such as jumping and sprinting (Samozino et al., 2014; Morin et al., 2019). In general, this approach offers, first, an individualized diagnostic for mechanical factors related to force production, and second, an interventional approach to target individual performance limits. In jumping, an individual profile can be generated by extrapolating a linear relationship between force and velocity (Samozino et al., 2008) by performing a series of vertical jumps with increasing loads. Vertical FVP allows to determine an optimal profile for jumping, taking individual anthropometrics into account. The individual relationship of force and velocity (FV relationship) is then referenced to the individual theoretic, optimal force-velocity relationship, graphically represented as the slope of the linear relationship (Samozino et al., 2012). For jumping, FVP has been used to implement specific individual deficit-oriented training methods, which might be superior to generic training recommendations (Jimenez-Reyes et al., 2019). In order to address a force deficit, the authors propose resistance training with high loads. Conversely, to improve a velocity deficit, it is recommended that practice should employ high velocities (Jimenez-Reyes et al., 2019).

The horizontal adequate, i.e., sprint performance, can be easily measured by the spatiotemporal variables; the time required for a given distance (Fernandez-Galvan et al., 2022). The evaluation of the horizontal force-velocity relationship during sprint acceleration (horizontal FVP) enables the determination of the mechanical effectiveness of linear sprint performance as the displacement of the body's center of mass in space per time allows the computation of the ground reactive forces that are changing with increasing speed, the equivalent of the increasing loads of the vertical profile (Rabita et al., 2015; Morin et al., 2016). The individual FV relationship can be modeled from maximum-intent horizontal sprint including split times (Samozino et al., 2016; Haugen et al., 2020). The profile consists of the following variables: maximum theoretic force (F_H0), maximum theoretic velocity (V_H0 (m/s)) and maximum power (P_{max} (W/kg)), the product of F_H0 and V_H0. F_H0 can be expressed as absolute (N) or relative to body weight (N/kg). The aforementioned variables can be calculated by linear regression over a 30m sprint. (Morin et al., 2019). The relationship of F_H0 and V_H0 can be described as a force-velocity (FV) slope. In addition, the FVP in sprinting includes the percentage of force generated in the horizontal direction (Morin et al., 2011; Samozino et al., 2016). The maximum ratio of horizontal to resultant force (RF_{max}) and the decrease in horizontal force ratio (DRF) are commonly used as measures of mechanical effectiveness (Morin et al., 2011).

The overall reliability and validity of the horizontal FV relationship described by Morin and Samozino has been demonstrated (Samozino et al., 2016; Simperingham et al., 2019; Haugen et al., 2020). One study created reference FVP from soccer players of different ages and maturational levels for F_H0, V_H0, P_{max}, RF_{max} and DRF by distinguishing youth-academy players in pre-, mid- and post-puberty (Fernandez-Galvan et al., 2022). The relationship of force and velocity including its theoretic optimum (FVopt), which exists for vertical FVP, can also be estimated for horizontal FVP (Samozino et al., 2022a) – but has not been explored extensively yet. The complete biomechanical derivation for horizontal FVP can be obtained from Samozino et al. (2018, p. 240-244), while the mathematical derivation for the optimal relationship of FVopt can be found in Samozino et al. (2022a, p. 561-563). In short, the time (t) needed to move the center of mass for a given distance (x) can be minimized for only one and therefore optimal FV slope with an individual P_{max} (Samozino et al., 2022a). The difference (FV_{Diff}) between FV_{opt} and FV slope can be expressed in percent (Giroux et al., 2016; Samozino et al., 2022a):

$$F_V Diff = 100 * \left| \frac{S_{FV}}{S_{FV_{opt}}} \right|$$

To date, there are several studies that have analyzed the horizontal FVP of team sports athletes (Fernandez-Galvan et al., 2022; Bustamante-

Garrido et al., 2023; Hicks et al., 2023). However, none of these studies have included FV_{opt}. The aim of this study is to determine the horizontal FVP and the APHV in young soccer players and thus interpret a complete FVP including FV_{opt} in relation to maturation. This includes the parameters F_H0, V_H0, P_{max}, RF_{max}, DRF and the relationship between F_H0 and V_H0, FV slope, the optimal FV slope, FV_{opt}, and the difference between the latter two, FV_{Diff}. The elevation of the full FVP in relation to growth has the potential to modify training methodologies for young players considering their individual levels of performance and maturation.

METHODS

Study Design

The study used a cross-sectional design in which sprint performance was measured using split times for 5 m, 10 m, 15 m, 20 m, and 30 m of a linear sprint in young soccer players of a soccer academy. Split times were assessed to identify the different components of horizontal FVP, F_H0, V_H0, P_{max}, DRF, and RF_{max}, according to Samozino et al. (2016). In addition, the FV slope was determined and FV_{opt} was calculated (Samozino et al., 2022a) for each individual P_{max}, the product of F_H0 and V_H0, after which FV_{Diff} could be determined.

APHV was estimated using the Mirwald formula (2002). The corresponding maturation offset (MO, time difference between the day of measurement and APHV) was then individually documented (Toselli et al., 2019). A cross-sectional statistical analysis was carried out to establish a possible relationship between the horizontal FVP and MO and thus connect maturation to the mechanical characteristics of a sprint.

Participants

For the categorical comparison of horizontal FVP, 85 elite-level junior players from U14-U19 teams in a professional youth academy were studied (age range: 12.8 to 18.7 years). Measurements were taken during the first half of the 2022/2023 season. Players had a specific soccer training experience of 10.18 ± 1.97 years. Only players who were medically cleared to play, free of injury, and without physical limitations were tested. Players were informed verbally and on a written basis about the aims and risks of the study and gave written consent to be part of this research project, while for minors, parents signed that they consented to the research project and data processing.

Methodology

Following the procedure of Fernandez-Galvan et al. (2022), prior to sprint testing, anthropometric variables were measured. Body mass (SECA© – 769, accurate to 0.1 kg), body height, and seated height (wall-mounted stadiometer, accurate to 0.1 cm) were recorded. Based on the date of birth, APHV was subsequently estimated according to Mirwald's method (2002). The Mirwald formula has been established as a valid and economical tool to determine the APHV and consequently, MO (Toselli, et al., 2019), using the following equation (Mirwald, 2002):

*Maturity offset = -(9.236 + 0.0002708 * Leg Length and Sitting Height interaction) - (0.001663 * Age and Leg Length interaction) + (0.007216 * Age and Sitting Height interaction) + (0.02292 * Weight by Height ratio).*

Participants were asked to follow their normal eating, drinking, and sleeping habits on the testing day, which was at least 72 hours after their last match. The testing took place immediately before an outdoor pitch training session. The test was carried out indoors on a PVC surface, therefore, whether conditions (wind, temperature, etc.) were neutral and equal for all players. The experimental setup was based on the research of Haugen et al. (2020) and the original experiments of Samozino et al. (2016) and Morin et al. (2019). The design of the estimation of FVP by split times has been criticized in the recent past (Lindberg et al., 2021), but Samozino et al. (2022b) point out that valid results can be ensured with a high degree of accuracy and reliable measurement. Split times were recorded using doubled timing gates, 10 mW (Microgate©, Witty-Gate), a method that can be assumed to have very high reliability (Haugen et al., 2014b). The starting position was a staggered stance with the forefoot 50 cm behind the first timing-gate. As accurate horizontal FVP requires catching the "first rise of the force production" (Haugen et al., 2020, p. 1771), players had their head or chest very close (5-10 cm) to the first timer and the starting position was very carefully controlled. Instructed by their strength and resistance coach, participants performed a standardized, 15-minute warm-up, including common running drills, dynamic stretching, and two submaximal sprints over 30 m. Participants were then familiarized with the starting position. Players performed three maximal sprints over 30 m with split times at 5 m, 10 m, 15 m, and 20 m. They had a minimum of 3 min rest between each trial. The horizontal FVP was extrapolated from the best time with an offset of +0.21 s, which is recommended when using timing gates instead of a radar camera (van den Tillaar et al., 2022).

Data Procedure

Maturity data were processed using the BioFinal Tool 3.4 (IAT, Leipzig, Germany). Respecting the limitations of ±6 months for Mirwald's equation (Mirwald et al., 2002), players were divided into four groups according to their maturational stage: Within 12 months of APHV (mid-PHV), 1-2 years after APHV (1-2y-post-PHV), 2-3 years after APHV (2-3y-post-PHV) and more than three years after APHV (>3y-post-PHV). Together with body mass and stature, split times were used to extrapolate the horizontal FVP via linear regression using a prespecified Excel sheet (https://jbmorinnet.files.word-press.com/2022/01/fvpsprint_2019_basic.xlsx.) by Morin (2019). FV_{opt} was calculated using a recent method (Samozino et al., 2022). Briefly, the individual P_{max} was given for their best 30-m time, and the FV slope was changed in 0.002 steps until the equation reached its minimum. Body mass was considered by using an individual k value, which is a function of body mass, height, drag, and barometric pressure. As the equation describes the forces acting on the center of mass during sprinting, both temperature and barometric pressure must be integrated (Samozino et al., 2022). However, even bigger changes in air pressure have a marginal effect on k (Samozino et al., 2018), so barometric pressure (*PB* = 760hPa) and temperature (T = 20° C) were assumed to be constant, resulting in p = 1.205. The whole procedure, including the mathematical derivation, can be found in detail in Samozino et al. (2022). Following the calculation of FV_{opt}, the difference between FV_{opt} and the individual FV slope was described in percentages using the equation for FV_{Diff}. The equation has been created for training recommendations in vertical profiling (Jiménez-Reyes et al., 2019) and allows for an overview of imbalances between force and velocity output in jumping.

Statistical analyses were performed using IBM SPSS Statistics 28 (IBM, Armonk, NY, USA) and JAMOVI 2.3 (The Jamovi project, Sydney, Australia). Prior to all statistical analyses, data were tested for normality of distribution and homogeneity of variances using a Shapiro-Wilk test and a Levene test, respectively. Kruskal-Wallis' non-parametric one-way analysis of variance (ANOVA) was used to detect group differences in horizontal FVP. It expresses effect size in epsilon-squared (ε^2) and according to Cohen (1992), it can be interpreted like eta-squared as low (< 0.25), moderate (0.25 to 0.49), and high (> 0.5). The ANOVA was followed by the Dunn-Bonferroni adjusted post-hoc test. As FV_{Diff} was determined in a separate procedure and then statistically tested, Fisher's ANOVA and Bonferroni's post-hoc tests were used. Multiple linear regression assumptions were tested using residual vs. adjusted, normal QQ and Cook's distance plots. No evidence of heteroscedasticity or multicollinearity was found. Descriptive data of the dependent variables (i.e., F_H0, V_H0, P_{max}, FV slope, D_{RF} and RF_{max}, split times up to 30 meters) are presented as means and standard deviations. The significance threshold was set at $p < 0.05$ for all analyses.

RESULTS

Table 1 displays the descriptive data for anthropometric measures age, APHV, MO, height, body mass, seated height, training age (in years), youth academy since (in years), strength training experience (in years), strength training per week this season (in hours) of participants for each group.

As can be seen in Table 1, all parameters except the APHV increase with increasing MO. Figure 1 displays descriptive data for split times up to 30 meters.

Figure 1 illustrates the sprint times of all groups. While no significant group differences were observed for the 5m time in any group, the times improved with increasing maturity offset (MO) from the 10m distance onwards. Significant group differences were found for the 10m (p = 0.02) and 15m times (p = 0.018) between mid-PHV and 2-3y-post-PHV.

Significant group differences were observed for 20 m times, with both the 2-3y-post-PHV (p < 0.001) and >3y-post-PHV (p = 0.002) groups demonstrating faster times than the mid-PHV group. For the 30 m times, all three groups of 1-2y-post-PHV (p = 0.018), 2-3y-post-PHV (p < 0.001) and >3y-post-PHV (p < 0.001) exhibited significantly faster times than the mid-PHV group.

Table 1. Descriptive data (average and standard deviation) for anthropometric and other measures of participants for each group.

Parameter	mid-PHV (n=26)	1-2y-post-PHV (n=21)	2-3y-post-PHV (n=21)	>3y-post-PHV (n=17)
Age (years)	13.9 ± 0.6	15.2 ± 1.0	16.7 ± 0.56	17.7 ± 0.89
APHV (years)	13.68 ± 0.66	13.69 ± 0.79	14.21 ± 0.49	13.89 ± 0.66
Maturity offset (years)	0.21 ± 0.57	1.54 ± 0.31	2.52 ± 0.32	3.78 ± 0.64
Body height (cm)	168.9 ± 6.6	176.4 ± 5.1	179.0 ± 7.2	181.44 ± 7.7
Body mass (kg)	56.4 ± 6.8	64.9 ± 5.3	72.0 ± 7.1	77.8 ± 9.6
Seated height (cm)	86.4 ± 3.9	91.2 ± 2.6	92.2 ± 1.9	96.8 ± 3.2
Training age (years)	8.6 ± 1.3	10.1 ± 1.3	10.8 ± 2.1	12.0 ± 1.5
Youth academy since (years)	2.25 ± 1.68	2.93 ± 1.97	2.69 ± 2.47	4.79 ± 3.58
Strength practice since (years)	0.89 ± 0.50	1.62 ± 0.71	2.57 ± 1.00	2.91 ± 1.19
Strength exercises (h / week)	0.79 ± 0.43	1.93 ± 1.10	2.81 ± 1.32	3.18 ± 1.56

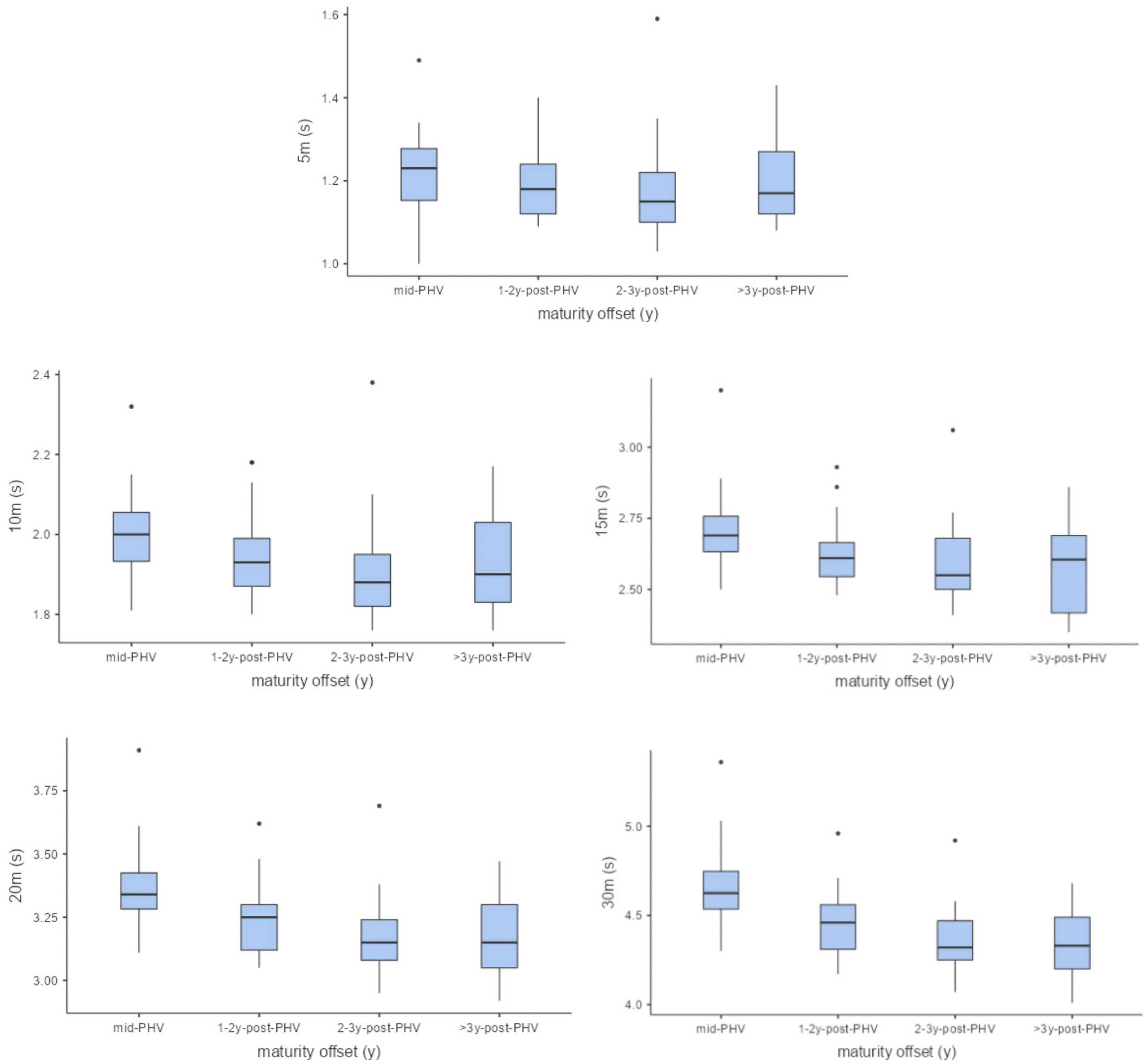

Figure 1. Split times up to 30 m for each group.

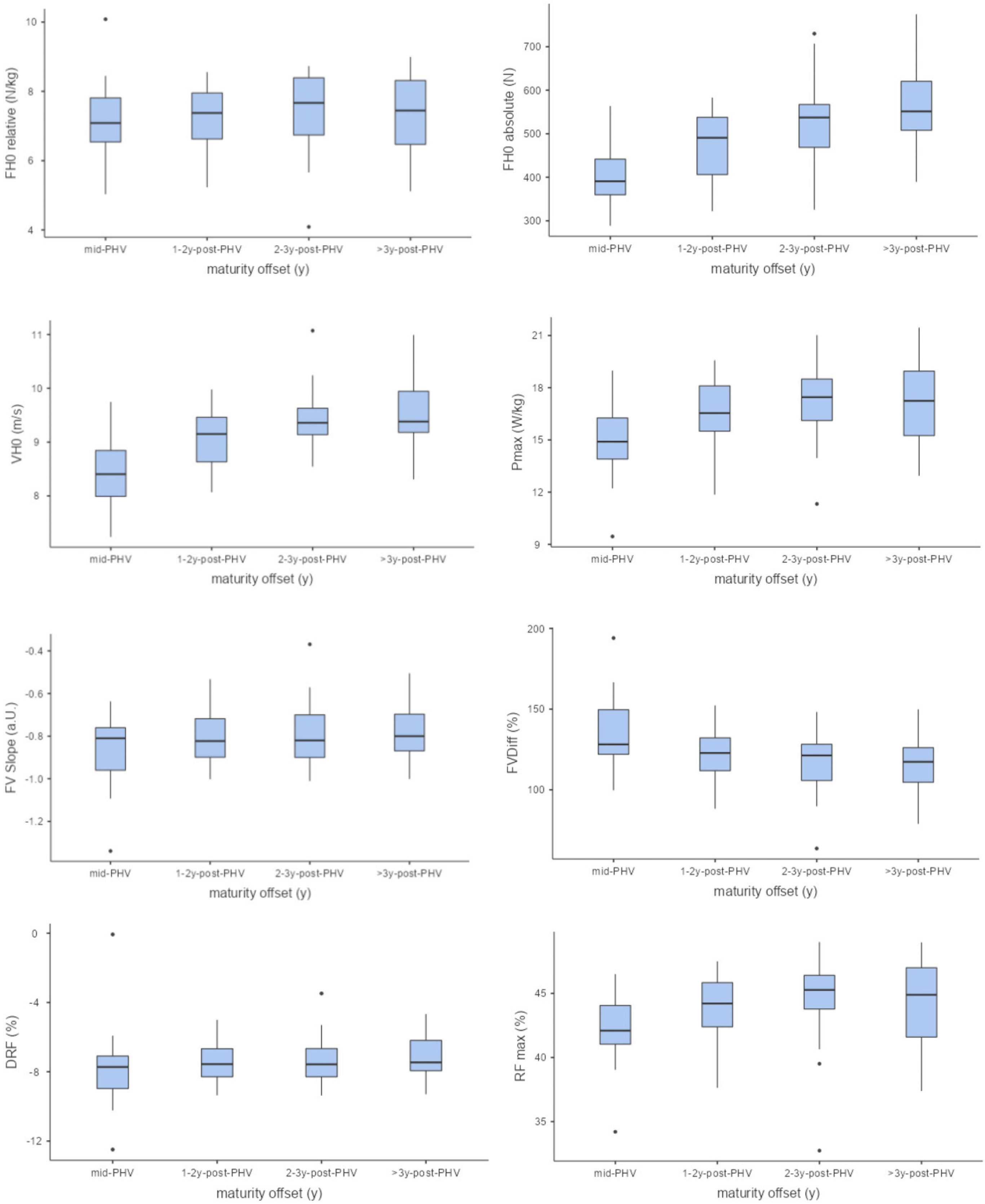

Figure 2. Parameters of FVP of each group.
F_H0 relative (N/kg), F_H0 absolute (N), V_H0 (m/s), P_{max} (W/kg), FV slope (a.U.), FV_{Diff} (%), D_{RF} (%), RF_{max} (%)

Figure 2 displays the parameters of the FVP, F_H0 (absolute and relative numbers), V_H0, P_{max}, FV slope, FV_{Diff}, D_{RF}, and RF_{max} of participants for each group. The corresponding data can be found in the appendix.

As described in Fig 1., significant intergroup differences were found for the split times >=10 m, with the largest differences for the 30m time with the fastest times occurring with higher MO. This resulted in significant higher values for V_H0 (m/s) and P_{max} (W/kg) with increasing MO, but not for F_H0 (N/kg). However, F_H0 in absolute numbers (N) showed significantly higher values for higher MO. Additionally, RF_{max} (%) and FV_{Diff} showed significant group differences, with RF_{max} (%) being higher and FV_{Diff} being lower with increasing MO. The specific group differences can be observed in detail in Tables 2 and 3, while the exact numbers are provided in the appendix.

Table 2 shows the differences in sprint performance variables and force-velocity components between maturity groups through one-way ANOVA (Kruskal-Wallis) and Fisher's ANOVA for FV_{Diff}.

As shown in table 3, there are significant group differences between all groups for the 30m time and thus the parameter V_H0. Faster times are produced by players with a higher MO. At the same time, only marginal but increasing differences can be seen in the 10m to 20m times. This results in the exclusive group difference between mid-PHV and 2-3y-post-PHV for F_H0, and RF_{max} (%). Consequently, the product of V_H0 and F_H0, P_{max}, represents the mean, with group differences evident between mid-PHV and both 1-2y-post-PHV and 2-3y-post-PHV. Concurrently, analogous group differences are evident for FV_{Diff}.

DISCUSSION

The aim of this study was to determine a cross-sectional overview of the horizontal FV profile in the U14-U19 teams of a professional soccer youth academy. Furthermore, it is the first systematic study that determines the FVDiff for junior soccer players. The horizontal FVP was calculated from a 30m sprint with split times at 5 m, 10 m, 15 m, and 20 m, relative to biological age. The APHV was determined using Mirwald's formula and the distance to the date of measurement was determined to derive the MO. Based on the MO, the players were divided into groups to make statements about FVP variations in different age ranges and thus maturational stages.

Older players, expectedly, have a larger MO, more years of training and more strength training and consequently should have higher performance capabilities. For sprint performance, significant differences were found between the sprint times for 10 m, 15 m, 20 m, and 30 m, but not for the 5m times. The effect size increased progressively with increasing distance (ε^2 = 0.05 - 0.33). The observation that the acceleration over 5m is not

Table 2. X^2: Ratio of the variation between groups to the variation within groups; df: degrees of freedom; p: p-value; ε^2: effect size

Parameter	X^2	df	*p*	ε^2
5m (s)	4.22	3	0.239	0.0502
10m (s)	9.77	3	0.021	0.1163
15m (s)	11.1	3	0.011	0.1563
20m (s)	20.82	3	<.001	0.2479
30m (s)	27.43	3	<.001	0.3265
F_H0 relative (N/kg)	1.21	3	0.751	0.0144
F_H0 absolute (N)	28.92	3	<.001	0.3443
V_H0 (m/s)	30.03	3	<.001	0.3575
P_{max} (W/kg)	13.12	3	0.004	0.1562
FV slope (a.U.)	2.25	3	0.522	0.0268
RF_{max} (%)	9.05	3	0.029	0.1078
D_{RF} (%)	2.47	3	0.480	0.0294

Parameter	F	df	*p*	Eta²
FV_{Diff} (%)*	4.81	3	0.004	0.151

Table 3. shows the statistical results for Dunn-Bonferroni adjusted post-hoc tests.

Parameter	Group	1-2 y-post PHV	2-3 y-post PHV	>3 y-post PHV
	mid-PHV	stand. t = 1.714; adj. p = 0.519	**stand. t = 2.938; adj. p = 0.020**	stand. t = 2.192yd; adj. p = 0.170
Time 10m	1-2y-post PHV	-	stand. t = 1.163; adj. p = 1.000	stand. t = 0.579; adj. p = 1.000
	2-3y-post PHV	-	-	stand. t = -0.546; adj. p = 1.000
	mid-PHV	stand. t = 2.065; adj. p = 0.234	**stand. t = 2.973; adj. p = 0.018**	stand. t = 2.278; adj. p = 0.136
Time 15m	1-2y-post PHV	-	stand. t = 0.911; adj. p = 1.000	stand. t = 0.575; adj. p = 1.000
	2-3y-post PHV	-	-	stand. t = -0.199; adj. p = 1.000
	mid-PHV	stand. t = 2.617; adj. p = 0.053	**stand. t = 4.048; adj. p < .001**	**stand. t = 3.590; adj. p = 0.002**
Time 20m	1-2y-post PHV	-	stand. t = 1.361; adj. p = 1.000	stand. t = 1.078; adj. p = 1.000
	2-3y-post PHV	-	-	stand. t = -0.209; adj. p = 1.000
	mid-PHV	**stand. t = 2.945; adj. p = 0.019**	**stand. t = 4.613; adj. p < .001**	**stand. t = 4.173; adj. p < .001**
Time 30m	1-2y-post PHV	-	stand. t = 1.585; adj. p = 0.678	stand. t = 1.341; adj. p = 1.000
	2-3y-post PHV	-	-	stand. t = -0.158; adj. p = 1.000
	mid-PHV	stand. t = 1.714; adj. p = 0.519	**stand. t = 2.938; adj. p = 0.020**	stand. t = 2.192; adj. p = 0.170
F_H0 absolute (N)	1-2y-post PHV	-	stand. t = 1.163; adj. p = 1.000	stand. t = 0.554; adj. p = 1.000
	2-3y-post PHV	-	-	stand. t = -0.546; adj. p = 1.000
	mid-PHV	**stand. t = -2.967; adj. p = 0.018**	**stand. t = -4,621; adj. p < .001**	**stand. t = -4.611; adj. p < .001**
V_H0 (m/s)	1-2y-post PHV	-	stand. t = -1.572; adj. p = 0.695	stand. t = -1.740; adj. p = 0.491
	2-3y-post PHV	-	-	stand. t = -0.253; adj. p = 1.000
	mid-PHV	stand. t = -1.978; adj. p = 0.288	**stand. t = -3.299; adj. p = 0.006**	**stand. t = -2.736; adj. p = 0.037**
P_{max} (W/kg)	1-2y-post PHV	-	stand. t = -1.257; adj. p = 1.000	stand. t = 0.838; adj. p = 1.000
	2-3y-post PHV	-	-	stand. t = 0.351; adj. p = 1.000
	mid-PHV	stand. t = -1.804; adj. p > 0.050	**stand. t = -2.784; adj. p = 0.032**	stand. t = -2.164; adj. p = 0.183
RF (%)	1-2y-post PHV	-	stand. t = -0.932; adj. p = 1.000	stand. t = -0.446; adj. p = 1.000
	2-3y-post PHV	-	-	stand. t = 0.435; adj. p = 1.000
	mid-PHV	stand. t = 2.292; adj. p = 0.147	**stand. t = 3.131; adj. p = 0.015**	**stand. t = 3.234; adj. p = 0.011**
FV_{Diff}* (%)	1-2y-post PHV	-	stand. t = 0.798; adj. p = 1.000	stand. t = 1.031; adj. p = 1.000
		-	-	stand. t = 0.276; adj. p = 1.000

superior in older players seems unexpected at first glance. However, it is consistent with the findings of Loturco et al. (2018) who found faster 0-5m times in U15 players than in U20 and senior players.

ANOVA showed a constant rise in V_H0 (m/s) with increasing MO and significant differences in V_H0 between the mid-PHV group and the three post-PHV groups (p = 0.018, p < .001, p < .001), but not between the other groups. The mean difference was also greatest between mid-PHV and 1-2y-post-PHV (M Diff = 0.66 m/s). Thus, the largest increases in V_H0 occur in the period shortly after APHV. These results are consistent with those of Meyers et al. (2015) and Morris et al. (2018), who found the largest increases in linear velocity in boys at ages during and immediately after the APHV. A possible explanation may be changes in neuromuscular activation and morphological factors like tendon and muscle properties that allow greater force production during sprinting (Radnor et al., 2018; Radnor et al., 2020). The results of this study suggest that the greatest increases in VH0 occur immediately after the APHV, which would allow predictions about the future performance of maximum sprint velocity. This is important in the context of talent identification. However, these predictions should be made with caution as the trainability of V_H0 has been demonstrated (Lahti, Jiménez-Reyes et al., 2020).

While V_H0 (m/s) and P_{max} (W/kg) increase steadily with increasing MO, F_H0 (N/kg) shows no significant difference between groups. Group differences in V_H0 appear to be large enough to significantly alter P_{max} (product of V_H0 and F_H0) between groups, although F_H0 shows no significant differences. An explanation for the results found for F_H0 (N/kg) could be that F_H0 is relative to body weight and players with a greater distance to the APHV have a greater body weight ($M_{mid\text{-}PHV}$ = 56.4 ± 6.75kg, $M_{>3\ y\ post\text{-}PHV}$= 77.8 ± 9.62kg). This was confirmed with the absolute F_H0 values (N). The mid-PHV group had significantly lower absolute F_H0 values (N) compared to the other groups (with increasing MO: p = 0.024, p < .001, p < .001). Furthermore, significantly higher absolute F_H0 values were found in the >3y-post-PHV group compared to the 1-2y-post-PHV group (p = 0.046). F_H0 increases continuously in absolute terms, but not in relation to body weight. This suggests that players with a larger distance to the APHV lack relative strength in sprint, which could be optimized via tailored interventions, e.g., strength-power training (Loturco et al., 2018). Notably, low expressions of F_H0 (N/kg) are linked to an increased risk of injury to the hamstrings (Mendiguchia et al., 2016; Edouard et al., 2021; Lahti et al., 2022). Absolute F_H0 (N) increases (M Diff = 67.6 N) the most between mid-PHV and 1-2y-post-PHV and thus immediately after APHV. Since all groups show significant differences from mid-PHV, but not in successive groups, it can be assumed that the largest increase in absolute F_H0 (N) occurs immediately after APHV. This is expectable as strength and quickness develop during puberty and both are sensitive to training (Haywood & Getchell, 2021). This is also consistent with the findings of Huijgen et al. (2010), suggesting growth-related constant increases in rate of force across the APHV. The improvements in absolute strength during maturation are linked to morphological factors and increased muscle size (Olivier et al., 2013). Simultaneously, the increase in body weight might limit increases in F_H0 (N/kg). This is consistent with the findings of Dugdale et al. (2024), who suggested that momentum (the product of mass and velocity) has a large effect on sprint performance and change of direction in maturing adolescents. However, the relative F_H0 is more important for soccer players since their own body weight has to be accelerated for game and practice performance.

There has been no research to date that has classified horizontal FV_{Diff}. Nevertheless, vertical and horizontal FVP have a lot in common, which suggests that the principles of classification for vertical FVP according to Jiménez-Reyes et al. (2019) can also be applied to the FV_{Diff} of horizontal FVP - although a final confirmation is still pending. For the entire population, an average FV_{Diff} of M = 124.0 ± 21.0% is calculated for the 30m sprint, which is a significant deviation from 100%. According to the Jiménez-Reyes et al. (2019) classification, this can be interpreted as a moderate speed deficit of 24%. In cross-section, junior soccer players show a speed deficit for the 30m sprint distance. Supramaximal (-110%) assisted sprints can be used to improve the deficit (Lahti et al., 2020). From descriptive statistics, the speed deficit is greatest during the APHV and decreases as the MO increases. This is supported by the significant group differences (p = 0.011) between mid-PHV (M = 135.74 ± 21.73%) and >3y-post-PHV (M = 115.90 ± 20.15%). The steady increase of VH0 and P_{max} with increasing MO is accompanied by the reduction of FV_{Diff} and a convergence towards FV_{opt}, possibly due to the growth process and training. Interestingly, no significant differences between groups can be shown for the slope of the FVP (p = 0.522). Thus, the ratios of F_H0 (N/kg) and V_H0 (m/s) did not differ significantly, but the ratio to FV_{opt}, which depends on the individual P_{max}. Based on the data of this study, it can be argued that FVP change with maturation. FV_{Diff} changes with increasing MO, but FV slope does not. Therefore, FV slope is not sensitive enough to detect changes. This might be due to the ratio computation of F_H0 relative to body weight, as players become heavier with increasing MO. This leads to the need to determine FV_{opt} to assess the mechanical characteristics of the FVP. Statements made solely based on FV slope do not have the same validity as conclusions based on FV_{Diff}.

The results of this study are limited in multiple ways. Regarding methodology, the process is based on a theoretic model that has been applied in this study for the first time. Furthermore, the classification of force and velocity deficits was created for the vertical plane, not the horizontal. However, since both concepts rely on the same principles, it is very likely to be valid in the horizontal plane as well; yet a final validation remains to be done. This could be done by assessing many athletes in different sports; similar to what Giroux et al. (2016) suggested for the vertical plane. Additionally, the average sprint distance in a game is 5.9 m. For shorter sprint distances, FV_{opt} is influenced stronger by F_H0 (Samozino et al., 2022), which questions the transfer of the 30m FV_{opt} to the game. Nonetheless, sprints in a game do not occur from a resting position, but mostly from jogging, which in turn reduces the significance of F_H0 (Aughey et al., 2011). Further research needs to be done to (1) validate the concept of FVP for the horizontal plane and (2) analyse the sprints in a soccer match to find the FV_{opt} which influences performance most.

CONCLUSION AND FUTURE RECOMMENDATIONS

The horizontal FVP of soccer players from a youth academy was established using a 30m sprint with split times at 5 m, 10 m, 15 m, and 20 m. The APHV of the soccer players was determined using the Mirwald formula. Group differences of sprint performance in relation to maturation were then examined. Significant differences were found for the split times >=10 m, with the largest differences for the 30m time. This resulted in significant differences for maximum theoretic velocity (m/s), but not for maximum theoretic force in relation to body weight. The greatest differences in maximum theoretic force and velocity occurred immediately after growth spurt, which supports the hypothesis of an influence of the biological development process on the horizontal FVP. In the whole sample, FV_{Diff} showed an average speed deficit of 24%, with the largest deficit around APHV and a convergence to FV_{opt} with increasing MO. FV_{Diff} showed significant group differences with highest values at APHV, while the relationship of force and velocity did not change significantly. This stresses the need to determine FV_{Diff} since analyses solely relying on force-velocity relationships are not sensitive enough. FV_{Diff} was determined for the 30m distance. While respecting individual training adaptation, it is therefore recommended that young soccer players train to improve maximum theoretic velocity and thus their performance, especially around APHV. Supramaximal (-110%) assisted sprints have been shown to be effective in the past Further research should explore the relationship between biological maturity and horizontal FVP in more detail and determine FV_{Diff} for other sprint distances and different populations.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

FUNDING DETAILS

This study received no specific funding in order to be completed.

ETHICAL APPROVAL

The study was approved by the Universities Ethics Committee. All subjects were informed verbally and on a written basis about the aims and risks of the study and gave written consent to be part of this research project, while for minors, parents signed that they consented to the research project and data processing.

DATES OF REFERENCE

Submission - 30/11/2023
Acceptance - 21/11/2024
Publication - 28/03/2025

REFERENCES

1. Barnes, C., Archer, D. T., Hogg, B., Bush, M., & Bradley, P. S. (2014). The evolution of physical and technical performance parameters in the English Premier League. International journal of sports medicine, 35(13), 1095–1100. https://doi.org/10.1055/s-0034-1375695
2. Baxter-Jones, A. (2007). Growth and maturation. In Paediatric Exercise Physiology (p. 157–168). Elsevier. https://doi.org/10.1016/B978-0-443-10260-8.50006-0
3. Bustamante-Garrido, A., Izquierdo, M., Miarka, B., Cuartero-Navarrete, A., Pérez-Contreras, J., Aedo-Muñoz, E., & Cerda-Kohler, H. (2023). Mechanical determinants of sprinting and change of direction in elite female field hockey players. Sensors, 23(18), 7663. https://doi.org/10.3390/s23187663
4. Cormie, P., McGuigan, M. R., & Newton, R. U. (2011). Developing maximal neuromuscular power: part 1 – biological basis of maximal power production. Sports medicine, 41(1), 17–38. https://doi.org/10.2165/11537690-000000000-00000
5. Dugdale, J. H., Myers, T., Sanders, D., Andrew, M., Clarke, R., & Hunter, A. M. (2024). Evaluation of multi-directional speed qualities throughout adolescence in youth soccer: The non-linear nature of transfer. Journal of sports sciences, 42(4), 301–312. https://doi.org/10.1080/02640414.2024.2329846
6. Edouard, P., Lahti, J., Nagahara, R, Samozino, Navarro, L., Guex, K., Rossi, J., Brughelli, M, Mendiguchia, J., & Morin, J.-B. (2021). Low horizontal force production capacity during sprinting as a potential risk factor of hamstring injury in football. International journal of environmental research and public health, 18(15), 7827. https://doi.org/10.3390/ijerph18157827
7. Faude, O., Koch, T., & Meyer, T. (2012). Straight sprinting is the most frequent action in goal situations in professional football. Journal of sports sciences, 30(7), 625–631. https://doi.org/10.1080/02640414.2012.665940
8. Fernández-Galván, L. M., Jiménez-Reyes, P., Cuadrado-Peñafiel, V., & Casado, A. (2022). Sprint performance and mechanical force-velocity profile among different maturational stages in young soccer players. International journal of environmental research and public health, 19(3), 1412. https://doi.org/10.3390/ijerph19031412
9. Ferrauti, A., Fett, J., & Frytz, A. (Hrsg.). (2020). Lehrbuch. Trainingswissenschaft für die Sportpraxis: Lehrbuch für Studium, Ausbildung und Unterricht im Sport. Springer Spektrum. https://doi.org/10.1007/978-3-662-58227-5
10. Giroux, C., Rabita, G., Chollet, D., & Guilhem, G. (2016). Optimal balance between force and velocity differs among world-class athletes. Journal of applied biomechanics, 32(1), 59–68. https://doi.org/10.1123/jab.2015-0070
11. Haugen, T. A., Breitschädel, F., & Samozino, P. (2020). Power-force-velocity profiling of sprinting

athletes: Methodological and practical considerations when using timing gates. Journal of strength and conditioning research, 34(6), 1769–1773. https://doi.org/10.1519/JSC.0000000000002890
12. Haugen, T., Tønnessen, E., Hisdal, J., & Seiler, S. (2014a). The role and development of sprinting speed in soccer. International journal of sports physiology and performance, 9(3), 432–441. https://doi.org/10.1123/ijspp.2013-0121
13. Haugen, T. A., Tønnessen, E., Svendsen, I. S. & Seiler, S. (2014b). Sprint time differ-ences between single- and dual-beam timing systems. Journal of strength and conditioning research, 28(8), 2376–2379. https://doi.org/10.1519/JSC.0000000000000415
14. Hicks, D. S., Drummond, C., Williams, K. J., & van den Tillaar, R. (2023). The effect of a combined sprint training intervention on sprint force-velocity characteristics in junior Australian football players. PeerJ, 11, e14873. https://doi.org/10.7717/peerj.14873
15. Jiménez-Reyes, P., Samozino, P., & Morin, J.-B. (2019). Optimized training for jumping performance using the force-velocity imbalance: Individual adaptation kinetics. PLoS one, 14(5), e0216681. https://doi.org/10.1371/journal.pone.0216681
16. Lago-Peñas, C., Lorenzo-Martinez, M., López-Del Campo, R., Resta, R., & Rey, E. (2022). Evolution of physical and technical parameters in the Spanish LaLiga 2012-2019. Science and medicine in Football, 7(1), 41–46. https://doi.org/10.1080/24733938.2022.2049980
17. Lahti, J., Huuhka, T., Romero, V., Bezodis, I., Morin, J. B., & Häkkinen, K. (2020). Changes in sprint performance and sagittal plane kinematics after heavy resisted sprint training in professional soccer players. PeerJ, 8, e10507. https://doi.org/10.7717/peerj.10507
18. Lahti, J., Jiménez-Reyes, P., Cross, M. R., Samozino, P., Chassaing, P., Simond-Cote, B., Ahtiainen, J., & Morin, J. B. (2020). Individual sprint force-velocity profile adaptations to in-season assisted and resisted velocity-based training in professional rugby. Sports, 8(5), 74. https://doi.org/10.3390/sports8050074
19. Lahti, J., Mendiguchia, J., Edouard, P., & Morin, J.-B. (2022). A novel multifactorial hamstring screening protocol: association with hamstring muscle injuries in professional football (soccer) – a prospective cohort study. Biology of sport, 39(4), 1021–1031. https://doi.org/10.5114/biolsport.2022.112084
20. Lames, M., Augste, C., Dreckmann, C., Görsdorf, K., & Schimanski, M. (2008). Der "Relative Age Effect" (RAE): Neue Hausaufgaben für den Sport. Leistungssport, 38, 4–9.
21. Leyhr, D., Kelava, A., Raabe, J., & Höner, O. (2018). Longitudinal motor performance development in early adolescence and its relationship to adult success: An 8-year prospective study of highly talented soccer players. PLOS one, 13(5), e0196324. https://doi.org/10.1371/journal.pone.0196324
22. Lindberg, K., Solberg, P., Bjørnsen, T., Helland, C., Rønnestad, B., Thorsen Frank, M., Haugen, T., Østerås, S., Kristoffersen, M., Midttun, M., Sæland, F., & Paulsen, G. (2021). Force-velocity profiling in athletes: Reliability and agreement across methods. PloS one, 16(2), e0245791. https://doi.org/10.1371/journal.pone.0245791
23. Loturco, I., Jeffreys, I., Kobal, R., Cal Abad, C. C., Ramirez-Campillo, R., Zanetti, V., Pereira, L. A., & Nakamura, F. Y. (2018). Acceleration and speed performance of Brazilian elite soccer players of different age-categories. Journal of human kinetics, 64, 205–218. https://doi.org/10.1515/hukin-2017-0195
24. Malina, R. M., Bouchard, C., & Bar-Or, O. (2004). Growth, maturation, and physical activity (2nd edition). Human Kinetics.
25. Mendiguchia, J., Edouard, P., Samozino, P., Brughelli, M., Cross, M., Ross, A., Gill, N., & Morin, J.-B. (2016). Field monitoring of sprinting power-force-velocity profile before, during and after hamstring injury: two case reports. Journal of sports sciences, 34(6), 535–541. https://doi.org/10.1080/02640414.2015.1122207
26. Meyers, R. W., Oliver, J. L., Hughes, M. G., Lloyd, R. S., & Cronin, J. B. (2016). The influence of maturation on sprint performance in boys over a 21-month period. Medicine and science in sports and exercise, 48(12), 2555–2562. https://doi.org/10.1249/MSS.0000000000001049
27. Meylan, C., Cronin, J., Oliver, J., & Hughes, M. (2010). Talent identification in soccer: the role of maturity status on physical, physiological and technical characteristics. International journal of sports science & coaching, 5(4), 571–592. https://doi.org/10.1260/1747-9541.5.4.571
28. Mirwald, R., Baxter-Jones, A., Bailey, D., & Beunen, G., (2002). An assessment of maturity from anthropometric measurements. Medicine and science in sports and exercise, 34(4), 689–694. https://doi.org/10.1097/00005768-200204000-00020
29. Morin, J.-B., Edouard, P., & Samozino, P. (2011). Technical ability of force application as a determinant factor of sprint performance. Medicine and science in sports and exercise, 43(9), 1680–1688. https://doi.org/10.1249/MSS.0b013e318216ea37
30. Morin, J.-B., Samozino, P., Murata, M., Cross, M., & Nagahara, R. (2019). A simple method for computing sprint acceleration kinetics from running velocity data: replication study with improved design. Journal of biomechanics, 94(13), 82–87. https://doi.org/10.31236/osf.io/vgqzs
31. Morin, J.-B. & Samozino, P. (2016). Interpreting power-force-velocity profiles for individualized and specific training. International journal of sports physiology and performance, 11(2), 267–272. https://doi.org/10.1123/ijspp.2015-0638
32. Oliver, J., Lloyd, R. & Rumpf, M. (2013). Developing speed throughout childhood and adolescence: the role of growth, maturation and training. Strength and conditioning journal. 35. 42-48. https://doi.org/10.1519/SSC.0b013e3182919d32

33. Rabita, G., Dorel, S., Slawinski, J., Sàez-de-Villarreal, E., Couturier, A., Samozino, P., & Morin, J. B. (2015). Sprint mechanics in world-class athletes: a new insight into the limits of human locomotion. Scandinavian journal of medicine & science in sports, 25(5), 583–594. https://doi.org/10.1111/sms.12389
34. Radnor, J. M., Oliver, J. L., Waugh, C. M., Myer, G. D., & Lloyd, R. S. (2020). The influence of maturity status on muscle architecture in school-aged boys. Pediatric exercise science, 32(2), 89–96. https://doi.org/10.1123/pes.2019-0201
35. Radnor, J. M., Oliver, J. L., Waugh, C. M., Myer, G. D., Moore, I. S., & Lloyd, R. S. (2018). The influence of growth and maturation on stretch-shortening cycle function in youth. Sports medicine, 48(1), 57–71. https://doi.org/10.1007/s40279-017-0785-0
36. Samozino, P., Edouard, P., Sangnier, S., Brughelli, M., Gimenez, P., & Morin, J.-B. (2014). Force-velocity profile: imbalance determination and effect on lower limb ballistic performance. International journal of sports medicine, 35(06), 505–510. https://doi.org/10.1055/s-0033-1354382
37. Samozino, P., Morin, J.-B., Hintzy, F., & Belli, A. (2008). A simple method for measuring force, velocity and power output during squat jump. Journal of biomechanics, 41(14), 2940–2945. https://doi.org/10.1016/j.jbiomech.2008.07.028
38. Samozino, P. (2018). A simple method for measuring force, velocity and power capabilities and mechanical effectiveness during sprint running. In J.-B. Morin & P. Samozino (Hrsg.), Biomechanics of Training and Testing (p. 237–267). https://doi.org/10.1007/978-3-319-05633-311
39. Samozino, P., Peyrot, N., Edouard, P., Nagahara, R., Jimenez-Reyes, P., Vanwanseele, B., & Morin, J.-B. (2022a). Optimal mechanical force-velocity profile for sprint acceleration performance. Scandinavian journal of medicine & science in sports, 32(3), 559–575. https://doi.org/10.1111/sms.14097
40. Samozino, P., Rivière, J. R., Jimenez-Reyes, P., Cross, M. R., & Morin, J. B. (2022b). Is the Concept, Method, or Measurement to Blame for Testing Error? An Illustration Using the Force-Velocity-Power Profile. International journal of sports physiology and performance, 17(12), 1760–1768. https://doi.org/10.1123/ijspp.2021-0535
41. Samozino, P., Rabita, G., Dorel, S., Slawinski, J., Peyrot, N., Sàez-de-Villarreal, E., & Morin, J.-B. (2016). A simple method for measuring power, force, velocity properties, and mechanical effectiveness in sprint running. Scandinavian journal of medicine & science in sports, 26(6), 648–658. https://doi.org/10.1111/sms.12490
42. Samozino, P., Rejc, E., Di Prampero, P. E., Belli, A., & Morin, J. B. (2012). Optimal force-velocity profile in ballistic movements--altius: citius or fortius? Medicine and science in sports and exercise, 44(2), 313–322. https://doi.org/10.1249/MSS.0b013e31822d757a
43. Simperingham, K. D., Cronin, J. B., Pearson, S. N., & Ross, A. (2019). Reliability of horizontal force-velocity-power profiling during short sprint-running accelerations using radar technology. Sports biomechanics, 18(1), 88–99. https://doi.org/10.1080/14763141.2017.1386707
44. van den Tillaar, R., Haugen, M. E., & Falch, H. N. (2022). A comparison of sprint mechanical parameters measured with timing gates and a laser gun. Frontiers in sports and active living, 4, 877482. https://doi.org/10.3389/fspor.2022.877482
45. Wallace, J. L. & Norton, K. I. (2014). Evolution of World Cup soccer final games 1966-2010: game structure, speed and play patterns. Journal of science and medicine in sport, 17(2), 223–228. https://doi.org/10.1016/j.jsams.2013.03.016

APPENDIX

Appendix 1

Table 4. Descriptive data for split times and adjusted split times up to 30 meters, and the parameters of the FVP, F_H0 (absolute and relative numbers), V_H0, P_{max}, FV slope, FV_{Diff}, DRF, and RF_{max} of participants for each group.

Parameter	Ca.-PHV (n=26)	1-2-y-post-PHV (n=21)	2-3-y-post-PHV (n=21)	>3y-post-PHV (n=17)
5m (s)	1.22 ± 0.10	1.19 ± 0.09	1.18 ± 0.13	1.20 ± 0.11
10m (s)	2.00 ± 0.11	1.95 ± 0.11	1.92 ± 0.14	1.92 ± 0.12
15m (s)	2.71 ± 0.14	2.63 ± 0.12	2.60 ± 0.16	2.58 ± 0.17
20m (s)	3.37 ± 0.16	3.24 ± 0.15	3.18 ± 0.16	3.18 ± 0.15
30m (s)	4.66 ± 0.23	4.46 ± 0.20	4.36 ± 0.19	4.35 ± 0.19
Adj. 5m (s)	1.43 ± 0.10	1.40 ± 0.09	1.39 ± 0.13	1.41 ± 0.11
Adj. 10m (s)	2.21 ± 0.11	2.16 ± 0.11	2.13 ± 0.14	2.13 ± 0.12
Adj. 15m (s)	2.92 ± 0.14	2.84 ± 0.12	2.81 ± 0.16	2.79 ± 0.17
Adj. 20m (s)	3.58 ± 0.16	3.45 ± 0.15	3.39 ± 0.16	3.39 ± 0.15
Adj. 30m (s)	4.87 ± 0.23	4.67 ± 0.20	4.57 ± 0.19	4.56 ± 0.19
F_H0 (N/kg)	7.20 ± 1.02	7.25 ± 0.91	7.37 ± 1.21	7.28 ± 1.22
F_H0 absolute (N)	404.07 ± 63.56	471.67 ± 78.14	529.07 ± 97.46	564.83 ± 107.53
V_H0 (m/s)	8.40 ± 0.65	9.06 ± 0.58	9.43 ± 0.56	9.52 ± 0.65
P_{max} (W/kg)	15.08 ± 2.02	16.38 ± 2.05	17.26 ± 2.35	17.23 ± 2.54
FV slope (a.U.)	-0.863 ± 0.16	-0.804 ± 0.12	-0.789 ± 0.16	-0.775 ± 0.16
FV_{Diff} (%)	135.74 ± 21.73	122.52 ± 16.46	117.68 ± 19.50	115.90 ± 20.15
RF_{max} (%)	42.32 ± 2.55	43.67 ± 2.74	44.41 ± 3.69	44.22 ± 3.44
DRF (%)	-7.82 ± 2.15	- 7.46 ± 1.13	-7.29 ± 1.42	-7.15 ± 1.44