Are There Sensitive Periods for Skill Development in Male Adolescent Basketball Players?

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ABSTRACT

GUIMARÃES, E., A. D. G. BAXTER-JONES, A. M. WILLIAMS, D. I. ANDERSON, M. A. JANEIRA, F. GARBELOTO, S. PEREIRA, and J. MAIA. Are There Sensitive Periods for Skill Development in Male Adolescent Basketball Players?. *Med. Sci. Sports Exerc.*, Vol. 56, No. 8, pp. 1437–1445, 2024. **Purpose:** Although spurts in physical capacities during adolescence are well known, little is known about the existence of such spurts in sport-specific skill development, especially during the period of rapid growth in stature. Our aims were to examine the timing, intensity, and sequence of basketball-specific skill spurts aligned with biological (years from peak height velocity (PHV)) rather than chronological age. We then defined putative sensitive periods (windows of optimal development) for each skill aligned to the adolescent growth spurt. **Methods:** Altogether, 160 adolescent male basketballers aged 11–15 yr were tested biannually over 3 consecutive years. The years from attainment of PHV was estimated, and six skill tests were aligned to each year from PHV in 3-month intervals. Skill velocities were estimated using a nonsmooth polynomial model. **Results:** Maximal gains in slalom dribble occurred 12 months before PHV attainment (intensity, 0.18 $m \cdot s^{-1} \cdot yr^{-1}$), whereas in speed shot shooting (intensity, 9.91 $pts \cdot yr^{-1}$), passing (intensity, 19.13 $pts \cdot yr^{-1}$), and slalom sprint (intensity, 0.19 $m \cdot s^{-1} \cdot yr^{-1}$), these skill spurts were attained 6 months before PHV attainment. The mean gains in control dribble (intensity, 0.10 $m \cdot s^{-1} \cdot yr^{-1}$) and defensive movement (intensity, 0.12 $m \cdot s^{-1} \cdot yr^{-1}$) peaks coincided with attainment of PHV. We identified different sized windows for optimal development for each skill. **Conclusions:** Peak spurts in skill development, for most basketball skills, were attained at the same time as PHV. The multiple peaks observed within the defined windows of optimal development suggest that there is room for skill improvement even if gains might be greater earlier rather than later in practice. Our findings highlight the need to make coaches aware of where their players are relative to the attainment of PHV because different skills appear to develop differently relative to PHV. Such knowledge may help in designing more relevant training regimes that incorporate the athlete's current growth status so that skill development can be maximized. **Key Words:** TECHNICAL SKILLS, PEAK SPURTS, WINDOWS OF OPTIMAL DEVELOPMENT, YOUNG ATHLETES, BASKETBALL

Over the last 30 yr, researchers have discussed the existence of periods of accelerated change in physiological systems (1), physical capacities (2), and motor skill development (3). These changes are related to periods of accelerated growth during adolescence. These periods have been given various names, but are commonly referred to as either "sensitive periods" or "windows of opportunity." They have been discussed relative to the acquisition of new skills (4) improvements in motor abilities (3), and the optimal times to train physical capacities and skills (5). The potential existence of sensitive periods may have significant implications for coaches in relation to how best to design and implement training programs that utilize the fact that rapid growth is occurring. In this article, we describe the development of basketball skills in young males and identify potential sensitive periods/windows of opportunity. We align skills by biological rather than chronological age, so that coaches can use the process of growth to enhance skill development. Our findings have the potential to revise recommendations made by the Long-Term Athlete Development (LTAD) model that infer that basic sport-specific skills are most trainable for males before the onset of the adolescent growth spurt (6).

The background to these discussions can be found in the work by Beunen and Malina (2), who identified developmental spurts (i.e., maximum gains) in physical performance

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during the adolescent growth spurt. These changes were only apparent when outcomes were aligned to biological age (e.g., years from the attainment of peak height velocity (PHV)) rather than chronological age. The findings were confirmed in measures of motor abilities by Viru et al. (3), who reported spurts in motor abilities in both pre- and circum-adolescence. Such findings supported the LTAD model, which identifies chronological age sensitive periods of optimal trainability, labeled as "windows of opportunity" (5,7). Notwithstanding the widespread use of the LTAD model as a framework for athlete development, the absence of longitudinal empirical evidence that controlled for the growth process that supported the existence of sensitive periods has led to criticisms of the LTAD model (8–10).

Spurts in maximum aerobic power using a statistical strategy developed by van't Hof et al. (11) were identified in children and adolescents in Europe (1), as well as in twins in Belgium but using the Preece–Baines model I growth function (12). Furthermore, using Beunen and Malina's (2) strategy of aligning physical performance with biological age (i.e., age-at-PHV), Yagüe and De La Fuente (13) and Silva et al. (14) reported the presence of physical performance spurts in nonathletic youth populations in Spain and Brazil, although the respective spurts varied in timing and intensity. Guimarães et al. (15) found similar spurts in physical performance, in a cross-cultural study involving adolescent boys in Canada, Brazil, and Portugal. In addition, such childhood spurts are reported to exist in gross motor coordination (16), as well as in motor performance (17,18). However, to the best of our knowledge, only two reports (from basketball and soccer) have examined links between growth and skill development in male youth sports, and both only examined sensitive periods/windows of opportunity in the development of physical capacities rather than specific skills (19,20). In both studies, distinct physical capacities peaked around the attainment of PHV (~14 yr of age), findings that contrasted with Viru et al. (3), as well as with predictions arising from the LTAD model (7).

Although there is evidence for spurts in physical capacities during identifiable periods in adolescent development, the question of whether such periods exist for spurts in sport-specific skills remains unknown. In the present study, we had two aims. First, we examined the developmental timing, intensity, and sequence of basketball-specific skills spurts. Second, we defined putative sensitive periods (windows of optimal development) for each skill. It is believed that coaches can greatly enhance improvements in performance if they apply appropriate training during these periods/windows. According to the basketball national and international federation manuals (21,22), coaches are expected to place a greater emphasis on the development and improvement of technical skills at chronological ages 13 and 14 yr (i.e., at the under-14 age category) rather than aligned to a biological age. Based on these recommendations, and the prior findings of Guimarães et al. (19) and Philippaerts et al. (20), we hypothesized that young male basketballers would attain basketball-specific skill performance spurts around the attainment of PHV (~14 yr of age), and that these periods/windows of skill development may potentially be optimized. We predicted that these periods/windows would not alter between different skill tests.

METHODS

Participants. Participants were recruited from the *In Search of Excellence—a Mixed-longitudinal Study in Young Athletes* (INEX study), a 3-yr mixed-longitudinal study carried out in Porto, Portugal, from 2017 to 2019. The INEX study aims, design, and recruitment of basketball players are extensively described elsewhere (23). The total sample consisted of 293 male adolescent basketball players (11–15 yr at baseline) recruited from 20 out of the 25 clubs in the Porto Basketball Association. During the study, all under-12, under-14, and under-16 players regularly trained 4.5 $h \cdot wk^{-1}$, whereas under-18 players practiced 6.0 $h \cdot wk^{-1}$. Players were assessed biannually over 3 consecutive years at the lead institution's facilities, but no direct observation of practices was carried out at the clubs. We only included 160 players in the present analyses as they fulfilled the conditions of not being injured during the data collection periods and having complete data on 5 to 6 time points for anthropometry and basketball-specific skills measures. Written informed consent was obtained from parents or legal guardians as well as individual assent from each participant. The Ethics Committee of the lead institution (CEFADE 13.2017) approved the study, and the Porto Basketball Association gave formal permission for data collection.

Anthropometry. Height (cm) was measured by experienced anthropometrists following the International Working Group on Kinanthropometry protocols (24), without shoes and with the participant's head positioned in the Frankfurt plane, and using a Harpenden stadiometer (Holtain Ltd., Crymych, UK) with a precision of 0.1 cm.

Basketball-specific skills. Basketball-specific skills were assessed using the American Alliance for Health, Physical Education, Recreation and Dance test battery (25), as well as two slalom tests (26). The complete set of tests included the following: (i) speed shot shooting (points)—players shot the ball from five positions, collected their own rebound, dribbled to another designated position and repeated this sequence as quickly as possible over 60 s; (ii) passing (points)—players performed chest passes against a wall marked with six targets and retrieved the ball while moving laterally over 30 s; (iii) control dribble ($m \cdot s^{-1}$)—players dribbled the ball while running as quickly as possible through an obstacle course defined by six cones; (iv) defensive movement ($m \cdot s^{-1}$)—players performed as quickly as possible lateral slides while keeping the basic defensive position and without crossing their feet in a course defined by six cones; (v) slalom sprint ($m \cdot s^{-1}$)—players ran and changed direction as quickly as possible in a zigzag pattern defined by 12 cones; and (vi) slalom dribble ($m \cdot s^{-1}$)—players dribbled and controlled the ball while running and changing direction as quickly as possible in a zigzag pattern defined by 12 cones. Using the total distances covered by the players, we converted to $m \cdot s^{-1}$ the outcome of the skill tests whose result was in seconds so that velocity was the unit of measurement. A detailed description of the protocol of each test is reported elsewhere (23).

Data quality control. We ensured data quality control using a five-step procedure: (i) anthropometric measurements were performed by trained personnel from the lead institution; (ii) an in-field reliability check was done using a random sample of three-to-five participants per day; (iii) reliability estimates were computed using the technical error of measurement (TEM) and ANOVA-based intraclass correlations (R). The TEM was 0.17 cm for height, and the corresponding coefficient of variation was 0.10%. R values for skill tests ranged from 0.91 (95% confidence interval, 0.78–0.96) in speed shot shooting to 0.98 (95% confidence interval, 0.95–0.99) in defensive movement; (iv) data cleaning was undertaken to control for errors in data entry and the putative presence of outliers; and (v) normality checks in the distributions of all variables were undertaken.

Statistical analysis. Peak spurts in height and basketball-specific skill tests were fitted using a modified nonsmoothed polynomial method that was initially proposed by van't Hof et al. (27) and subsequently used by Beunen et al. (28), Yagüe and De La Fuente (13), and Philippaerts et al. (20) in studies dealing with physical performance. A mathematical generalization of this methodology was developed and used by our research group (14–19). In this article, sensitive periods were conceived as the period between maximum gain increase before the peak spurt and maximum gain loss after the peak spurt.

We developed mean velocity curves and defined these in terms of biological age (i.e., months before PHV and after PHV) strictly following indications by van't Hof (27): (i) low measurement error in all variables and (ii) a single increase in velocity (i.e., a real spurt followed by a definite slowdown). Although measurements were taken every 6 months, the method allowed estimation of individual velocities every 3 months. Because we used a mixed-longitudinal design, the number of observations available to estimate mean velocities, in the mean–constant curve, from −18 months before PHV and +18 months after PHV varied. This fact was reported in previous studies (13,14,20).

We estimated growth velocities using the Peak Growth software developed by a mathematician and software programmer from the University of Porto. Graphical data were displayed using a cubic spline procedure, implemented in GraphPad Prism 9.0 (GraphPad Software Inc., San Diego, CA). The cubic spline used interpolating cubic polynomials and used information from neighboring points to obtain a degree of global smoothness. The cubic spline was chosen over other curve-fitting procedures because it maintained the integrity of the data without transforming or modifying the underlying growth characteristics.

RESULTS

Growth velocities relative to age-at-PHV are presented in Table 1 and Figure 1. Although a peak spurt in height was identified in 159 out of the 160 players, the same did not occur in all six skills as seen in different sample sizes across ages before (−) and post (+) PHV. On average, players attained PHV at 13.90 ± 1.40 yr. Statural velocity increased from 5.12 cm·yr^{-1} at 18 months before PHV to 7.99 cm·yr^{-1} at PHV. After the attainment of PHV, the velocity quickly declined to 2.86 cm·yr^{-1} at 18 months after PHV.

The timing and intensity of specific skills spurts are presented in Table 1 and illustrated in Figure 2. A window of optimal development delimited by the moment of maximum gain increase before the peak and by the moment of maximum gain loss after the peak (gray area) was defined for each skill. For speed shot shooting, the mean gains fluctuated from 18 months before PHV (8.01 pts·yr^{-1}) to 12 months before PHV (7.31 pts·yr^{-1}). Subsequently, there was a spurt exhibiting a window of optimal development for shooting from 9 months before PHV (6.92 pts·yr^{-1}) to 3 months before PHV (7.66 pts·yr^{-1}) with a peak 6 months before PHV (9.91 pts·yr^{-1}). Thereafter, shooting gains slightly increased until the occurrence of PHV (8.28 pts·yr^{-1}) and continued to fluctuate until 18 months after PHV (5.98 pts·yr^{-1}).

For passing, the average gains quickly decreased from 20.43 pts·yr^{-1} at 18 months before PHV to 13.59 pts·yr^{-1} at 15 months before PHV and fluctuated until 14.87 pts·yr^{-1} at

TABLE 1. Mean constant curve velocities for height and basketball-specific skills aligned by months from PHV.

		Months from PHV (0 = PHV)												
Variables		**–18**	**–15**	**–12**	**–9**	**–6**	**–3**	**0**	**3**	**6**	**9**	**12**	**15**	**18**
Height (cm·yr^{-1})	Mean	5.12	5.91	6.49	6.20	5.77	7.42	**7.99**	6.71	4.74	4.24	4.13	3.76	2.86
	n	32	40	34	50	96	99	159	130	136	110	100	88	84
Speed shot shooting (pts·yr^{-1})	Mean	8.01	6.64	7.31	6.92	**9.91**	7.66	8.28	6.11	6.22	5.86	6.08	4.57	5.98
	n	19	28	20	30	46	57	61	71	47	55	34	36	19
Passing (pts·yr^{-1})	Mean	20.43	13.59	15.05	14.87	**19.13**	14.88	17.08	15.81	17.56	14.09	16.59	14.97	19.29
	n	15	31	15	40	56	79	103	79	66	71	43	37	25
Control dribble (m·s^{-1}·yr^{-1})	Mean	0.09	0.07	0.05	0.06	0.09	0.08	**0.10**	0.07	0.07	0.06	0.06	0.06	0.08
	n	8	27	11	36	40	68	68	83	65	63	42	48	35
Defensive movement (m·s^{-1}·yr^{-1})	Mean	0.09	0.07	0.05	0.06	0.10	0.08	**0.12**	0.08	0.06	0.05	0.05	0.05	0.07
	n	16	32	19	40	52	86	91	93	71	60	42	46	31
Slalom sprint (m·s^{-1}·yr^{-1})	Mean	0.18	0.15	0.17	0.12	**0.19**	0.15	0.15	0.13	0.12	0.11	0.10	0.09	0.09
	n	21	36	17	37	59	75	89	84	64	51	31	38	29
Slalom dribble (m·s^{-1}·yr^{-1})	Mean	0.18	0.15	**0.18**	0.13	0.17	0.14	0.17	0.13	0.11	0.09	0.07	0.09	0.11
	n	20	35	16	37	49	73	80	77	55	50	32	37	25

Peak velocity values are in bold.
n = number of players with estimated individual velocities.

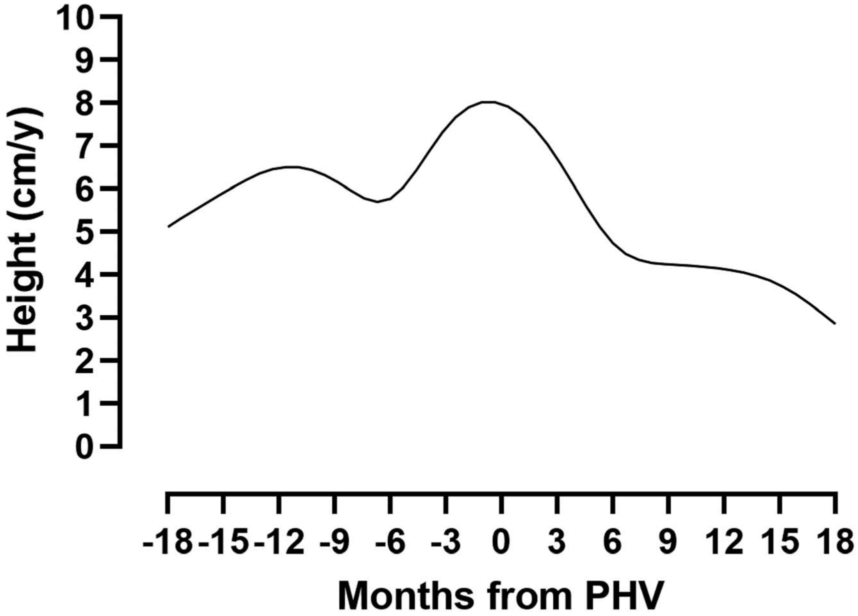

FIGURE 1—Mean velocity curves for height aligned by biological age (months from PHV); 0 (13.90 ± 1.40 yr) = PHV.

9 months before PHV. At this moment, passing gains rapidly increased showing a window of optimal development for this skill until 3 months before PHV (14.88 pts·yr^{-1}) with a peak 6 months before PHV (19.13 pts·yr^{-1}). Then, a fluctuation in mean gains was observed until 18 months after PHV (19.29 pts·yr^{-1}).

For control dribble, the gains declined from 0.09 m·s^{-1}·yr^{-1} at 18 months before PHV to 0.05 m·s^{-1}·yr^{-1} at 12 months before PHV, but increased right after resulting in a window of optimal development for control dribble until 3 months after PHV (0.07 m·s^{-1}·yr^{-1}) with a peak coincident with PHV attainment (0.10 m·s^{-1}·yr^{-1}). Thereafter, the average gains displayed a plateau until 18 months after PHV (0.08 m·s^{-1}·yr^{-1}).

For defensive movement, the mean gains dropped from 0.09 m·s^{-1}·yr^{-1} at 18 months before PHV attainment to 0.05 m·s^{-1}·yr^{-1} at 12 months before PHV. Subsequently, there was a spurt displaying a window of optimal development for defensive movement until 9 months after PHV (0.05 m·s^{-1}·yr^{-1}) with a peak at PHV (0.12 m·s^{-1}·yr^{-1}). Gains then showed a plateau until 15 months after PHV, followed by a slight increase until 18 months after PHV (0.07 m·s^{-1}·yr^{-1}).

For slalom sprint, another skill without ball handling, the average gains fluctuated between 18 months before PHV (0.18 m·s^{-1}·yr^{-1}) and 9 months before PHV attainment (0.12 m·s^{-1}·yr^{-1}). Thereafter, gains rapidly increased displaying a window of optimal development for slalom sprint from this moment (i.e., 9 months before PHV) to 15 months after PHV (0.09 m·s^{-1}·yr^{-1}) with a peak at 6 months before PHV (0.19 m·s^{-1}·yr^{-1}).

For slalom dribble, the mean gains decreased from 18 months before PHV (0.18 m·s^{-1}·yr^{-1}) to 15 months before PHV (0.15 m·s^{-1}·yr^{-1}). It then increased, attaining a peak at 12 months before PHV attainment (0.18 m·s^{-1}·yr^{-1}) and exhibiting a window of optimal development for this skill until 12 months after PHV (0.07 m·s^{-1}·yr^{-1}). The mean gains then slightly increased until 18 months after PHV (0.11 m·s^{-1}·yr^{-1}).

DISCUSSION

We examined the timing, intensity, and sequence of sport-specific skill spurts in a sample of young basketball players, followed twice annually over 3 consecutive years. In addition, we defined putative sensitive periods (windows of optimal development) for each skill where it is believed that adequate training may have an optimal effect on performance development. Once aligned by biological age, technical skill spurts displayed more than one peak (with different intensities) in all six skills. These findings raise questions about how to define, with precision, the onset and the end of such sensitive periods. Because of this complexity, we framed the discussion in terms of theoretical considerations and our interpretation of the findings.

Theoretical considerations. Are motor abilities and/or sport-specific skills more trainable (i.e., with a higher rate of improvement) within certain temporal windows if coaches implement proper training stimuli? If coaches do not properly exploit these windows of optimal development, does this imply that athletes may never reach their full potential? Although these are enthralling questions, the truth is that the available data supporting the existence of such time periods throughout the development of young athletes are extremely limited, or nonexistent. However, it must be highlighted that the lack of evidence does not imply that these windows do not exist (4).

Well known in ontogenetic development, the notion of critical periods asserts the presence of specific time periods during which an individual is most susceptible to environmental influences and assumes that several changes underlying physical growth, biological maturation, and development occur more

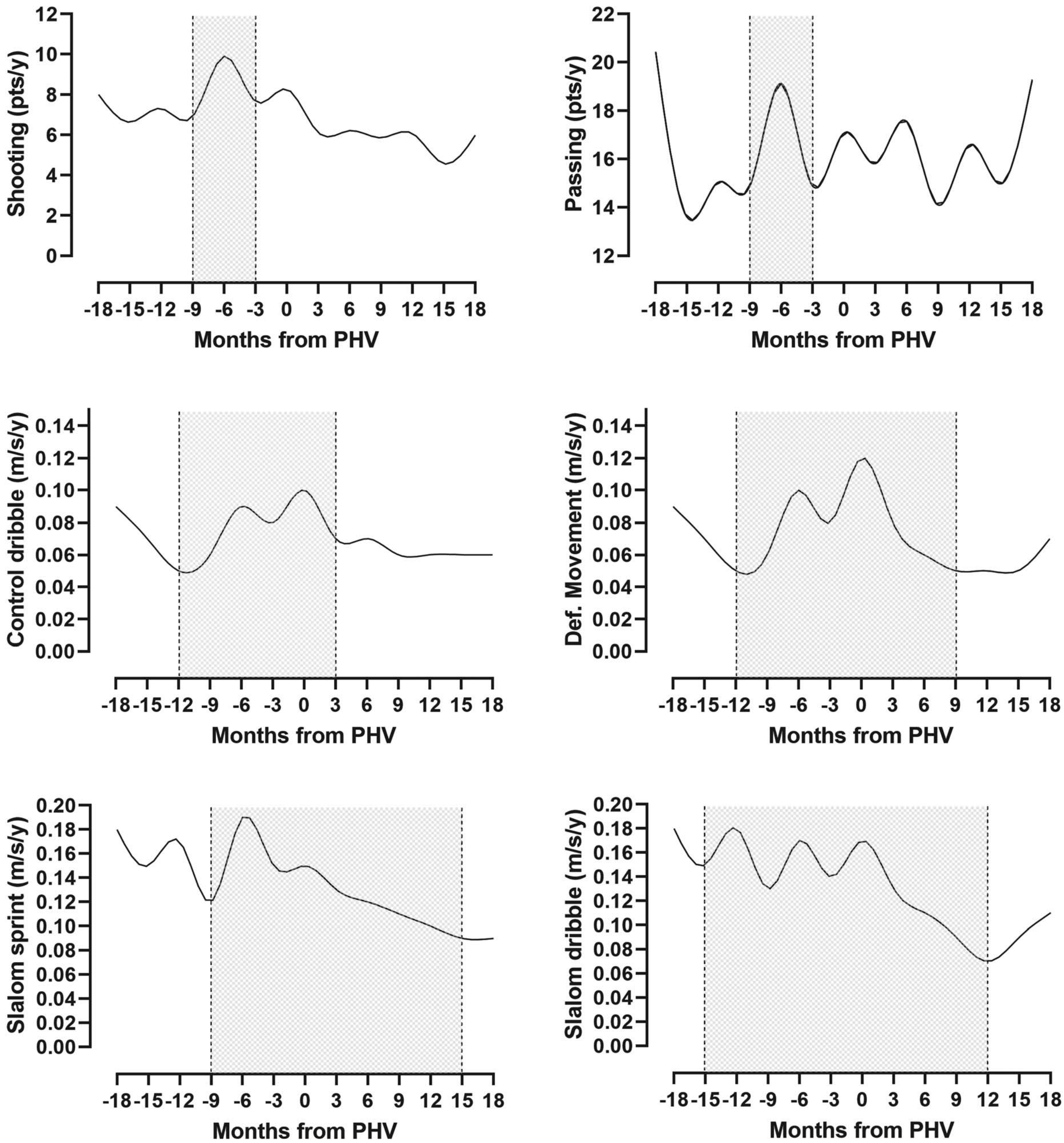

FIGURE 2—Mean velocity curves and windows of optimal development (gray area) for basketball-specific skills aligned by biological age (months from PHV); 0 (13.90 ± 1.40 yr) = PHV.

rapidly and efficiently during this time (29,30). The theory behind critical periods contends that the organization of a system is most easily modified during its time of most rapid development, which typically occurs close to the beginning of the organizational process (31). Early conceptions of critical periods contend they were typically short in duration, occurred early in life, and led to irreversible anatomical, physiological, or behavioral changes (3,30,32,33). However, subsequent evidence suggested that the periods were rarely brief and seldom led to changes that were irreversible, and consequently, contemporary researchers have preferred to use the label-sensitive period rather than critical period to refer to heightened periods of sensitivity or susceptibility to environmental input (4,34,35). These sensitive periods are viewed through at least three different lenses: (i) time periods during which an individual is most sensitive to learning a particular skill (4), (ii) periods of accelerated improvements in motor abilities (3), and (iii) periods in the development of a specific ability when training has an optimal effect (5). Consequently, the label-sensitive period is probably a better descriptor of the windows of optimal development or windows of opportunity identified in the current study.

The sensitive period concept has been closely associated with the readiness concept because both concepts suggest that the timing of experiences has a major influence on the rate and magnitude of changes induced by those experiences (32,34). In fact, if precisely identified, sensitive periods might represent windows of maximal/optimal readiness in athletes' responses to the demands of training (36,37). In other words, during sensitive periods, athletes may be more "ready" to enhance their skills and aptitudes. This latter point is important because the readiness concept is much more entrenched in the motor skills development literature and in the physical education context than the sensitive periods concept (38–40). Nevertheless, neither the readiness nor sensitive period concepts can currently be defined precisely enough in the sport science literature to permit clear predictions about, and descriptions of, their manifestations in the development of sports skills. With that caveat in mind, we offer a cautious interpretation of our findings in the next section.

Interpretation of empirical results. Confirming our hypothesis, the peak spurt for most basketball-specific skills occurred around the attainment of PHV. Although we were unable to locate any study reporting similar data, our findings are in line with various basketball federations recommendations for technical skill development (21,22). Although players are expected to make significant improvements in performance immediately after they start the basketball skill acquisition process, consistent with what occurs when any new motor skill is acquired (41), a major skill improvement in accordance with competitive demands is expected to occur when players move into the under-14 age category (the approximate timing of PHV). In this age category, without discouraging the training of basic skills, coaches are compelled to develop a mature pattern of skill performance by enhancing each player's efficiency in the different basketball fundamentals.

Available longitudinal data show that basketball players who perform physically better tend to be more skilled over time (42). Although testing procedures predominantly focus on quantitative performance outcomes rather than the qualitative processes underlying putative mechanisms of change, it is reasonable to assume that the impact of physical capacities on skill outcomes helps to explain the present findings. For example, as shown in Table 2, the timing of peak spurts in accuracy tests (i.e., shooting and passing) did not differ from those found in strength tests performed by young basketball (19) and soccer (20) players. Likewise, spurts in skill tests requiring speed of execution (i.e., control dribble, defensive movement, and slalom sprint) peaked at the same time as those reported previously in physical tasks of agility, speed, and change of direction (43). We contend, therefore, that basketball coaches should exploit well-known increases in muscle mass, and the corresponding plasma testosterone increases occurring during the attainment of PHV (28,44,45) not only to boost the development of physical capacities but also to maximize gains in basketball-specific skills.

Once we had identified the peak spurts in performance improvement, we placed our attention on defining putative windows of optimal development for each skill. This task was not easy because along with the absence of previous roadmaps, mean gains displayed multiple developmental accelerations and decelerations in all six skills (see Fig. 2). The multiple accelerations and decelerations are likely a function of individual differences in the ages at which players started to learn basketball skills, the volume, intensity, and quality of prior practice, and their skill levels at the start of the study (46). For example, players who showed higher levels of technical skill at the beginning of the study had less room for improvement as practice continued, given that the skills had diminishing rates of return from practice and ceiling effects (2,41). Nevertheless, despite the potential for these individual differences to mask sensitive periods in skill development, we were able to identify such periods for the skills studied. What differed was the size of the window of optimal development for each skill. The window was narrow for shooting and passing and wider for the

TABLE 2. Windows of opportunity and timing of peak spurts of five performance components aligned by age-at-PHV.

	Windows of Opportunity	Timing of Peak Spurts		
Performance Components[a]	LTAD Model Balyi and Hamilton (7)	Tests	Basketball Players Present Study, Guimarães et al. (19), and Tavares and Guimarães (43)	Soccer Players Philippaerts et al. (20)
Suppleness (flexibility)	Before PHV	Sit and reach	—	12 mo after PHV
Speed 1 (agility, quickness, change of direction, and segmental speed)	Before PHV	20 m sprint	6 mo before PHV	—
		30 m dash	—	Coincident with PHV
		t-Test	6 mo before PHV	—
		5 × 10 m shuttle run	—	Coincident with PHV
Skills (fundamental movement skills and sport-specific skills)	Before PHV	Speed shot shooting	6 mo before PHV	—
		Passing	6 mo before PHV	—
		Control dribble	Coincident with PHV	—
		Defensive movement	Coincident with PHV	—
		Slalom sprint	6 mo before PHV	—
		Slalom dribble	12 mo before PHV	—
Stamina (aerobic endurance)	Coincident with PHV	Yo-Yo IR1	Coincident with PHV	—
		Endurance shuttle run	—	Coincident with PHV
Speed 2 (anaerobic power and capacity)	Coincident with PHV	Shuttle run	—	Coincident with PHV
Strength	After PHV	30 s sit-ups	—	Coincident with PHV
		60 s sit-ups	6 mo before PHV	—
		Handgrip	Coincident with PHV	—
		Seated medicine ball throw	Coincident with PHV	—
		Squat jump	6 mo after PHV	—
		Countermovement jump	Coincident with PHV	Coincident with PHV

[a] According to the five Ss of the LTAD model.
Yo-Yo IR1, Yo-Yo Intermittent Recovery Test—Level 1.

control dribble, defensive movements, slalom sprint, and slalom dribble. Where other researchers and practitioners might disagree with us is the point we selected to demarcate the end of the windows of optimal development. After extensive discussion among our team members, we chose this point because it objectively marks the end of the greater loss in performance after the peak spurt, even though this rate varied among skill tests. In any case, this approach and our findings support the suggestion that the year-around PHV is of utmost importance for the development of skill in youth basketball.

At first glance, our empirical results appear not to corroborate the LTAD model's suggestion that sport-specific skills are more trainable before PHV in boys (5,7). However, our findings cannot refute this suggestion because of the lack of data pre-18 months before PHV. The high rates of gain at 18 months before PHV observed in every skill test may indicate that optimal periods occur before the age of 11 (when we started data collection with our sample of players) and, therefore, between 9 and 12 yr of age as reported in the LTAD model. Also, the age range chosen considers the development of early maturers who can attain PHV up to 2 to 3 yr earlier than average (47–50). Given the negatively accelerating learning curve seen during the acquisition of any motor skill (41), we contend that it is quite probable that the period of maximum rate of improvement occurs shortly after the skill acquisition process begins. This latter suggestion should not be construed as evidence that we have likely missed the "optimum" window of opportunity for learning the skills tested. It simply highlights the complexity of identifying sensitive periods in the development of culturally meaningful sport skills, exposure to which and the acquisition of which are determined by a multitude of factors that are outside of experimental control. The aforementioned suggestion highlights the remarkable nature of our findings because the odds are stacked against finding noticeable changes in the rates at which skills improve when the changes are examined months or years after the start of practice. However, in the current study, we did identify skill spurts deep into the learning process, and their existence implies that multiple windows of optimal development probably exist throughout a player's career. As basketball coaches often say, players can always get better.

This study is not without limitations. First, we recommend caution when generalizing our findings because our sample was not broadly representative of all Portuguese players, let alone players in Europe or elsewhere, although there is no obvious reason to believe that they were very different from players in other Portuguese regions or countries. In any case, in the future, it would be helpful for researchers to gather data from different countries to investigate cross-cultural variations across young athletes. The second limitation concerns the sample size, even though available reports aligning motor performance to age-at-PHV have used smaller samples. Please note that PHV was only identified in 159 out of the 160 players who had complete data on 5 to 6 time points. Furthermore, depending on data availability, the sample used to estimate peak spurts varied across the six skill tests because our study relied on a mixed-longitudinal design, with five age cohorts (11, 12, 13, 14, and 15 yr) with two overlapping years, rather than a pure longitudinal design. Although this was a challenging issue, this is a common shortcoming in this type of research with athletic (19,20) and nonathletic (13–15,28) populations. Third, as alluded to the discussed previously, we acknowledge that our method of identifying sensitive periods is quasi-experimental, as we examined naturally occurring changes in performance. We are aware that this challenges our interpretation. As such, we suggest that in the future, researchers should consider using a true experimental approach in which "naïve" players of different ages or distances to/from PHV are grouped and given the same amount and type of training on specific skills to determine which groups show the most rapid gains and attain the highest performance levels. Although tremendously challenging, this type of research design has the greatest potential to identify veritable sensitive periods in the development of sports skills (50). Fourth, players usually undergo their training routines according to a periodization plan developed by their coaches given their age group and the competitive season calendar. In our study, we did not have access to such data for confidentiality reasons. Although differences may occur within and between players and coaches, the general training plans follow the recommendations set by the Portuguese Basketball Federation for youth athlete development (21). In any case, we suggest that, if available, in the future, researchers should consider using these plans to model skill developmental using statistical methods based on the mixed model with a piecewise approach.

CONCLUSIONS

In conclusion, peak spurts in performance for most basketball skills were observed when PHV was attained. Because physical capacities have been reported to peak coincident with PHV or within 6 months of its attainment, this finding suggests that the maximal gains in technical skills are most probably linked with increases in muscle mass and with high levels of physical performance. In addition, the multiple peaks observed within the defined windows of optimal development suggest that there is always room for skill improvement even if gains might be greater earlier in practice than later. This novel study improves current understanding of skill development in youth basketball. However, it is of utmost importance that basketball coaches consider the following practical implications. First, given that at early-age players are more different than alike, coaches of youth teams need to know where their players are relative to PHV. Although there are many ways of acquiring this knowledge, the maturity offset is a suitable option because it is a straightforward and noninvasive process of estimating biological age. Second, it is important that coaches and researchers recognize that other factors beyond PHV may influence skill development. Previous physical exercise and sports participation, psychological traits, parental support, coach experience, and club conditions can all play a crucial role, although these factors have never been examined using a multilevel approach, especially using a longitudinal design. Third, when designing their training regimes, coaches should consider that different skills seem to have varying optimal windows relative to PHV. Four, when planning long-term development programs, coaches must be aware that if the players continue to practice, their windows of opportunity will naturally occur. Finally, we recommend that in the future, researchers include data on both boys and girls using information from their previous training experience, hormonal and putative genetic markers, and environmental factors to provide a more encompassing understanding of putative sensitive periods in athletic development.

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