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Biological Maturation of Youth Athletes: Assessment and Implications

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What is new? This review offers...

- ... a critical summary of methods of maturity assessment commonly used in the sport sciences, including non-invasive protocols
- ... an updated summary of available data on maturity status (skeletal age, pubertal status) and timing (ages at peak height velocity and menarche) among youth athletes
- ... a critical discussion of the implications of maturity-associated variation for the development of youth athletes

How might this impact clinical practice?

- Sport is selective, especially during the pubertal years and often occurs along a maturity-related gradient
- Non-invasive methods of maturity assessments have limitations when applied to youth athletes and need to be applied with caution
- The discussion of implications suggests directions for new research in youth athlete development

Abstract

The search for talent is pervasive in youth sports. Selection/exclusion in many sports follows a maturity-related gradient largely during the interval of puberty and growth spurt. As such, there is emphasis on methods for assessing maturation. Commonly used methods for assessing status (skeletal age, secondary sex characteristics) and estimating timing (ages at peak height velocity [PHV] and menarche) in youth athletes and two relatively recent anthropometric (non-invasive) methods (status – percentage of predicted near adult height attained at observation, timing – predicted maturity offset/age at PHV) are described and evaluated. The latter methods need further validation with athletes. Currently available data on the maturity status and timing of youth athletes are subsequently summarized. Selection for sport and potential maturity-related correlates are then discussed in the context of talent development and associated models. Talent development from novice to elite is superimposed upon a constantly changing base – the processes of physical growth, biological maturation and behavioral development, which occur simultaneously and interact with each other. **The processes which are highly individualized also interact with the demands of a sport *per se* and with involved adults (coaches, trainers, administrators, parents/guardians).**

INTRODUCTION

Although participation in sport is a fact of life among youth the world over, attention and resources are often focused on the development of those who have potential for success at elite levels of competition. Formal protocols for identifying, selecting and developing talented youth were developed in several former Soviet Bloc countries among which priority was "...given to the selection of those children and young people thought most likely to benefit from intensive sport training and to produce top-class results in national and international competition." [1 p 50] "Windows of opportunity" were implicit in all protocols, especially enhanced trainability during adolescence. Programs were extended to and modified for other countries, most recently perhaps in the Long Term Athlete Development (LTAD) model which specifically suggested age at PHV as the reference for programming training protocols. [2]

In the context of the preceding, we review methods for estimating biological maturation, summarize available data for youth athletes and discuss implications for athlete development.

ASSESSMENT OF MATURITY STATUS AND TIMING

Biological maturation is a process that occurs in all bodily tissues, organs and systems. Outcomes of underlying processes are observed and/or measured to provide an indication of progress towards maturity (mature state). Maturation is assessed in terms of status – level of maturation at the chronological age (CA) of observation, and timing – CA at which specific maturational events occur. Though related, the two are not equivalent. [3, 4] **Tempo or rate of maturation is a related aspect, but is difficult to estimate.** [3, 4]

Maturity Status

Secondary sex characteristics indicate pubertal status. They include pubic (PH) and axillary hair in both sexes; breasts (B) and menarche (first menstrual flow) in girls; and genitalia

(G, penis, scrotum, testes and testicular volume), voice change and facial hair in boys. Their development reflects maturation of the hypothalamic-pituitary-gonadal and hypothalamic-pituitary-adrenal axes of the neuroendocrine system. Initial development of B and G is driven by gonadal hormones while that of PH is driven by adrenal hormones, especially in girls.[5]

Stages of G, B and PH from initial development to the mature state are assessed relative to specific criteria.[6] Stages are typically assessed clinically, although self-assessments are also used. Accuracy of **both** clinical- and self-assessments is a concern.[7-10]

Stages are not equivalent for G, B and PH. A youngster is “in stage” at the time of observation. Age at entry into a stage (timing) and duration of a stage (tempo) are not known. Variation by stage within a CA group can be considerable. Youngsters are often combined by stage independent of CA which overlooks variation by CA within a stage.

Menarcheal status (whether or not menarche has occurred) is a useful indicator of sexual maturity status within single year CA groups 11-15 years. Comparisons of status independent of CA are confounded by variation in CA.

Testicular development can be evaluated with a Prader orchidometer, a set of models (ellipsoids) indicating specific testicular volumes. The protocol requires matching volume of the testes based on palpation with the models; volumes can also be estimated with sonography.[11]

Skeletal age (SA) is an indicator of maturation of the hand-wrist skeleton viewed on a standard radiograph. Changes in each bone from initial ossification to the adult state mark progress from immaturity to maturity. Major limitations are expense and minimal radiation, and lack of qualified individuals knowledgeable of assessment protocols, limitations and interpretations. With modern technology, exposure to radiation is minimal (0.001 millisievert) and less than background radiation and exposure equivalent to three hours daily television viewing.[12, 13]

Three methods for estimating SA are used: Greulich-Pyle (GP)[15] developed on higher socioeconomic status (SES) children from Cleveland, Ohio; Tanner-Whitehouse (TW)[16-18] developed on British children (TW1, TW2), though reference values in the most recent version (TW3) are based on British, Belgian, Spanish, Italian, Argentine, Japanese and a higher SES sample of American youth; and Fels[19] developed in the Fels Longitudinal Growth Study of middle class children in south-central Ohio.

The methods are similar in principle, but criteria and procedures for deriving SA vary.[3, 14] GP calls for assessment of individual bones, but is often applied clinically by comparing the radiograph as a whole to the pictorial standards. Variation in level of maturity among individual bones is overlooked. Interpolation between standards is an additional problem.

TW3 provides SAs for the radius, ulna, metacarpals and phalanges (RUS SA) or for seven carpals (excluding the pisiform, CARPAL SA); the hand-wrist skeleton as a whole is not considered. **TW3 RUS SAs are, on average, consistently less than corresponding TW2 SAs among youth athletes 11-17 years.** In addition, the criterion for the final stage of maturation of the distal radius and ulna: “fusion of the epiphysis and metaphysis has begun,”[18 pp 63,65] overlooks the time lag between onset and complete union. GP and Fels consider onset through complete fusion of the two bones.

Fels uses the radius, ulna, short bones and carpals. Specific criteria for individual bones are used at certain ages; it is thus calibrated to some extent relative to CA. The method provides a standard error of estimate for SA which is not available with the others.

Allowing for variation in protocols and reference samples, SAs with each method are not equivalent. SA represents the CA at which a specific level of maturity of the hand-wrist bones was attained by the reference sample. SA is ordinarily compared to CA; within a CA group

standard deviations for SA are about three times those for CA. SA may be expressed as a difference (SA minus CA) or ratio (SA/CA). SA is not assigned to youth who have attained skeletal maturity; they are simply noted as skeletally mature. Other protocols for the assessment of skeletal maturity are available, but have had limited application and validation to date.[14, 20]

Maturity Timing

Age at peak height velocity (PHV) refers to the estimated CA at maximum rate of growth in height during the adolescent spurt, which begins with acceleration in rate of growth in height (take-off), continues to accelerate until it reaches a peak (PHV), and then decelerates, eventually terminating in the late teens/early twenties. Age at PHV is estimated from height measurements of individual children taken annually or semiannually across adolescence. Historically, growth rates from individual height records were graphically plotted to identify when the peak occurred. Mathematical modeling or fitting of individual height records is currently used. Depending on model and completeness of data, other aspects of the spurt can be estimated: age, size and rate of growth at take-off, size and rate of growth at PHV, and mature height. Estimates vary by method but are generally more uniform for age at PHV than for PHV (cm/yr). Mean ages at PHV are reasonably similar in longitudinal studies of European youth,[3] but variation among individuals is considerable: 9.0 to 15.0 years and 11.5 to 17.3 years among British, Swiss and Polish girls and boys, respectively.[3, 21, 22]

Menarche typically occurs after PHV. There are three methods for estimating age at menarche. The prospective method applies to individuals followed at relatively short intervals in longitudinal studies (3-6 months, though annually in some studies). Girls and/or their mothers are interviewed whether or not menarche has occurred; if it occurred, further questions pinpoint the time/age. The status quo method applies to a sample. It requires two pieces of information

from girls spanning 9 through 17 years – CA and whether or not menarche has occurred. The data are analyzed with probits or logits to derive the median age at menarche for the sample.

The retrospective method requires individuals to recall CA at menarche. It is influenced by memory and recall bias (the shorter the recall interval, the more accurate the recall, and vice versa). Recalled ages tend to be reported as whole years, typically CA at the birthday before menarche.[23, 24] Detailed interview can aid women to recall ages more precisely. The method is commonly used with late adolescent/young adult athletes.

Non-Invasive Estimates

Given the perceived invasiveness of secondary sex characteristic assessment, negligible radiation exposure with SA and logistical difficulties in conducting longitudinal studies, there is interest in anthropometric estimates of maturity status and timing. Percentage of predicted adult height (actually near adult height) attained at the time of observation provides an estimate of status, while predicted maturity offset/time before age at PHV provides an estimate of timing.

Most adult height prediction protocols require SA. Midparent target height,[25] a commonly used clinical guide, has large associated error. An alternative protocol predicts adult height from CA, height and weight of the child and midparent height.[26, 27] Current height is then expressed as a percentage of predicted adult height to provide an estimate of maturity status. Among youth of the same CA, the one closer to adult height is more mature than another who is further from adult height. The method had moderate concordance with status classifications based on SA in youth American football and soccer players.[28, 29] Use of reported parent heights potentially increases error in predicted heights.

Sex-specific equations incorporating CA, height, weight, sitting height and estimated leg length are used to predict maturity offset.[30] Age at PHV is estimated as CA minus offset.

Validation studies in Polish youth followed from 8 to 18 years indicated several limitations.[21, 22] Predicted offset and estimated age at PHV increased with CA at prediction. Predicted ages at PHV had a reduced range of variation (SDs ~0.5 yr), which approximated standard errors of the equations in boys (0.59) and girls (0.57).[30] Among early maturing boys and girls, based on actual ages at PHV (also age at menarche), predicted ages were later than actual ages at PHV, while among late maturing youth, predicted ages were earlier than actual ages at PHV. Identical results were obtained in the Fels longitudinal sample.[31] Observations for a small longitudinal sample of female artistic gymnasts were consistent with those for late maturing girls.[32]

Maturity offset was suggested as a categorical variable, pre- or post-PHV.[30] This appears useful near the time of actual PHV in average maturing boys within a narrow CA range, 13.00 to 14.99 years,[21, 31] which limits its utility with male athletes who tend to be early maturing.[14] The protocol appears to overestimate age at PHV in girls more than in boys,[22, 31] which may limit its use. Ethnic variation in sitting height and leg length may be potential confounders in predictions.[3]

Maturity status classifications of soccer players with SA and predicted age at PHV had reasonable concordance, but most players were classified as average by the latter.[29] This reflected the reduced range of variation in predicted ages.

The original maturity offset prediction equations have been simplified and calibrated with external samples.[33] The new equations include age and sitting height in boys and age and height in girls; given the lack of sitting height in some studies, an alternative equation for boys includes age and height. The need for validation with athletes and different ethnic groups was indicated.

Overview of Methods

Only skeletal maturation spans infancy through adolescence; other indicators are limited to puberty/adolescence. Each **method** has strengths and limitations of which potential users, specifically those working with youth athletes, should be aware. No single method is the “gold standard” as has been suggested.[34] The two non-invasive estimates have significant limitations and require evaluation in further validation studies.

MATURITY STATUS AND TIMING IN YOUTH ATHLETES

Skeletal Age

Information on the skeletal maturity status of youth athletes is reasonably extensive, more so for males than females, except for artistic gymnasts.[14, 35, 36] Data are based largely on samples of European ancestry, with limited data for Japanese and Chinese athletes. Ethnic variation in skeletal maturation requires consideration,[37-40] but identifying ethnicity may not be permitted in some countries.[41]

With few exceptions, data for males in several team (soccer, American football, baseball, ice and roller hockey) and individual (swimming, athletics) sports indicated that SAs spanned the spectrum from late (delayed) through early (advanced) maturation in samples 10-12 years. With increasing age, numbers of late maturing athletes declined and early maturing and skeletally mature athletes increased.

Corresponding data for females are limited to swimming, athletics and artistic gymnastics, and are lacking for team sports. Swimmers under 14 years of age spanned the maturity spectrum, though more tended to be average and early. Swimmers 14-15 years were primarily average or advanced in SA, while most swimmers 16-17 years were skeletally mature. Among track and field athletes 13-16 years, SAs tended to lag somewhat behind CAs in runners, but were advanced in jumpers and throwers.

SAs and CAs were about equal among female artistic gymnasts 5-10 years; late and early maturing girls were about equally represented. At subsequent ages, SAs lagged behind CAs, and the lag was greatest in later adolescence. By inference, female gymnasts late and on time in skeletal maturation were predominant while early maturing gymnasts were a minority. Although not always reported, significant numbers of gymnasts 15-18 years were skeletally mature. Less extensive data for male gymnasts suggested a similar trend, and many gymnasts 16-18 years were skeletally mature.

SA and fusion of the distal radius have been used to “verify” CA in competitions,[14, 20] but neither **method** is a valid indicator of CA. SA and fusion of the distal radius should not be used for age verification in sport. The advanced skeletal maturation of males in many sports and later maturation in female artistic gymnasts, increase the likelihood of CA misclassifications.[14] Ethnic variation is an additional factor.

Pubertal Status

Many studies consider limited CA ranges or competitive age groups, and often report only a mean stage. Distributions of stages by CA group are not commonly reported, while some studies are limited to select samples, e.g., pre- or early-pubertal.

Stages of PH for recent samples of soccer players 11-18 years are summarized in Table 1. All five stages were represented among players 12 and 13 years, while four stages were represented among players 11 and 14 years. Within specific CA groups, players in advanced stages of PH tended to be older, taller and heavier, on average, than players in less advanced stages. Among players at the same stage, older boys tended to be taller and heavier, on average, than younger boys. The need to consider variation by CA within a stage and by stage within a specific CA group is obvious, but is not ordinarily done.

Table 1. Distributions of soccer players 11-18 years by stage of pubic hair within **chronological age (CA)** group and descriptive statistics for CA, height and **body mass** by age and stage

CA Group	N	Stage of Pubic Hair (PH)														
		Prepubertal			PH 2			PH 3			PH 4			>Mature		
		n	M	SD	n	M	SD	n	M	SD	n	M	SD	n	M	SD
CA, yrs																
11	104	62	11.5	0.3	38	11.5	0.3	3	11.7	-	1	11.9	-			
12	71	24	12.5	0.3	25	12.5	0.2	17	12.6	0.3	4	12.8	0.1	1	12.6	-
13	89	6	13.3	0.1	22	13.6	0.3	28	13.6	0.3	27	13.7	0.2	6	13.8	0.2
14	115				6	14.3	0.2	23	14.5	0.4	64	14.5	0.3	22	14.6	0.3
15	60							2	15.2	-	30	15.4	0.4	28	15.6	0.3
16	36										15	16.3	0.3	21	16.4	0.3
17-18	23										6	17.6	0.4	17	17.9	0.4
Height, cm																
11			142.9	5.6		150.0	6.4		152.7	-		156.3	-			
12			146.9	7.0		150.3	6.3		158.1	5.7		164.1	7.0		163.6	-
13			155.8	3.1		153.8	6.7		164.7	7.3		166.7	7.3		170.8	4.2
14						161.3	7.4		164.1	8.3		170.6	6.6		176.3	6.6
15									167.5	-		172.6	4.3		176.9	5.1
16												175.8	5.3		174.1	5.2
17-18												177.0	4.9		176.5	4.7
Body Mass, kg																
11			35.7	4.9		42.7	5.3		41.1	-		48.8	-			
12			38.5	4.5		41.9	6.5		48.1	6.8		56.3	9.0		51.1	-
13			43.5	4.4		42.7	6.2		54.1	7.4		56.4	7.1		62.2	6.2
14						53.2	9.5		54.0	7.9		60.6	6.5		66.6	7.4
15									48.7	-		65.5	6.9		70.4	6.7
16												68.0	5.0		68.9	6.5
17-18												70.6	4.0		70.6	6.9

*Collated from data for Portuguese,[42-45] Spanish[46] and Italian[14] players.

Lack of data for younger players 8-10 years and small numbers of older players limited the utility of the data for estimating age at entry into a stage and age at being in a stage. Allowing for these limitations, mean CA of soccer players in PH 4 was similar to, while that for players in PH 5 was earlier than estimates from a representative sample of American White boys.[47] The trend was consistent with advanced SA[14] and increased testicular volume[47] in soccer players 14-16 years.

Similar size trends were noted among female athletes classified by menarcheal status within CA groups 13-17 years (Table 2). Post-menarcheal athletes were taller and heavier within CA groups. Variation in size by menarcheal status across CA groups was suggested for height but was not consistent for weight, perhaps reflecting selectivity and emphasis on weight control in the three sports.

Age at PHV

Longitudinal data for youth athletes spanning late childhood through adolescence are limited as are estimated ages at PHV in European athletes (Table 3). Studies generally began too late and ended too early. In the 4-5 year mixed-longitudinal study of 76 soccer players,[54] age at PHV could be estimated for only 33 in whom CA (12.1 ± 0.7 yrs) approximated SA (12.4 ± 1.3 yrs) at initial observation. PHV was apparently attained by 25 players (CA 12.6 ± 0.5 yrs, SA 13.5 ± 1.2 yrs) before/too early in the study and was not attained by 18 players (CA 11.5 ± 0.8 yrs, SA 11.1 ± 1.1 yrs) during the study.

Except for artistic gymnasts, studies which spanned most of adolescence indicated ages at PHV consistent with earlier maturation of boys involved in sport, while corresponding data for female athletes indicated ages at PHV which approximated means for the general population. Ages at PHV of artistic gymnasts of both sexes were later.

Table 2. Distributions of youth athletes in three sports by menarcheal status (pre-, post-) **within chronological age (CA)** group and descriptive statistics for **CA**, height and **body mass** by age and menarcheal status (numbers of pre-menarcheal divers and figure skaters at older ages were too small)

CA Group	Junior Olympic Divers ⁴⁹						Club Figure Skaters ⁵⁰						Elite Artistic Gymnasts ⁵¹					
	Pre-			Post-			Pre-			Post-			Pre-			Post-		
	n	Mean	SD	n	Mean	SD	n	Mean	SD	n	Mean	SD	n	Mean	SD	n	Mean	SD
CA, yrs																		
13	17	13.4	0.3	13	13.3	0.2	14	13.4	0.3	12	13.5	0.4						
14	5	14.6	0.2	18	14.5	0.2	8	14.5	0.3	13	14.6	0.3	28	14.6	0.3	16	14.8	0.2
15							5	15.5	0.4	18	15.4	0.3	28	15.4	0.3	20	15.4	0.3
16													10	16.4	0.3	21	16.5	0.3
17													7	17.3	0.3	31	17.5	0.3
Height, cm																		
13		154.1	6.1		158.3	4.9		154.0	7.2		157.9	3.5						
14		156.4	3.4		159.2	5.0		152.8	5.0		158.2	5.9	150.5	5.7		153.4	4.4	
15								155.5	9.9		161.9	5.6	152.6	6.0		156.0	6.2	
16													153.7	5.6		157.5	6.1	
17													153.9	8.0		157.5	5.6	
Body Mass, kg																		
13		44.6	6.7		49.0	5.7		43.0	7.6		50.0	6.8						
14		47.3	7.5		51.5	4.1		41.8	5.2		51.4	6.3	40.4	5.1		46.7	5.3	
15								45.7	11.2		52.6	6.5	42.6	5.3		47.2	5.1	
16													42.8	5.2		49.7	4.3	
17													44.8	4.4		49.3	6.2	

Table 3. Estimated ages at **peak height velocity** (PHV, years) in longitudinal studies of youth athletes in Europe* **Duration of study refers to the specific age ranges over which athletes were followed**

Duration of Study, yrs	Sport	Boys		Girls		Method**, Country
		n	Age at PHV Mean SD	n	Age at PHV Mean SD	
11-16	Soccer	8	14.2 0.9			P, Denmark ⁵²
12-15	Soccer	32	14.2 0.9			PB, Wales ⁵³
10-13/14-17	Soccer	33	13.8 0.8			P, Belgium ⁵⁴
10-15	Ice Hockey	11	12.8 0.5			G, France ⁵⁵
12-15	Ice Hockey	16	14.5 1.0			G, former Czechoslovakia ⁵⁶
12-15	Cycling	6	12.9 0.4			G, “
12-15	Rowing	11	13.5 0.5			G, “
11-18	Basketball	8	14.1 0.9			G, former Czechoslovakia ⁵⁷
11-18	Rowing	11	12.6 0.9	9	12.0 0.9	KR, Poland ⁵⁸
11-18	Athletics	10	13.6 0.8	13	12.1 0.8	KR, “
10-12/15-18	Gymnastics	12	15.0 0.8	8	13.2 0.7	P, Poland ^{59 36}
			14.8 0.8		13.2 0.9	KR, “
~9/15-16	Gymnastics			13	12.9 1.5	PB, Belgium ⁶⁰
8-18	Several	25	13.6 0.9	13	12.3 0.8	PB, Poland ⁶¹
	Non-athletes***		13.8-14.4			

*Studies date from the 1960s through 1980s, one in the 1990s-early 2000s.

**Methods for estimating age at PHV: G-graphic interpolation, P-polynomials, PB-Preece-Baines model I, KR-kernel regression.

***Range of mean ages at PHV in longitudinal studies of European youth. Among males, 25 of 26 estimated ages at PHV were between 13.8 and 14.2 years, and among females 24 of 25 estimated ages at PHV were between 11.6 and 12.2 years. Standard deviations ranged from 0.8 to 1.3 years in boys and 0.7 to 1.2 years in girls.[3]

Available ages at PHV of Japanese youth athletes (Table 4) were generally consistent with those for the general population with two exceptions, the earlier age in the combined sample of male basketball players and track athletes, 11.6 ± 0.9 years,[62] and the later age in soccer players, 13.6 ± 1.1 years.[63] The regional school players contrasted elite Japan League academy soccer players 13-15 years who were advanced in skeletal maturation.[68]

Age at Menarche

Prospective and status quo estimates in samples of youth athletes are summarized in Table 5. Data are not extensive. Mean/median ages at menarche for gymnasts, figure skaters and divers were, on average, later, while those for athletes in other sports approximated values for the general population in the respective countries. All other data for athletes are retrospective. Mean recalled ages overlapped those in Table 5, but were somewhat later in some sports.[3, 81] The trend reflects potential sampling bias associated with dropout, persistence and/or selectivity in specific sports, whereas prospective and status quo surveys include more variability among adolescent participants.

Youth Athletes in a Secular Perspective

Several studies of the growth and maturation of youth athletes date to the 1950s and 1960s; studies increased in the 1970s and 1980s, and continued through the present.[76, 82] Given the time span, secular changes towards larger size and earlier maturation observed in the general population[3] are potential confounders in evaluating samples of athletes. Secular trends vary among countries. Median heights of U.S. youth have not changed appreciably since the 1960s,[83, 84] while evidence for change in **age at menarche** is equivocal.[85] Changes in heights and ages at menarche in European youth were marked for several decades after World War II but have since slowed or stopped in some countries.[3, 86-88] European data also

Table 4. Estimated ages at **peak height velocity** (PHV, years) in longitudinal studies of youth athletes in Japan and South Korea

Boys		Age at PHV			Girls		Age at PHV		
Level/Sport	n	Mean	SD	M*	Level/Sport	n	Mean	SD	M
Japan									
School, Basketball/Athletics**	15	11.6	0.9	W ⁶²	Prefecture level select 11 ind/team sports	144	11.1	1.0	W ⁶⁵
Junior High, non-select					Prefecture level select				
Baseball	126	13.1	1.0	PB ⁶³	6 ball games	90	11.2	1.0	W ⁶⁶
Basketball	39	12.8	1.1		Tennis	16	11.6	0.9	
Soccer	83	13.7	1.1		Basketball	15	10.9	0.9	
Volleyball	53	13.2	0.8		Volleyball	21	11.0	1.1	
Elite, Distance runners	4	12.6		G ⁶⁴	Softball	7	11.1	1.2	
South Korea									
					High school, national select 13 sports, all individual sports except one	77	11.0	1.1	W ⁶⁷
Non-athletes***		12.2-13.1					10.4-11.5		

*Methods for estimating age at PHV: G-graphic interpolation, PB-Preece-Baines model I, W-wavelet interpolation. All studies were based on serial heights of individuals from 6 to 17 years which were extracted from school records; measurements were routinely taken in April. Data were collected mostly in the 1980s and 1990s.

**One-half of a year (0.5) was added to the reported mean age⁶² because exact ages were not used in calculating ages at PHV; whole years were used (6.0, 7.0, etc.) which probably underestimated the age by 0.5 year (Fujii, personal communication).

***Range of mean ages at PHV in several Japanese longitudinal studies and one South Korean study. Standard deviations ranged from 0.8 to 1.4 in boys and 0.8 to 1.2 cm in girls.[3, 65, 66] Ages at PHV are earlier, on average, in Japanese than in European adolescents.

Table 5. Prospective and status quo estimates of ages at menarche (years) in adolescent athletes*

Prospective		N	Mean	SD	Status Quo Estimates		N	Age Range	Median	SD
Gymnastics	Poland ⁵⁹	16	15.1	0.9	Gymnastics	World Champ ⁷⁴	200	13-21	15.6	2.1***
	Switzerland ⁶⁹	11	14.5	1.2**		Hungary ⁷⁶	132	9-19	15.0	0.6
	Switzerland ⁷⁰	21	14.4	1.2	Figure skating	US-Canada ⁵⁰	159	11-19	14.2	0.5
	Sweden ⁷¹	21	14.5	1.4**	Diving	US ⁴⁹	160	8-18	13.6	1.1
	UK ^{72 73}	65	14.5	1.5**						
Swimming	UK ^{72 73}	57	13.3	1.4**	Swimming	US ⁷⁷	268	10-18	13.1	1.1
	Sweden ⁷⁴	29	12.9	1.1**		US ⁷⁷	85	8-17	12.7	1.1
	Switzerland ⁶⁹	15	12.9	0.9**	Athletics	Hungary ⁷⁸	256	10-17	12.6	
Tennis	UK ^{72 73}	75	13.3	1.4**		Hungary ³⁵	288	10-18	13.1	1.1
Rowing	Poland ⁵⁸	13	13.2	0.8		Poland ⁷⁹	173	11-15	13.1	1.1
Athletics	Poland ⁵⁸	9	13.3	0.7	Soccer	US ⁸⁰	82	10-18	12.9	1.1
Several	Poland ⁶¹	13	13.3	1.0	Team sports	Hungary ⁷⁸	157	10-17	12.7	

*One study dates to the 1960s; all others date to the 1980s and 1990s.

**Several athletes in each sample had not attained menarche when the study was completed. Recalled ages at menarche in subsamples of the athletes in the UK study eight years after the conclusion of the original study were as follows: gymnasts, 14.5±1.5 yrs, swimmers, 13.8±1.8 yrs, and tennis players, 13.0±2.1 yrs.[73]

***The late age for gymnasts at the 1987 World Championship is biased. The CA cut-off was 13 years so that younger athletes were lacking in derivation of the estimated median age.

suggested that declines in ages at menarche **over time** were due to reductions at the 90th percentiles rather than in medians and 10th percentiles.[86] Similar trends were apparent in Japan where secular changes in heights and estimated ages at PHV and menarche were marked after WW II, but have leveled since the 1990s.[3]

Allowing for selectivity, changes in sport demands, and relatively limited data, it is reasonable to assume that secular changes in maturity status and timing of youth athletes are negligible. Based on data from the 1960s through the past decade, mean heights of youth soccer players[89] and track and field athletes by discipline[35] indicated considerable overlap across time. Changing emphases in some sports are most apparent in artistic gymnastics where CA limits and performance requirements (level of difficulty) have changed over time.[90]

IMPLICATIONS FOR THE DEVELOPMENT OF YOUTH ATHLETES

Maturity-Associated Gradients

Sports are selective.[91, 92] Selection/exclusion in many sports follows a maturity-related gradient largely during the interval of puberty and growth spurt. Numbers of late maturing males (SA, pubertal status) in several team sports, swimming and athletics decrease between 11-12 and 15-16 years of age with a corresponding increase in numbers of average, early and mature youth. The trends reflect both selective inclusion/exclusion and voluntary cessation, and are particularly noticeable in sports that demand speed, strength, and power, and at more elite levels. In contrast, preference for later maturing boys in artistic gymnasts and distance runs in athletics is also suggested.[14, 35, 36]

Some late maturing boys do reach elite levels if they persist in and/or are retained by a sport. This relates to a combination of factors related to catch-up in growth and maturation, motivation, and systematic efforts to nurture, perhaps to protect, skilled late maturing athletes

during adolescence. It has been suggested that late maturing boys within a CA group may have more athletic potential as young adults due to challenges experienced during adolescence.[93] To remain competitive with peers, the late maturing boy compensates for physical disadvantages by developing superior technical and strategic skills, and/or a more adaptive, resilient psychological profile. Evidence supporting this contention is limited.

Though limited to small numbers, differential success of late maturing adolescent players among young adult players in elite European soccer clubs has been proposed.[94] Except for skeletal maturity status, no information on the adolescent characteristics of the players was reported. In contrast, elite soccer players who signed and did not sign professional contracts did not differ in skeletal maturity and functional characteristics during adolescence, though those who signed contracts were taller.[95]

A maturity-related gradient among female athletes is most apparent in artistic gymnastics which favors later maturing girls. This is consistent in all data – SA, pubertal status, and ages at PHV and menarche.[36] A similar gradient is suggested for figure skating, diving and distance runs in athletics, though data are limited to menarche. Maturity data for female athletes in other sports are generally equivocal, although the physical and functional characteristics associated with advanced maturation (greater stature, absolute strength) may afford an advantage in elite swimming[14] and tennis[96] where girls advanced in SA were well-represented among participants 10-14 years. Retrospective ages at menarche suggested selective preference for average and later maturing women athletes.[3, 81] Allowing for variation within and among sports, it appears that early maturing girls are less represented among late adolescent/young adult female athletes.

Correlates of Maturity-Associated Variation

Maturity-related gradients are most apparent during the pubertal transition from early through mid-adolescence when contrasts among youth at the extremes of the maturity continuum become most apparent. As adolescence progresses, especially between 13 and 15 years, boys advanced in maturity status have an advantage in size, strength and power compared to average and later maturing peers. Between 16 and 18 years, however, maturity-related differences are reduced and largely eliminated in both non-athletes and athletes,[3, 90] though data for athletes are limited and are variable. For example, late maturing soccer players 11-14 years performed better in aerobic tasks (intermittent shuttle runs),[43] while players of contrasting maturity status did not differ in sport-specific skills.[43, 97] However, the most skilled players based on a composite score performed better in an aerobic shuttle run.[98]

Maturity-related trends in size for girls are consistent with those in boys, but differences in functional capacities are less apparent. Limited data suggest that late maturing girls perform better than early maturing girls in some tasks, but overall maturity-associated variation is not consistent from task to task and across age.[3] Girls of contrasting maturity status also do not differ, on average, in size and strength in late adolescence.[3] Data for female youth athletes of contrasting maturity status are lacking. Among girls 13-15 years in a sports school, those advanced in maturity status were, on average, taller, heavier and stronger (grip strength), while those later in maturation performed better in the standing long jump; the two groups did not differ in a 2 kg ball throw and sprint.[79] Contrasting maturity groups (recalled ages at menarche) of late adolescent/young adult elite university athletes in seven sports (18.7 ± 0.5 yrs) did not differ in height and weight (Malina, unpublished).

There is a need to consider potential behavioral correlates that may influence the maturity-related gradients. Interactions between biological maturation and behavior among

adolescents have long been a topic of interest,[99] but have received limited attention in the context of sport. Potential behavioral factors associated with inter-individual differences in maturity status/timing may influence selection, exclusion and/or persistence in sport. Influences of biological maturation on behavior can be both direct and indirect. Direct effects represent direct impacts of biological changes upon behavior, whereas indirect effects reflect individual perceptions and beliefs related to biological changes and/or the interpretations and evaluations of significant others.[100]

Selectivity and Talent Development Models

Although labels and age ranges vary among proposed models, many distinguish between early and late entry sports. The former emphasize intensive sport-specific training in late childhood and transition into puberty. Focus on skills in early entry sports (artistic gymnastics, figure skating, diving) reinforces the notion that childhood (pre-puberty) is an interval for emphasis on movement proficiency. Otherwise, models generally emphasize a changing balance between general and sport specific training during the pubertal years.[2, 101-103] The models implicitly view the adolescent years as a “window of opportunity” for selection and sport-specific training, and imply enhanced trainability. A “trigger hypothesis” has been proposed for increased sensitivity of the muscular and cardiovascular systems to training associated with pubertal hormonal alterations during adolescence,[104] whereas the LTAD model specifically indicated the interval of PHV as the reference for programming training protocols.[2]

Emphasis on pubertal hormones, especially growth hormone and sex steroids, and timing of PHV in enhanced trainability suggests a “maturation threshold”.[105] A critical review of evidence addressing youth responses to aerobic-, strength- and speed-specific training, however, was not consistent with such a threshold,[105] while evidence supporting underlying principles

of the LTAD model was also lacking.[106] Given focus on age at PHV, limitations of predicted ages with youth athletes and potential for misclassification must be recognized.,[21, 22]

Differential timing of adolescent spurts of other body dimensions and functional capacities presents an additional concern in the models. Allowing for methodological variation among studies, growth spurts in lower body dimensions occur, on average, before PHV, while spurts in body weight, lean tissue mass, bone mineral content, and upper body dimensions occur after PHV in both sexes.[3, 107-109] Variation in timing of spurts is evident in functional capacities but data are less extensive. Data for speed and flexibility suggested peak gains before PHV in boys,[107] while tests of strength and power attained peak gains after PHV [3, 107, 110] and peak velocity in maximal aerobic capacity (VO_2 max) occurred coincident with PHV in both sexes.[111, 112]

The preceding are based on means; intra-individual variation needs attention. Performances in several motor tasks declined temporarily during the interval of PHV in some but not all boys, but boys who declined in performance were generally good performers at the beginning of the interval of PHV.[110] Although means ages at peak velocity for height and VO_2 max were similar, peak gains in the latter occurred after PHV in the majority of individual boys but were evenly distributed before and after PHV among individual girls.[112] Though limited, the results highlight intra-individual variability in the timing of adolescent spurts functional capacities.

Corresponding data for youth athletes are limited. Peak ages for PWC 170 occurred, on average, by about one year after PHV among female non-athletes and participants in rowing and athletics, but occurred about 0.5 year before PHV in male non-athletes and participants in athletics and about 0.5 year after PHV in male rowers.[58] Estimated peak gains in speed, power,

strength, and muscular and aerobic endurance occurred, on average, at PHV in male soccer players, but estimated gains maintained a plateau after PHV for several capacities.[54]

Most studies of youth athletes have focused on characteristics related to growth, maturation, functional capacities and technical skills, though data vary by sport. Given the reduction in maturity-associated variation in size, strength and power among athletes in late adolescence, particularly boys, there is a need to consider other characteristics of youth athletes. For example, **tactical skills related to positioning and decision making played an important role in selection and exclusion among elite late adolescent players** .[113, 114]

Training, Growth and Maturation

Intensive training for sport is often indicated in the short stature and late maturation of artistic gymnasts, specifically females, and later menarche of athletes in other sports. The evidence is descriptive and correlational. Moreover, hours/years are limited indicators of training intensity.[36] Allowing for normal variability, training does affect pubertal growth and maturation of gymnasts[36] and age at menarche in athletes,[5] and is not a factor affecting growth in height in children and adolescents.[115] Studies of athletes have not systematically considered many factors known to influence growth and maturation – familial correlation, family size, status at birth/early growth, household environment, diet, **and perhaps** others.[3, 36, 82, 116, 117]

Athlete Development: A Dynamic Process

Talent development from novice to elite is superimposed upon a constantly changing base – physical growth, biological maturation and behavioral development. These processes occur simultaneously and interact with each and with the demands of sport.

Sport does not occur in a social vacuum. The body and skills of a young athlete hold important social stimulus value which impacts perceptions and evaluations, and the nature and quality of interactions with peers, parents and adults involved with sport. Boys who are perceived as physically suited for a sport generally experience greater success; are identified at an earlier age, are given more important roles; receive more playing time, encouragement and resources; and more likely have access to elite coaches. The opposite may occur in artistic gymnasts. Taller and heavier high school female gymnasts (relative to sport peers) perceived their coaches as less reinforcing, encouraging and instructive, and as more likely to ignore mistakes and engage in punitive behaviors irrespective of ability.[118] Performance scores of participants in the 1987 artistic gymnastics World Championship were higher for pre- than post-menarcheal gymnasts within CA groups 14-16 years,[51] and had moderate negative relationships with subcutaneous fatness and endomorphy.[119] The latter is interesting as elite gymnasts are typically quite lean.

In contrast to select athletes, **relatively little is known about the physical, behavioral and performance characteristics of youth** who voluntarily withdraw or who are systematically excluded from a sport.[36, 120] Detailed study of these youth may serve to inform the process of athlete development and retention, progression in a sport, and the re-orientation of excluded skilled athletes to other sports where they may attain success.

There is a need to extend research on youth athlete development to the “cultures” of specific sports. “Sport culture” includes philosophy of athlete development; sport structure – administrators, coaches, trainers, and other adults; interactions between the structure and athletes; coaching styles, practices and demands; parental involvement and expectations; relationships between athletes and parents, family and peers; an increasingly common view of

youth athletes as commodities; an intrusive national and international spotlight; **and perhaps** other factors.

It is imperative to accept youth athletes as children and adolescents with the needs of children and adolescents! **Sport is superimposed upon these needs.**

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