J. Endocrinol. Invest. *24:* 708-715, 2001

REVIEW ARTICLE

Consequences of sport training during puberty

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ABSTRACT. Growth at puberty depends on one's genetic potential, nutritional status and a series of hormones. Energy expenditure may modify the effects of these three factors on the linear growth rate and the relative proportions of fat-free and fat mass. Participation in sports where weight control is not required does not seem to affect pubertal timing or alter linear growth rate. The growth and maturation of athletes in weight control sports have the additional burden of energy output greater than intake; however, in only a minority the energy deficit is great enough to slow growth and maturation. Studies focusing on male wrestlers and female gymnasts are reviewed. In the wrestlers the hormonal picture is consistent with mild-to-moderate GH resistance and perhaps mild maturational delay, especially in the lower weight classes. The deficits in lean body mass and fat mass "catch-up" quickly following the end of training and competitive season. The situation with the gymnasts is somewhat different, the goal being to develop muscular strength within a shorter and lighter physique. Marked under-nutrition can keep these adolescents pre-pubertal for many years of training and competition. Whether subsequent growth is disproportionate or not remains indeterminate, but the marked delay in the onset of estrogen action can permanently cause the skeleton to be under-mineralized. In conclusion, most athletes continue to track along the centiles of their genetic potential. To define the mechanisms of growth and maturational delay one must longitudinally study children in weight-control sports.

(J. Endocrinol. Invest. *24:* 708-715, 2001)

INTRODUCTION

Metabolic fuel availability modifies the timing and *tempo* of pubertal maturation and growth. Over-nutrition reduces the age of onset of pubertal maturation and accelerates growth (1, 2), while under-nutrition delays these linked processes (3, 4). The current review will apply this physiological framework to the combination of high energy expenditures and limited nutritional intake of some athletes and how under-nutrition may lead to delayed adolescence and slowed growth. The influence of moderate-to-vigorous physical activity and sport training in the absence of energy restriction on the timing and *tempo* of puberty has been previously reviewed and the data quite clearly show few effects on growth or maturation (5, 6).

GROWTH AND MATURATION

Growth and sexual maturation are controlled, in large part, by the GH, IGF-I and hypothalamic-pituitary-gonadal (HPG) axes. GH is the primary hormone responsible for somatic growth, having, in addition, potent actions on protein, carbohydrate and lipid metabolism. Many of the effects of GH, including long bone growth, are mediated through IGF-I, which is locally synthesized by target tissues or by the liver, the predominant source of circulating IGF-I (7).

Pre-pubertally, resting GH secretion is modulated primarily through two hypothalamic hormones, GHRH and somatostatin (8). From infancy to childhood genetic determinants and environmental influences, such as nutrition or chronic disease influence GH-IGF-I axis function, thereby affecting the growth potential. Serum IGF-I concentrations may

Key-words: Sport training, puberty, gymnasts, wrestlers, growth, body composition, nutrition, exercise, hormones.

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Accepted April 6, 2001.

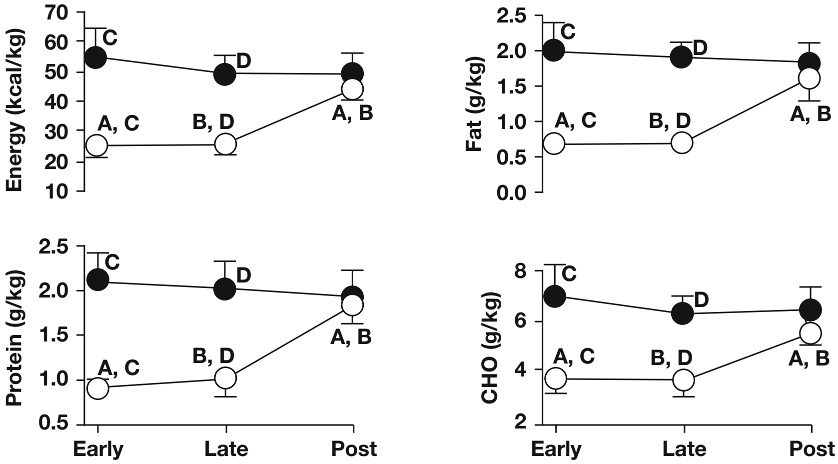

Fig. 1 - *Relative intake of energy (kcal/kg/day), protein (g/kg/day), fat (g/kg/day), and carbohydrate (CHO, g/kg/day) for wrestler (○, no.=9) and control (●, no.=7) groups. All subjects were tested in mid-November, one-to-two weeks prior to the first wrestling match (early), 3.5-to-4 months later (late) depending on when the wrestlers no longer qualified for tournament competition, and 3.5-to-4 months after the wrestling season ended (post). Like letters are significantly different. Values expressed as mean (±SE). Modified from (28), with permission.*

decline with poor nutrition or chronic illness opening up the negative feedback loop to increase GH release. The net result is relative GH resistance.

At the onset of puberty, a marked acceleration in growth velocity results from a complex network of interactions between the GH-IGF-I and HPG axes. Total GH secretion increases 2-to-3-fold controlled by rising estrogen concentrations, even in the male (9-11). Increases in serum IGF-I concentrations parallel the augmented GH secretion. Thus, at low concentrations, sex steroids act synergistically with GH to mediate skeletal growth. At greater concentrations, sex steroids, especially estrogen, induce epiphyseal fusion in boys and girls (12, 13).

NUTRITION MODIFIES GROWTH AND PUBERTAL TIMING

Pubertal timing and *tempo* are integrated through genetic, nutritional, and environmental cues (14), and are more a function of metabolic fuel availability than chronological age. For instance, age at menarche declined from the mid-1800 to mid-1900 in developed nations even though the body weight at menarche remained stable (14). The signals that reawaken the HPG axis at the onset of puberty and keep it operative during puberty remain unclear. The hormone leptin, secreted primarily from adipocytes in direct relation to lipid content (15), acts as a nutritional signal to the reproductive centers of the brain (14, 16-18) including GnRH neurons of the mouse (19). Release of GnRH is necessary for pubertal onset and proper leptin signaling may be necessary for adeguate GnRH release. Mutations in the leptin protein or leptin receptor genes (20-23) prevent pubertal maturation in humans. However, leptin does not act as the sole trigger of puberty, but rather as one of several metabolic signals necessary for pubertal onset and progression (14, 16, 18). For instance, Wade *et al.* (24), have established the importance of metabolic fuel availability, especially glucose, for maintaining reproductive function. Serum IGF-I concentrations decrease with undernutrition and may modulate pubertal onset. Serum IGF-I levels increase before puberty in primates (25) and central IGF-I infusions accelerate pubertal onset in rats (26).

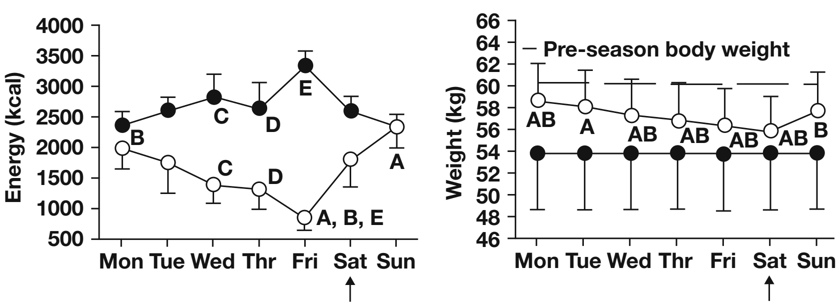

Fig. 2 - *Daily energy intake (kcal/day) and body weight (kg) for the wrestler (○, no.=9) and control (●, no.=7) groups during one week with a weight certification for the wrestlers on Saturday. Like letters are significantly different. Values expressed as mean (±SE). Modified from (28), with permission.*

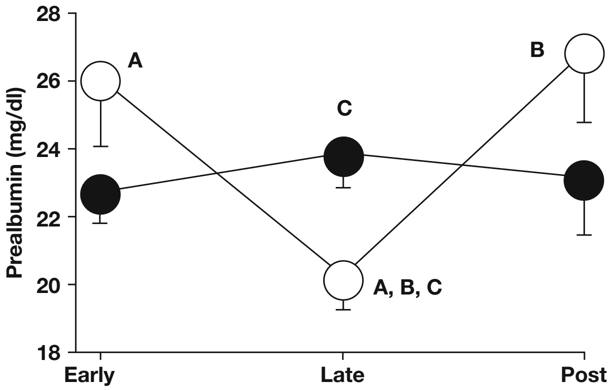

Fig. 3 - *Serum prealbumin concentration (mg/dl) for the wrestler (○, no.=9) and control (●, no.=7) groups. Like letters are significantly different. Values expressed as mean (±SE). For definitions see Figure 1. Modified from (28), with permission.*

GROWTH AND MATURATION OF ATHLETES IN WEIGHT CONTROL SPORTS

Participation in sports where weight control is not required does not appear to delay pubertal timing or alter growth. Youth who participate in these sport are normal or slightly advanced in their rates of growth and maturation (5). Greater body size and pubertal maturation are probably self-selected because the strength and power advantages associated with earlier maturation are major factors attracting children to sport and for their success at sport (5).

Although all athletes participating in weight control sports such as wrestling, gymnastics, distance running, and dance are at risk for energy drain and limited metabolic fuel availability, only a small number actually experience a combination of high energy expenditure and restricted energy intake great enough to slow growth and maturation. The remainder of this review will focus on the growth and maturation of two of these athletic groups: male wrestlers and female gymnasts.

Male wrestlers

Wrestlers compete in weight classes and must weigh-in before each competition to certify that their body weight is less than the upper limit of the weight class. Wrestlers reduce their body weight through a combination of exercise and dietary restriction to compete in a lower weight class in the hope of gaining a competitive advantage against a younger, less experienced opponent. The typical wrestler practices 2 h to 2.5 h/day, 5 to 6 days/week and, after correction for the basal metabolic rate, expends about 800 kcals per practice (27). Despite great energy expenditures, Roemmich *et al*. (28) found that wrestlers had nutrient intakes 50% below recommended amounts (Fig. 1). Moreover, when the energy intake and body weight were monitored one week before a competition, on no day did the wrestlers consume adequate energy to meet the combined requirements of resting metabolism, sport training, and growth (Fig. 2). When repeated each week of a 12-to-16 week sport season, a chronic period of under-nutrition occurs as confirmed by reductions in protein nutritional status (Fig. 3) (28-30).

The under-nutrition of adolescent wrestlers may lead to alterations in the HPG and GH-IGF-I axes, which, as described above, control the rate of growth and pubertal maturation. Roemmich *et al*. (31) found that at the end of a sport season, wrestlers had low testosterone and free-testosterone concentrations while their serum LH concentrations remained unchanged (Fig. 4) suggesting a central disruption of

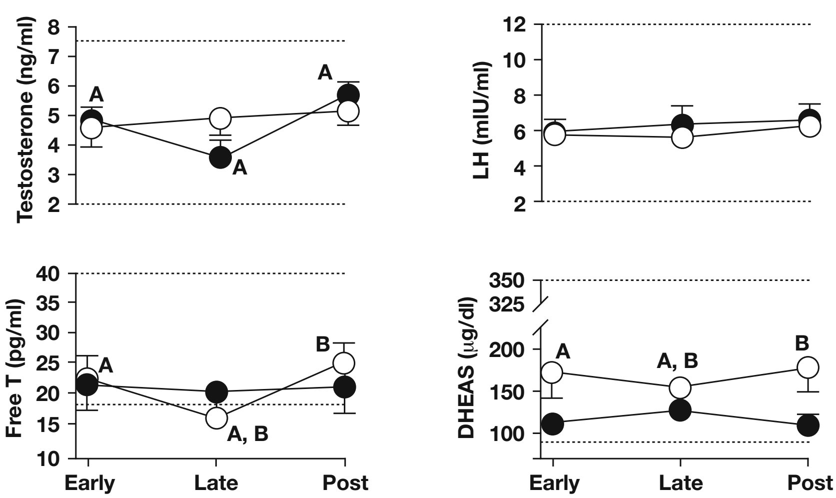

Fig. 4 - *Mean (±SE) concentrations of testosterone, free testosterone, LH, and DHEAS in the wrestler (○, no.=9) and control (●, no.=7) groups during the early and late portions of the wrestling season and during the post-season. Like letters are significantly different (p<0.05). Serum hormone concentrations are the mean of 8 samples drawn every 20 minutes. Like letters indicate p≤0.05. Dashed lines indicate upper and lower normal range for each hormone concentration. For definitions see Figure1. Modified from (28), with permission.*

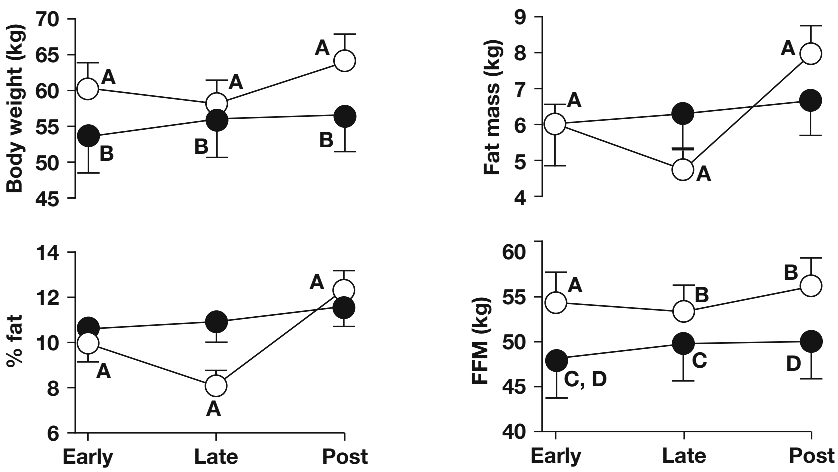

Fig. 5 - *Body weight, percentage of body fat, fat mass, and fat-free mass (FFM) for the wrestler (○, no.=9) and control (●, no.=7) groups. Like letters are significantly different. Values expressed as mean (±SE). For definitions see Figure 1.*

the HPG axis. Similar data have also been reported for collegiate wrestlers (32). Reduced serum testosterone concentrations would reduce protein accrual and the wrestlers had slowed growth in fat-free mass (Fig. 5) as well as mid-arm and mid-thigh muscle plus bone cross-sectional areas, two anthropometric measures of lean tissue accrual (28-30).

GH-IGF-I axis function was also disrupted during the wrestling season (Fig. 6). A partial GH resistance was indicated by late-season elevations in the wrestlers' serum GH concentrations while their serum IGF-I concentrations were reduced due to an opening of the IGF-I-mediated feedback inhibition of GH release. Decreases in serum growth hormone-binding protein (GHBP) concentration may have also modulated serum GH concentrations. GHBP enhances the growth promoting effects of GH and GH secretion is modified to account for the GHBP concentration to ensure genetically determined growth continues (33). When GHBP concentrations are reduced, more GH is released to continue growth at its genetically determined rate. Reductions in GHBP concentrations may also signify a down-regulation of GH receptors, since GHBP is an index of GH tissue receptor number (34). Down-regulation would result in GH resistance and reduced growth, so that even with increased GH concentrations, growth will be slowed to conserve energy for critical body functions.

What effect do these hormonal alterations have on the growth and maturation of wrestlers? Generally, wrestlers are shorter than the average for their age but this is probably due to self-selection (5). For instance, a cross-sectional study (35) found that a reference group of boys was taller (1.9%) than a large group of wrestlers after the age of 16.4 years, but that the slope values for gain in height did not differ. However, these data do not address whether

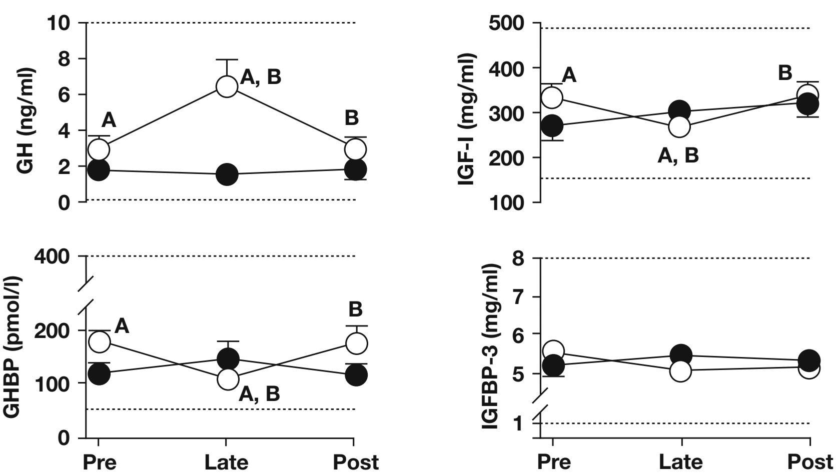

Fig. 6 - *Mean (±SE) concentrations of GH, IGF-I, GH-binding protein (GHBP), and IGFBP-3 in the wrestler (○, no.=9) and control (●, no.=7) groups during the early and late portions of the wrestling season and during the post-season. Like letters are significantly different (p<0.05). Serum hormone concentrations are the mean of 8 samples drawn every 20 minutes. Like letters indicate p≤0.05. Dashed lines indicate upper and lower normal range for each hormone concentration. For definition see Figure 1. Modified from (28), with permission.*

linear growth is slowed during the sport season or if there is catch-up growth during the off-season. In a series of longitudinal studies, Roemmich *et al.* (28, 30) have shown that the incremental growth in stature and rate of skeletal maturation of wrestlers is similar to that of controls during both the sport season and post-season (Fig. 7). However, growth of fat-free mass and other soft tissues are slowed during the sport season followed by catch-up growth in the post-season (Fig. 6) (28, 29, 36).

Female gymnasts

Gymnasts gain a competitive advantage if they are able to develop muscular strength within a shorter and lighter frame. The performance of female gymnasts often decreases after the onset of puberty due to increases in height and fat mass and development of the secondary sexual characteristics. Gymnasts, then, often utilize exercise and dieting to maintain a lean physique in the hope of maximizing their strength/ weight ratio, for esthetics, and to delay puberty and growth. A controversial longitudinal study found that female gymnasts training 18 h/week had a delayed age at menarche, slowed linear growth, and reduced growth potential (37). Height standard deviation scores and predicted adult height (Fig. 8) continued to decrease and the gymnasts failed to have a pubertal growth spurt (Fig. 9). Leg length velocity slowed at puberty with almost no growth after a bone age of 12 years (Fig. 10). Growth reduction was speculated to be due to a reduction in sex steroids and IGF-I production, but that enough estrogens were released to fuse the growth plates of the lower limbs. Although additional longitudinal studies have not yet replicated these results, others have observed reduced serum IGF-I concentrations in gymnasts (38, 39) and relatively short lower limbs of female (36) and male (40) gymnasts. Similar to wrestlers, the growth and maturation of gymnasts may be explained by self-selection, as gymnasts tend to be the children of short parents who also had later than average puberty (41) and shorter limb lengths are present at baseline and do not worsen with training (36).

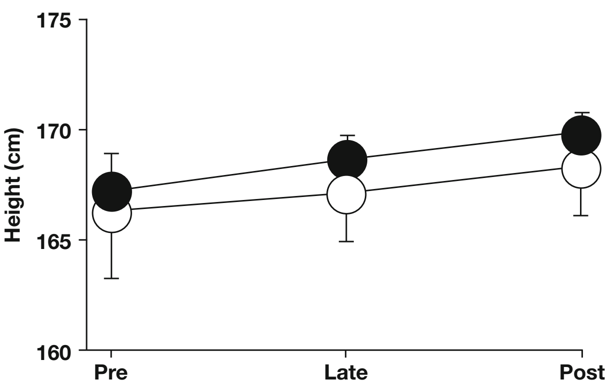

Fig. 7 - *Height for the wrestler (○, no.=9) and control (●, no.=7) groups. Like letters are significantly different. Values expressed as mean (±SE). For definitions see Figure 1.*

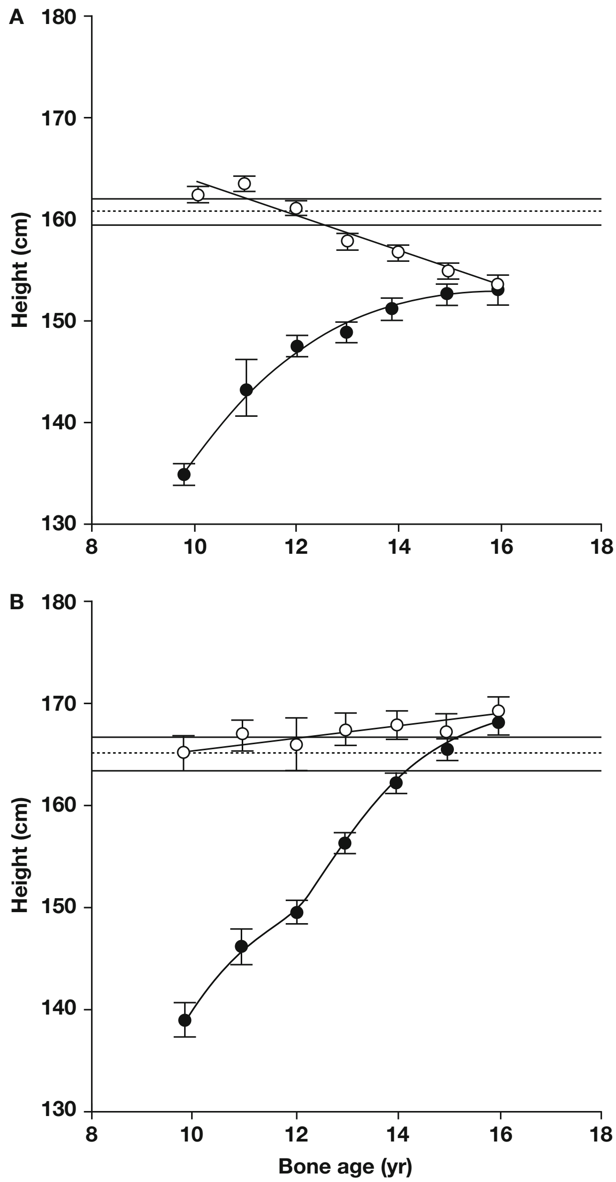

Fig. 8 - *Predicted and measured height plotted against bone age in female gymnasts (A) and female swimmers (B). Target height is represented by area within solid horizontal lines centered by dashed line. The gymnasts had a significant drop (p<0.001) in height predictions. From (37), with permission.*

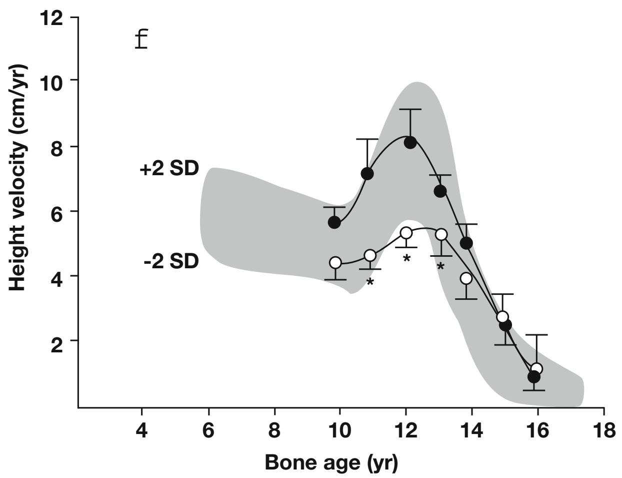

Fig. 9 - *Height growth velocity in gymnasts (○) and swimmers (●). Growth velocity was lower for the gymnasts at bone ages of 11, 12, and 13 years as indicated by the asterisks. The gray stippled area represents the normal (±2 SD) growth velocity as a function of chronological age for normal French children. From (37), with permission.*

CONCLUSIONS

Training for most athletes is not detrimental to normal growth nor pubertal development. Normal linear growth encompasses the 3rd to 97th percentile for height and height velocity. If an athlete's growth continues to track along the same percentile as before initiating training, there is little cause for concern. Individual differences in the timing of puberty may cause some athletes to temporarily change the percentile at which they track. Athletes who enter puberty earlier than average will have an increased height percentile while those who enter puberty later than average will have a decrease in height percentile. The average height for participants in some sports may be less than the 50th percentile, but this is probably due to self-selection rather than sport training. For example, boys and girls who participated in gymnastics as children and became relatively tall may participate in basketball or volleyball during adolescence because greater height can be a disadvantage in gymnastics but beneficial in other sports. Likewise, boys and girls with genetically determined delayed puberty and/or short stature would migrate towards gymnastics and wrestling because they will be at a disadvantage in some sports, but at a competitive (mechanical) advantage in gymnastics and wrestling. This situation is especially prevalent in the lighter weight classes of wrestling where boys with later maturity are recruited by coaches to participate because the weight classes often go unfilled or are filled by younger athletes because so few boys of the expected age are light enough to compete. When wrestlers lose weight to fill empty weight classes or to gain a competitive advantage or gymnasts try to delay puberty and growth through dietary restriction, under-nutrition occurs. Under-nutrition caused by wrestling training and dietary restriction appears to produce a disruption of the pituitary-testicular axis and a partial GH resistance. The effect of sport training and dietary restriction on the neuroendocrine axes of gymnasts has not been adequately studied. Wrestling training has little effect

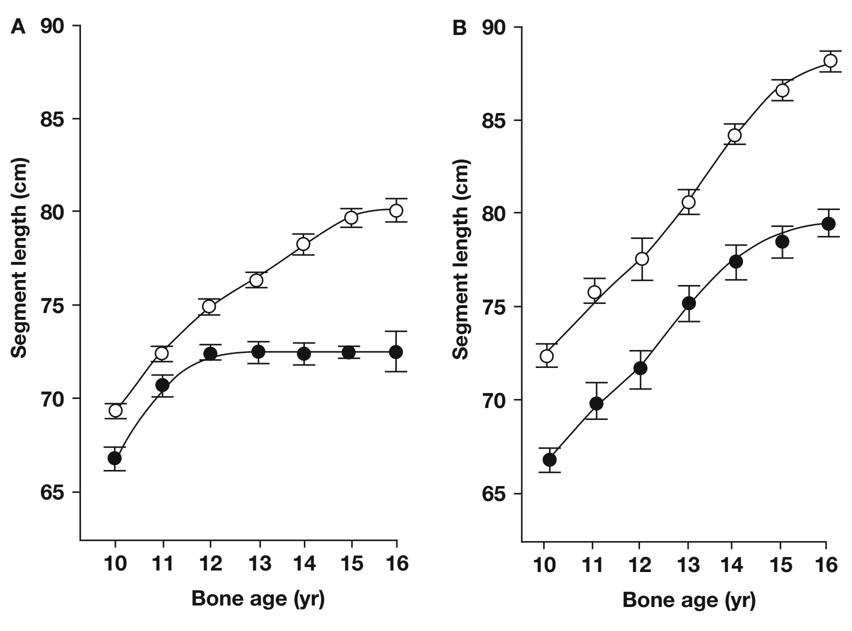

Fig. 10 - *Growth in sitting height (○) and leg length (●) from bone age of 10 years to bone age of 16 years. Gymnasts are shown in panel A and swimmers in panel B. Note the lack of increase in leg length after bone age of 12 years in the gymnasts. From (37), with permission.*

on linear bone growth or pubertal maturation. For wrestlers, the 3- to-4 month period of under-nutrition is followed by long periods of adequate nutrition such that the period of under-nourishment may not be long enough to slow growth or maturation or reduce the final height of wrestlers. Female gymnasts who are chronically training and limiting their dietary intake may be at greater risk for limiting their growth. Gymnastics training may slow growth of the lower limbs but more data are needed to confirm this result. The shorter limb lengths of gymnasts may be self-selected as gymnasts have shorter limb lengths when beginning training and the limb length discrepancy does not increase with training. Longitudinal research studies of athletes involved in wrestling, gymnastics, and other weight control sports must include appropriate control groups and move beyond descriptional research to determine the independent and interactive effects of sport training, nutritional, and hormones on their growth and maturation.

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