Gender-related differences in elite gymnasts: the female athlete triad

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Weimann, Edda. Gender-related differences in elite gymnasts: the female athlete triad. J Appl Physiol 92: 2146–2152, 2002; 10.1152/japplphysiol.00572.2001.—High-intensity training can alter the normal pattern of pubertal development in elite gymnasts. We investigated sex hormones, the ob gene product leptin, body composition, nutrition, and eating habits in female and male elite gymnasts from national cadres to elucidate gender-related differences. Serum leptin levels were decreased, particularly in pubertal girls, and did not show the normal developmental pattern. After leptin levels were transformed into standard deviation scores, mainly pubertal female gymnasts had significantly lower values than normal controls of the same gender, pubertal stage, and body mass index. The percentage of body fat was reduced compared with a normal age-matched population in both genders but to a higher degree in female gymnasts. When leptin standard deviation scores were based on percent body fat instead of body mass index, mean values were still significantly decreased compared with those of normal controls: −1.05 in girls (P < 0.001) and −0.60 in boys (P = 0.025). In both genders, total energy consumption and nutritional intake were insufficient, although to a lesser extent in male gymnasts. Pubertal development is influenced to a different degree in female and male elite gymnasts. In contrast to their male counterparts, high-intensity training takes place during the sensitive phase of pubertal maturation in female gymnasts. Whereas the girls displayed low estrogen levels, hypo leptinemia, reduced body fat mass, insufficient caloric intake, and retarded menarche, the pubertal development of male gymnasts remained almost unaltered.

growth velocity and a marked stunting of leg-length growth, and they fail to reach full familial height (43).

Even metabolism differs between female and male top athletes. Because of higher estrogen concentrations, the oxidation of amino acids and carbohydrate is lower during endurance training in girls, whereas there is a higher proportion of lipid oxidation (41). In ultra-endurance exercise, such as the Ironman triathlon, estradiol (EE) was 58% increased and testosterone was 58% decreased in men postrace, whereas no significant changes were noted for these hormones in women (20).

Practitioners of sport disciplines in which a thin body is required for better performance are at risk for developing the female athletic triad that is characterized by cycle abnormalities, eating disorders, and premature osteoporosis (37, 47). Various factors may cause the known disturbances of pubertal and physical development in athletes. High levels of physical activity result in increased secretion of endorphins (15), which, in combination with caloric undernutrition (28, 46), causes an abnormal regulation of the hypothalamus (3). This dysregulation decelerates the pulse frequency of gonadotropin secretion. The subsequent decrease in follicle-stimulating hormone (FSH) and luteinizing hormone (LH) levels (13, 45, 46) is likely to alter pubertal maturation. Furthermore, low estrogen levels and insufficient protein and calcium intake, combined with late menarche, potentially lead to an increased incidence of spontaneous stress fractures, scoliosis (48), and the development of premature osteoporosis (35).

The ob gene product leptin that is secreted by adipocytes is supposed to be involved in the regulation of energy intake and energy expenditure (9). It inhibits the synthesis of the appetite-stimulating neuropeptide Y (NPY) after binding to a specific receptor on NPY-producing neurons in the hypothalamus (40). Clinical studies have demonstrated that serum leptin reflects body fat mass (FM) in normal-weight and obese adults (12). This constitutive regulation of leptin synthesis is modulated by a number of nonhormonal and hormonal variables that superimpose a short-term (several hours

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to 1 day) regulation (5). Leptin levels increase with food intake and decrease during periods of starvation (24, 30). Apart from its effects on energy homeostasis, leptin also has a profound influence on the secretion of pituitary hormones. During starvation, low leptin levels influence the secretion of gonadotropins and, subsequently, sex steroids, possibly through a lack of suppression of NPY (1). Thus a decline in serum leptin exerts an overall suppressive effect on the reproductive axis, which can be restored by exogenous leptin administration in rodents (10, 21). These experimental findings are consistent with clinical observations. In anorexia nervosa, amenorrhea is a typical feature, and there is evidence that this disturbance is related to the very low leptin levels in this clinical condition (33).

Leptin is postulated to be the link among fat stores, pubertal development, and LH-releasing hormone (LHRH) secretion. There is evidence that in humans a rise in leptin can serve as a permissive signal for the onset of puberty (31). The regulation and variation of LH-secretion is closely associated with the presence of sex steroids, possibly through a lack of suppression of NPY (1). Thus a decline in serum leptin levels influence the secretion of gonadotropins and, subsequently, sex steroids, possibly through a lack of suppression of NPY (1). The regulation and variation of LH-secretion is closely associated with sex steroids, possibly through a lack of suppression of NPY (1).

We want to test whether there is a link among energy stores, leptin levels, and the pattern of pubertal development that can lead to gender-related differences in the pubertal and physical development of elite gymnasts.

SUBJECTS AND METHODS

Subjects. All German elite gymnasts training in national cadres gather and train on a regular basis at the Olympic Training Centre in Frankfurt/Main. During one common workout, the participating gymnasts (22 girls: 13.6 ± 1.0 yr, and 18 boys: 12.4 ± 1.6 yr) were enrolled in this study. Informed consent was obtained from both gymnasts and parents. The physical training load (number of hours per week) and the age at the start of the intensive training regime were recorded.

Assessments. Body mass index (BMI) was calculated as weight (kg)/height² (m). Body height of gymnasts was measured with a stadiometer (Seneca). Pubertal clinical staging was ascertained with a standard staging protocol (22).

Diagnostics), testosterone (RIA, Biodata Diagnostics), and insulin-like growth factor I (IGF-I, RIA, Nichols) were assayed to provide information about the gonadal and hypothalamic axes (7). In addition, the ratio of LH to FSH (LH/FSH) after 30 min was used to further grade the prepubertal (LH/FSH < 1) and pubertal (LH/FSH ≥ 1) stage (22).

Skinfold thickness and bioelectric impedance analysis (BIA) were used as indirect methods for the determination of body composition and to evaluate peripubertal changes in FM and fat-free mass (FFM). Triceps skinfold measurement was performed with a Holtain caliper; FM and FFM were calculated by using the Slaughter formula (39). Body composition by BIA was determined with the regression model of Schäfer et al. (38). The percentage of body fat (%BF) was calculated by the following equation: %BF = 100 × [weight − FFM]/weight.

To examine the nutritional status, caloric intake was recorded and assessed over 3 days, including 1 day without training, and analyzed by the computer program DIET 2000. Eating habits of female and male gymnasts were evaluated by a standardized interview.

Leptin RIA. Serum leptin levels were measured by a sensitive RIA by using recombinant human leptin (Mediagnost, Tübingen, Germany) for standards and tracer preparation (6). In brief, tracer was prepared with 2.5-μg leptin, as described in detail with the use of the chloramine T method (4). The radiolabeled tracer was further purified by exclusion chromatography on a 1.5 × 90 cm column of Sephadex G-50 (Pharmacia, Freiburg, Germany) and was stored at −20°C. Standards were prepared by geometrical dilutions of recombinant human leptin in assay buffer (0.05 mol/l sodium phosphate, pH 7.4, 0.1% (vol/vol) gelatine from teleost fish (Sigma Chemical, Munich, Germany), 0.1% (vol/vol) Triton X-100 (Serva, Heidelberg, Germany), 0.05% (wt/vol) NaCl between 12.5 and 0.049 μg/l. Serum samples were diluted 1:3 with assay buffer before measurement. Sensitivity with undiluted samples was 0.03 μg/l, corresponding to 0.003 ng per tube. The intra- and interassay coefficients of variation were 0.8 and 8.5%, respectively (n = 10). Excellent parallelism with the standard curve was obtained with serial dilutions of human sera. Spiking experiments with 0.1 ng per tube yielded a recovery of 97 ± 2.1%. Leptin levels were adjusted for gender, pubertal stage, and BMI by calculating leptin standard deviation scores (SDS) (BMI based) (6).

Statistics. Statistical analysis comparing the prepubertal and pubertal groups was performed with the Wilcoxon Mann–Whitney U-test; further analysis was done by using Spearman’s rank correlation test. Results are reported as means ± SD; P values < 0.05 were considered statistically significant. For comparison, leptin levels in a large cohort of healthy normal children and adolescents were used. To correct for gender, pubertal stage, and BMI, SDS (Z score) were calculated, applying the formulas given by Blum et al. (6). For calculation of leptin SDS referred to %BF, the following equations were derived from sufficiently large cohorts of healthy children and adolescents of corresponding age as the gymnasts, applying a similar approach as for SDS based on BMI (6): leptin(SDS) = [ln(leptin) – ln(0.8952) − 0.06877 × %BF]0.4892 for girls (n = 108) and leptin(SDS) = [ln(leptin) – ln(0.4836) − 0.07315 ÷ %BF]0.53849 for boys (n = 71).

RESULTS

Training intensity. Female gymnasts started an earlier age compared with male gymnasts and, therefore, had a longer history of high-impact training at the time of investigation (6.8 ± 1.3 vs. 3.9 ± 1.6 yr in boys). Also, they trained more hours per week than their male counterparts (22.1 ± 1.7 vs. 15.9 ± 5.0 h in boys). These differences, years of intensive training (P = 0.003), and number of training hours per week (P = 0.006) were statistically significant.
Table 1. Hormone levels in female and male elite gymnasts

<table>
<thead>
<tr>
<th></th>
<th>Prepubertal</th>
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<th>Prepubertal</th>
<th>Pubertal</th>
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</thead>
<tbody>
<tr>
<td><strong>Girls</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n</td>
<td>7</td>
<td>15</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>Estradiol, pg/ml</td>
<td>17.6 ± 4.2</td>
<td>23.9 ± 13.4</td>
<td>9.0 ± 3.7</td>
<td>14.0 ± 6.3</td>
</tr>
<tr>
<td>Testosterone, ng/dl</td>
<td>28.4 ± 5.4</td>
<td>36.3 ± 15.1</td>
<td>26.4 ± 8.1*</td>
<td>145.6 ± 135.8*</td>
</tr>
<tr>
<td>IGF-I, µg/l</td>
<td>347.8 ± 145.9</td>
<td>422.9 ± 171.4</td>
<td>197.2 ± 84.8*</td>
<td>338.1 ± 67.0*</td>
</tr>
<tr>
<td><strong>Boys</strong></td>
<td></td>
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<td></td>
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</tbody>
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Values are means ± SD scores (SDS); n, no. of subjects. IGF-I, insulin-like growth factor I. *Significant statistical difference between prepubertal and pubertal male gymnasts, P < 0.05.

Hormone levels. According to the LH/FSH in the LHRH test and Tanner stages, prepubertal and pubertal stages were classified (Table 1). A significant pubertal rise of EE levels indicating undisturbed sexual maturation did not occur in female gymnasts (17.6 ± 4.2 pg/ml prepubertal vs. 23.9 ± 13.4 pg/ml pubertal). In contrast, the male gymnasts mirrored their corresponding age-matched peers in that they showed a significant pubertal rise in testosterone levels (26.4 ± 8.1 to 145.6 ± 135.8 ng/dl), which were normal for age. IGF-I showed normal age-dependent serum levels, excluding severe growth hormone deficiency. LHRH testing exhibited normal hypophyseal stimulation in either gender, excluding the possibility of true secondary hypogonadism. Pubertal elevation of LH/FSH (LH/FSH ≥ 1) showed a delay of 2.3 yr in female gymnasts compared with nonathletic counterparts (14), whereas no pubertal delay was seen in male gymnasts.

Body composition. With the use of BIA and skinfold thickness to examine body composition indirectly, significant peripubertal changes in FM and FFM occurred (Table 2). BMI, FM, and FFM were significantly different in prepubertal and pubertal female gymnasts, whereas in boys only BMI and FFM were different. Body composition exhibited a dimorphic pattern during sexual maturation: in girls, there was a disproportionate increase in FM, whereas in boys FM increased in relation to body weight. The percentage of FM (%BF) by BIA was, on average, significantly higher in girls than in boys (14.4 vs. 10.4%, P < 0.05). In both genders, %BF was significantly lower than in normal (non-gymnasts) children and adolescents of the same age (6): 14.4 vs. 21.9% in girls (P < 0.01) and 10.4 vs. 15.2% in boys (P < 0.05). Whereas in female gymnasts the mean percentage of FM increased from 12.3 to 15.3% during pubertal development, the male gymnasts showed a decrease from 13.0 to 9.2%. The relatively higher increase in FFM during puberty was at least partially due to a more pronounced increase in muscle mass, as indicated by circumference measurements of the upper arm (22.9 cm in girls vs. 24.0 cm in boys).

Nutrition. As a heavy load of training takes place in elite gymnasts during the sensitive phase of pubertal growth and development, daily food intake was followed over 3 days and was examined on the basis of the national recommendations of the German Society for Nutrition. The percentage of the various consumed nutritional components was as follows: 54.9% carbohydrate, 13.5% protein, and 30.8% fat in girls, and 46.9% carbohydrate, 13.3% protein, and 36.2% fat in boys. Whereas in girls the proportion of the nutritional components was well compliant with the recommendations given by the German Society for Nutrition, the boys did not meet these guidelines. In both genders, total caloric intake was markedly insufficient, considering total energy expenditure during training, although less so in boys (female gymnasts: 1,418.4 ± 525.3 kcal/day vs. male gymnasts: 2,159.1 ± 42.4 kcal/day). This is reflected in the diminished %BF of gymnasts compared with the German age-matched population: 14.4 vs. 22% in girls and 10.4 vs. 20% in boys. Female gymnasts showed an average nutritional intake that was <50% for vitamin A, vitamin B complex, vitamin D, magnesium, calcium, and iodine, whereas male elite gymnasts showed a reported mean intake that was ≥50% less than the recommendation for vitamin A, vitamin D, iodine, and carbohydrates. In elite gymnasts, an increased utilization was observable for vitamin C, which was being consumed as a prophylactic anti-influenza supplementation.

Leptin levels. Mean leptin levels were 1.4 ± 0.9 and 0.7 ± 0.7 µg/l in girls and boys, respectively. Leptin levels in elite gymnasts did not follow the normal developmental pattern, with a steady increase in girls and a peak in boys of pubertal stage 2. Whereas leptin levels increased in female gymnasts with a peak at the pubertal stages of breast stage 2 and pubic hair stage 2, leptin levels slightly decreased in boys. In all gymnasts, leptin levels correlated with the amount of FM (r = 0.60, P = 0.005 in girls and r = 0.44, P = 0.038 in boys). Furthermore, in female but not in male gymnasts, leptin levels were significantly correlated with...
Table 3. Leptin levels in female gymnasts at various pubertal stages

<table>
<thead>
<tr>
<th>Tanner Stage</th>
<th>Prepubertal</th>
<th>Pubertal</th>
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<tr>
<td></td>
<td>&lt;1</td>
<td>≥1</td>
<td>≥1</td>
<td>≥1</td>
</tr>
<tr>
<td>Pubes</td>
<td>1.51 ± 0.59</td>
<td>1.72 ± 1.17</td>
<td>1.18 ± 0.5</td>
<td>1.15 ± 1.07</td>
</tr>
<tr>
<td>Breast</td>
<td>1.31 ± 0.45</td>
<td>2.02 ± 1.23</td>
<td>1.24 ± 0.65</td>
<td>1.15 ± 1.07</td>
</tr>
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Values are means ± SDS in μg/l. LH, luteinizing hormone; FSH, follicle-stimulating hormone.

BMI ($r = 0.33, P = 0.049$). Leptin was significantly inversely correlated with IGF-I ($r = -0.47, P = 0.027$) in boys but not in girls. Leptin did not correlate further with any other parameter examined. The results are summarized in Tables 3 and 4. To compare leptin levels of the examined groups of gymnasts with those of “normal” (nongymnasts) controls, leptin values were transformed into SDS (Z score) by using the equations derived previously from large cohorts of healthy children and adolescents, accounting for gender, pubertal stage, and BMI (6). In both genders, mean SDS values were clearly decreased: $-2.77 ± 1.96$ (range $-7.39$–$0.69$) in girls and $-0.93 ± 1.03$ (range $-2.68$–$1.07$) in boys. To obtain sufficiently large cohorts for the comparison of prepubertal and pubertal groups, Tanner stages 1 and 2 (prepubertal) and Tanner stages 3, 4, and 5 (pubertal) were combined. Whereas in girls adjusted leptin SDS decreased markedly from $-1.21 ± 1.32$ to $-3.99 ± 1.62$, leptin SDS remained unchanged in boys ($-0.94 ± 1.14$ vs. $-0.91 ± 1.10$) during pubertal development. Because leptin SDS were related to BMI and because BMI is a less reliable measure of body fat, leptin levels were also related to %BF determined by BIA and were compared with those in normal controls of corresponding age (6) (Fig. 1). Again, there was a significant decrease in leptin levels compared with that in the controls in both genders, although less marked: leptin SDS $= -1.05 ± 1.31$ in girls ($P < 0.001$) and $-0.60 ± 1.12$ in boys ($P = 0.025$).

DISCUSSION

More than two decades ago, clinical studies proposed a link between body FM and sexual maturation. An early onset of pubertal development was observed in obese children (49), whereas delayed puberty occurred in lean ballet dancers (19). In this context, Frisch and Revelle postulated the “critical weight” hypothesis for the induction of sexual maturation (18) and, thereby, provoked a controversial discussion (23). In the meantime, various investigations established an association between body FM and fertility (16, 17). In light of the discovery of leptin and its role as a permissive signal for the normal functioning of the hypothalamus-pituitary-gonadal axis (2), there is good reason to assume that leptin is the molecular link, the decisive permissive signal, among adequate energy stores, adipose tissue, and the onset of puberty. The question remains whether this mechanism plays a role in the retarded pattern of sexual maturation in elite gymnasts.

In the conducted study, leptin levels were low in elite gymnasts and did not follow the developmental pattern in normal children and adolescents, exhibiting a steady increase during sexual maturation in girls and a peak at Tanner stage 2 in boys (6, 11, 31, 44).
34). Leptin was associated with body fat, consistent with numerous reports on other cohorts. Because leptin levels in normal children and adolescents depend not only on FM but also on gender and pubertal stage (11), they were adjusted for gender, pubertal stage, and BMI by calculating leptin SDS (BMI based) (6). These adjusted leptin values were diminished compared with those in normal controls, especially in pubertal female gymnasts in whom leptin levels were clearly subnormal. However, BMI is not a very reliable measure of body fat for groups undergoing differing degrees of physical exercise. In highly trained athletes, an increase in BMI is due to an increase in muscle mass rather than FM as shown in this study. To circumvent this pitfall, leptin levels were also compared with %BF determined by BIA. Because the control groups were not large enough to stratify according to pubertal stage, the adjustment of leptin levels was performed only for gender and %BF. Again, the adjusted leptin levels (leptin SDS (%BF based)) were significantly reduced, especially in female gymnasts, although to a smaller degree. That is, the elite gymnasts had relatively lower leptin levels than normal nongymnast controls of the same age and %BF. This finding indicates the presence of additional suppressive regulators or the absence of stimulating regulators. However, to draw generally valid conclusions, a lack of statistical power related to the small sample sizes has to be taken into consideration. In particular, the groups become fairly small when the sample is divided into the four Tanner stages or into a prepubertal and pubertal category for both boys and girls. To obtain a bigger sample size and get a deeper insight into the physiological aspects of leptin secretion in elite gymnasts, it would be a challenge to set up a similar study including gymnasts from other European cadres.

Intense physical training can alter the normal pattern of pubertal development of athletes. Factors that influence sexual maturation are the time when heavy impact training starts, the amount of training hours per week, and whether a lean body shape is considered important to practice this sport. Athletes of leanness-related sport disciplines, such as gymnastics, ballet, rowing, figure skating, or long-distance running, belong to a high-risk category for developing eating disorders. Consequently, we evaluated the eating habits of female and male gymnasts by a standardized interview. In contrast to the boys, the girls, particularly slightly older ones, were aware of their daily body weight, took extreme care regarding low-caloric food products, were knowledgeable about the nutritional components of their daily diet, and were susceptible to altering their eating behavior. On the other hand, the nutritional intake of the boys reflected the unhealthy eating habits of the normal population, consuming too much fat and too few complex carbohydrates. A study in elite rowers revealed that the risk for eating disorders is moderated by age, gender, and the weight category. Regular evaluation of mood by using standardized questionnaires, such as the Profile of Mood States, may act as useful tools in identifying athletes at risk for developing eating disorders (42).

Nutritional deficiency certainly contributes to the development of various neuroendocrine and metabolic aberrations underlying exercise-related and psychogenic hypothyroid ammenorhea (25). Even psychogenic functional hypothalamic amenorrhea is associated with multiple endocrine-metabolic alterations that are very similar with highly trained female athletes with cycle abnormalities. Because food restriction has a profound, suppressive effect on leptin levels, which already becomes apparent after 1 day (24), it is most likely that the inappropriately low leptin levels in the gymnasts are due to their restrained eating behavior.

Typical hallmarks, such as reduced FM, delayed menarche, and delayed bone maturation, underline the inadequate metabolic reserve of female elite gymnasts. In addition, endocrine deficiencies such as low mean EE levels in pubertal girls were found. The elevated levels of testosterone in most of the examined female subjects might be caused by the low body FM, which is associated with diminished aromatase activity, leading to an insufficient conversion of androgens to estrogens. In contrast, the male counterparts displayed nearly unaltered pubertal development. The observed differences between female and male gymnasts are likely due to a later start of high-impact training, reduced training intensity during pubertal growth spurt, and more appropriate FM and energy intake of the male gymnasts.

In conclusion, the synopsis of recent scientific developments on the role of leptin and the findings of this study in elite gymnasts suggest the following scenario: high physical training load and, consequently, high-energy expenditure impair the development of FM appropriate for age. The lack of fat reserves per se leads to low leptin levels. This effect is further aggravated by insufficient caloric intake due to current aesthetic standards in this special sports discipline, particularly in girls. As a result, leptin levels are substantially decreased, which, in turn, does not allow the hypothalamus-pituitary-gonadal axis to be activated to induce puberty in a timely manner. As a consequence, pubertal development and the pubertal growth spurt are delayed or, in severe cases, never occur properly. Thus leptin may close the gap between the clinical observation of low FM and restrained eating behavior on one side and delayed sexual maturation and growth on the other side in elite gymnasts.

Elite female gymnasts are at risk for developing the female athletic triad showing late menarche, restrained eating behavior, and an increased rate of stress fractures. For that reason, it is advisable to monitor prepubertal and pubertal female gymnasts at short intervals, estimating individual training volume and training capacity to avoid harmful long-term side effects of high-intensity training.
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REFERENCES