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# The Association Between Athletic Training Time and the Sagittal Curvature of the Immature Spine

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## ABSTRACT

Strenuous physical activity is known to cause structural abnormalities in the immature vertebral body. Concern that exposure to years of intense athletic training may increase the risk for developing adolescent hyperkyphosis in certain sports, as well as the known association between hyperkyphosis and adult-onset back pain, led us to examine the association between cumulative hours of athletic training and the magnitude of the sagittal curvature of the immature spine. A sample of 2270 children (407 girls and 1863 boys) between 8 and 18 years of age were studied. An optical rasterstereographic method was used to measure the midsagittal curvatures of the surface of the back while the subject was in the upright standing position to quantify the angles of thoracic kyphosis and lumbar lordosis. These data were then correlated with self-reported hours of training measured by interview and questionnaire. The possible effects of age, sex, sport, and upper and lower body weight training were investigated. The results in these young athletes showed that larger angles of thoracic kyphosis and lumbar lordosis were associated with greater cumulative training time. Gymnasts showed the largest curves. Lack of sports participation, on the other hand, was associated with the smallest curves. Age and sex did not appear to affect the degree of curvature.

The normal development of spine sagittal curvatures depends on the interaction between heritable growth factors and the mechanical environment in which the spine grows. The research question addressed in this paper is whether exposure to long hours of athletic training is associated with increased sagittal curvature of the immature spine.

Spine sagittal curvature is known to be modifiable by altering the spine's exposure to certain mechanical loadings during growth. In this paper we tested the hypothesis that intense athletic training may alter the sagittal curvatures by increasing spine exposure to increased mechanical loading generated mainly by the trunk muscles. The capacity of the spine to withstand those forces, and the subsequent response of the spine to those forces and bending moments, will likely determine its sagittal shape. A positive and familiar example in the clinic is the reduction of thoracic hyperkyphosis induced by the long-term exposure to a relatively modest bending moment applied by a Boston brace.

What is known about the pathomechanics of hyperkyphosis? The presence of wedged vertebrae in Scheuermann's kyphosis suggests that asymmetric mechanical loading can alter vertebral endplate alignment.[29,41] Studies of immature rat tail vertebrae have shown similar alterations in vertebral growth.[29,41] Excessive compressive loading of the spine is known to affect normal spinal development at the apophyses.[21] For example, in biopsy specimens from seven patients with hyperkyphosis, the endosteal vertebral bone growth was stunted beneath the abnormal apophyseal plates.[21] In severe cases, regions of the vertebrae and apophyses were missing entirely. This growth retardation led to stunted ossification of the vertebrae along with wedging and unevenness at the vertebral surface. Finally, studies of immature rat tail have demonstrated that disk height can also be modulated by mechanical loading history.[41] In summary, these findings suggest that in both immature animals and humans, al-

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terations in mechanical loading can affect both vertebral and disk shape and thereby, potentially, spinal curvature.

Most athletic training and competition exposes the spine to large loads. This is because, according to Newton's laws, large muscle forces are required to rapidly accelerate or decelerate body segments. Intense training increases that exposure because it involves multiple, repeated loading cycles. Large angular body segment accelerations require large moments (or torques) to be developed at involved joints. These moments are developed by forceful contractions of the thoracic, abdominal, and paraspinous muscles about the spine which, in turn, induce significant compression, shear, and bending loads on the vertebral endplates, particularly in rapid weight-lifting activities.[2,3] In addition, if training or competition involves inadvertent falls or collisions involving impact on the back or trunk with noncompliant surfaces, these incidents can induce extremely rapid and large impulsive forces and bending moments on spine motion segments as trunk momentum is arrested.

We were led to research this subject because athletic training exposes the immature spine to large repetitive loads, the fact that several Olympic champion swimmers exhibit hyperkyphosis, and the report to us by a senior pediatric orthopaedic colleague, Dr. Robert Hensinger, of an apparent higher rate of hyperkyphosis among his patients who swam competitively. Our specific research question was whether long-term exposure to athletic training is associated with the development of thoracic hyperkyphosis in the immature athlete.

The primary null hypothesis tested was that larger angles of thoracic kyphosis or lumbar lordosis are not associated with increased exposure to athletic training as quantified by the number of annual training hours. Secondary null hypotheses tested were that the angles of kyphosis or lordosis would not differ by the primary sport of choice, by age, or by sex. Given that a longitudinal radiographic study of healthy young children was ethically indefensible, we elected instead to conduct a cross-sectional study in a sample of children aged 8 to 18 years using a noninvasive optical technique to measure spine curvature.

## MATERIALS AND METHODS

### Subjects

We studied 2270 children (407 girls and 1863 boys) between the ages of 8 and 18 years. These children volunteered at the annual summer athletic training sports camps held at the University of Michigan (2088 children) or attended local schools (182 children) between 1989 and 1996. All children were asked to participate via a letter addressed to the student and his or her parent or guardian. In the case of the local schools, permission to contact students was first obtained from the president of the school board. Written permission was then obtained from the parent or guardian. This research was approved by the University of Michigan Institutional Review Board.

To address our research hypothesis that intense athletic training might increase sagittal spinal curvature, the athletic subject population was recruited by the primary sport (football, gymnastics, ice hockey, swimming, track, volleyball, or wrestling) declared by the child. An age-matched group of children reporting no sports participation or experience of manual labor was recruited and used as a "nonathletic" control group.

### Group Selection (Inclusion/Exclusion Criteria)

*Controls.* Inclusion criteria were self-reported nonparticipation in any competitive sport or recreational extramural physical training program. Exclusion criteria were either a history of weight training, any regular physical labor that involved repetitively lifting objects greater than 10 pounds (for example, baling hay or stocking goods), traumatic back injury, a scoliosis exceeding 20° (Cobb angle), or a documented congenital spine abnormality.

*Athletes.* Inclusion criteria consisted of self-reported participation in regular extracurricular athletic training and competition for at least 1 year (4 or more days per week, and at least 3 months per year as determined by interview and questionnaire) in the sports of American football, gymnastics, hockey, track, swimming, volleyball, weight lifting, or wrestling. Exclusion criteria were history of a traumatic back injury, a radiographically documented scoliosis exceeding 20° (Cobb angle), or a documented congenital spine abnormality.

### Data Collected from Subjects

*Anthropometric Measurements.* Height, weight, shoulder, and abdominal breadths and depths, greater trochanter height, and the vertical distance from the greater trochanter to the first sacral segment (S-1) were measured for each subject. A finger-to-floor reach test was used as a screening for hamstring muscle tightness. This was accomplished by asking the subject to touch his or her fingertips to the floor while keeping the knees straight. Arm and leg lengths were measured based on landmarks, as were distances between the S-1 and the third lumbar segment (L-3), the tenth thoracic segment (T-10), and the first thoracic segment (T-1). These four bony spine landmarks (T-1, T-10, L-3, and S-1) were selected as the locations for surface markers for the photographic method for measuring sagittal spinal curvature.

*Questionnaire.* Each subject completed a questionnaire regarding personal demographic data, sports participation history, work activities, musculoskeletal injuries, and self-reported training programs. Each subject was then interviewed about the amount of time spent participating in upper and lower body training and conditioning programs (weight training or endurance conditioning), and off-season workout activity, as well as the length of the competitive season.

### Optical Measurement Method

The method used to measure spinal curvature was similar to that developed by Drerup and Hierholzer.[11,12]

*Equipment/Test Apparatus.* A tripod-mounted custom-made 35-mm projector, a motor-drive Canon F-1 35 mm film camera (Canon, U.S.A., Lake Success, New York), and a custom-built platform for standardizing subject position and orientation were used. This adjustable-height platform was designed to accommodate subjects between 4 and 7 feet tall, greater trochanter heights between 25 and 42 inches, and weights between 50 and 250 pounds. Fixed onto the platform were two vertical stanchions, each supporting a fixed array of four light-emitting diodes (LEDs) and a trochanter pad. The LEDs provided fixed points in three-dimensional space for the calibration procedure and thereafter served as fixed fiducial reference points in every image. Bilateral cupped trochanter pads served to fix the pelvis within the photographic reference plane. The same cups also supported a removable vertical calibration plane, which served as a calibration reference for the optical spinal shape measurements. The height of the platform relative to the stanchions was adjusted by a motorized leadscrew to allow the subjects' trochanters to be aligned with the support pads.

For the upright standing postures, the sagittal curvature of the surface of the midline from T-1 to S-1 was measured using the camera/projector stereographic pair (Fig. 1). A digital clock within the camera's field of view ensured correct sequencing of exposures for data analysis.

*Calibration.* Optical system calibration was performed by mounting a vertical flat white plane in the positioning apparatus (centered between the trochanter supports) for the camera/projector stereographic pair. A parallel-lined grating of known spacing and geometry was projected by the projector onto the plane. The distances between nine target points were measured on the plane, together with the distances from O (the intersection of the projected central ray with the plane) to two fixed LEDs on either side of the apparatus. An exposure of the image of the calibration board was taken to calibrate the apparatus at the beginning of each day. The calibration plane was then removed. The geometric measurements were input to a computer that used the stereophotogrammetry equations to calculate the positions and orientations of the camera and projectors relative to O in real world coordinates. The system was then calibrated for that day's photographs.

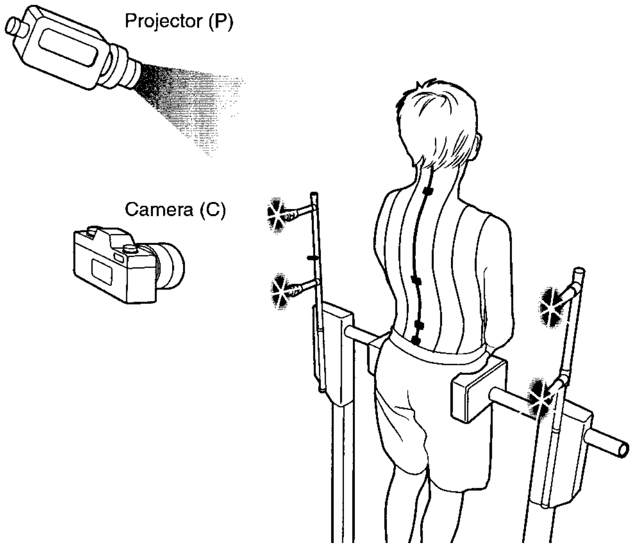

**Figure 1.** Schematic of projector (P) and camera (C) set up for photographing the profile of the midsagittal curvature and the locations of the T-1, T-10, L-3, and S-1 markers. The four light-emiting diodes served as fixed fiducial points.

*Technique/Photographic Method.* Photographs of the backs of each subject were obtained to measure the degree of thoracic and lumbar curvature. The cameras and their corresponding strobes were mounted 7 to 8 feet high on tripods and their positions were experimentally determined to yield the best fields of view and photographic resolution regardless of skin tone. Films were taken after instructing the subject to stand in a relaxed, upright position. Ektachrome 400 (Daylight) film (Kodak, Rochester, New York) was used, with cameras set at an f-stop of 4 and shutter speed of 1/8 sec. The projector was triggered to flash for 1/1000 sec by remote control.

*Data Reduction and Measurement.* Each 35-mm photographic image was converted to a bitmap file using a 1024 line Nikon CoolScan slide scanner (Nikon Corporation, Tokyo, Japan). Brightness and contrast were adjusted to enhance image quality, with customized gamma curves and red filtering added for clarity. Slides were scanned as black and white positive images and then cropped to reduce data storage. The bitmap files were then processed using a sequence of custom computer programs written to quantify the angles of thoracic kyphosis and lumbar lordosis of each subject. The calibration computer program recognized the nine points from the calibration board and four LEDs, assigning coordinate values to all recognized points. The digital image information from the calibration slides was then combined with the hand-measured values obtained from the calibration process to yield a "calibration file." This was necessary for the process of converting the digital image information (approximately 150 points along the spinal midline, the LED positions, and the landmark positions of each of the subject files) to camera-based digitizer coordinate pairs (U,V). The calibration file was used to define the projector/camera positions via direct linear transformation.

The U, V coordinate pairs from each subject were then converted to real world (X, Y) values. This computer program also aligned the calibration and subject slide LEDs for the purpose of minimizing errors of image rotation and magnification due to different degrees of cropping. These data yielded a rough outline of the subject's midline spinal topography. A fifth-order polynomial curve-fitting program was then used to smooth the resulting data. Finally, angles of thoracic kyphosis and lumbar lordosis were determined by 1) measuring the angles between tangents placed at the selected landmarks pairs (T-1, T-10, L-3, and S-1), and 2) alternatively, using the inflection points of the midsagittal curvature.

The first 247 subjects were processed using an ultrasonic two-dimensional spark gap digitizer (resolution, 2000 bits) to hand digitize the rear-projected images of the back surface curvatures using at least 100 points between T-1 and S-1. These 247 subjects were not included in the final data analysis. Twelve percent of the data were unusable because of photographic problems involving incorrect aperture, aiming, or flash photography. Complete data were obtained on a final subject population sample size of 1744 children.

*Accuracy/Repeatability of Optical Method.* Comparison of the measurements of a calibrated metal cylinder (1000 mm length and 300 mm diameter) with both precision calipers and the optical method showed that the photographic method was accurate to ±1 mm across the camera field of view.

Similarly, repeated measurements of 10 subject slides were taken to determine the error due to operator digitization and software angle calculations. Each of the ten slides were digitized and angles calculated on three separate occasions.

*Optical Method/Radiologic Validation.* Ten subjects who were also patients of the University of Michigan Pediatric Orthopaedic Clinic (five boys and five girls; average age, 15.1 years) participated in validating the noninvasive photographic technique using a radiographic comparison. Standing AP and lateral spine radiographs were taken of all 10 patients as part of their routine evaluations, and thoracic and lumbar angles were calculated using the Cobb method. Within 6 months of radiographic evaluation, these 10 patients volunteered to return for photographic measurements of their sagittal spinal curvatures. Patients were marked with fluorescent tape along the midline of the spine at T-1, T-10, L-3, and S-1. Using the subject as the control, a root-mean-square difference (RMS) was calculated to compare the optical methods and radiographic (Cobb) measurements of the maximum sagittal curvature in the thoracic and lumbar regions.

### Questionnaire Test/Re-test Reliability

Internal and external validation studies were performed on the main outcome variables (including self-reported training hours) from the questionnaire. The same questionnaire was given to a study subpopulation of 197 children (of the same age and sex distribution as the study population) on three separate occasions: two occurred within 24 hours of each other, while the third was distributed 2 weeks later. Each outcome variable was scored and compared with the first questionnaire for each individual subject. Kappa statistics were then obtained to determine level of repeatability.

### Data Management and Statistical Analysis

Standard statistical packages were employed to generate descriptive statistics for all parameters. Since data followed a Gaussian distribution, univariate analysis of variance (for the primary hypothesis) and two-sided post hoc $t$-tests with Bonferroni's correction factor (for the secondary hypotheses) were used to determine differences in thoracic and lumbar spine angles between sports, training time, and upper and lower body weight training. Adjustments in the significance levels were made to account for multiple comparisons. Step-wise regression analysis was used to assess appropriate predictor variables, and nonlinear regression was used to explore the relationship between the number of training hours and angle of kyphosis and lordosis.

## RESULTS

### Validation of Methods

*Optical Method.* The average error in surface measurements of kyphosis or lordosis was found to lie within 1° in repeated measurements of 10 subject slides.

*Radiographic Versus Photographic Technique.* The root-mean-square difference in thoracic kyphosis between standard lateral radiographs and the noninvasive photographic method of the 10 subjects was 6.9°, while the difference in lumbar angle was 7.5°. A systematic error was noted, with the photographic technique producing consistently larger angles compared with the radiographic technique.

*Questionnaire Test/Re-test Reliability.* Test/re-test studies for self-reported training times resulted in a kappa statistic of 0.91 within a day and 0.87 between days. The age of the subject was found to have a minor effect on the test/re-test results, with the older subjects tending to produce higher scores compared with the younger children. The subject's sex was found to have no effect on the test/re-test reliability score.

### Age and Sex Effects

No significant differences were found between surface measures of thoracic and lumbar spine sagittal angles and age (8 to 18 years), so therefore results were pooled for subsequent analyses. Similarly, no significant differences were found between thoracic and lumbar spine sagittal angles and sex, so results were pooled for further analyses.

### Training Effects

The average time each child devoted to his or her primary sport, the amount of time spent weight training the upper and lower body, and the average number of years each child participated in his or her primary sport are summarized in Table 1. Children participating in swimming and gymnastics spent the most time in training (379 and 439 hours/year, respectively). To put this in perspective, a child who spends 2 hours a day, 5 days a week participating in a sport for 3 months (an average length of season at the high school level) would log 120 hours per year.

The primary null hypothesis was rejected because both the thoracic and lumbar angles of curvature, measured by surface landmarks, were found to increase significantly with the number of annual training hours ($P < 0.04$) (Table 2). It is notable that in both the thoracic and lumbar spine, the nonathletic control subjects had the small-

TABLE 1
Average Annual Training Times Stratified by Sport

| Sport | Training exposure (hours/year) | No. Years in sport | Upper body weight lifting (hours/week) | Lower body weight lifting (hours/week) |
|---|---|---|---|---|
| Control group | 0 | 0 | 0 | 0 |
| Track | 198 | 2.9 | 1.9 | 1.8 |
| Volleyball | 150 | 3.0 | 0.4 | 0.4 |
| Football | 282 | 5.3 | 3.1 | 2.7 |
| Gymnastics | 439 | 5.1 | 0.3 | 0.2 |
| Hockey | 198 | 5.8 | 1.3 | 1.1 |
| Swimming | 379 | 5.2 | 0.8 | 0.8 |
| Wrestling | 228 | 4.0 | 2.5 | 1.9 |

TABLE 2
Mean (SD) Thoracic Kyphosis and Lumbar Lordosis Angles by Annual Training Time

| Training time (hours/year) | No. of children | Thoracic angle (deg) | Lumbar angle (deg) |
|---|---|---|---|
| <100 | 205 | 36.3 (13.5) | 41.4 (19.5) |
| 100 to 199 | 609 | 37.9 (13.6) | 41.8 (17.9) |
| 200 to 299 | 412 | 38.1 (13.6) | 42.0 (16.5) |
| 300 to 399 | 220 | 38.9 (13.5) | 42.2 (17.5) |
| ≥400 | 298 | 41.6 (13.1)[a] | 45.3 (16.4)[b] |
| Total | 1744 | 38.5 (13.6) | 42.4 (17.5) |

[a] Contrast with the <100 hours/year training group; $P = 0.0001$.

[b] Contrast with the <100 hours/year training group; $P = 0.0443$.

est curves. The increase in curvature in the athletes was proportional to the training time for thoracic kyphosis, but was essentially constant for the lumbar lordosis until it exceeded 400 hours/year. A similar trend was found using the cumulative training time (hours/year × years) (Table 3). Similar trends were also obtained when using the alternative method of inflection points to calculate curvature angles. The nonlinear regression of curvature angle on training time demonstrated coefficients of determination of 0.72 for thoracic kyphosis and 0.69 for lumbar lordosis (Fig. 2).

## Sport Effects

In a test of the secondary hypothesis, a significant difference was found in the thoracic and lumbar sagittal spinal

TABLE 3
Mean (SD) Thoracic Kyphosis and Lumbar Lordosis Angles by Cumulative Training Time

| Cumulative training time[a] | No. of children | Thoracic angle (deg) | Lumbar angle (deg) |
|---|---|---|---|
| <500 | 568 | 37.4 (13.5) | 41.5 (18.3) |
| 500 to 999 | 442 | 38.1 (13.5) | 42.1 (17.6) |
| 1000 to 1499 | 238 | 39.0 (13.8) | 42.8 (17.3) |
| 1500 to 1999 | 149 | 37.1 (15.0) | 40.4 (16.9) |
| ≥2000 | 343 | 41.3 (12.6)[b] | 45.0 (16.1)[c] |
| Total | 1740 | 38.5 (13.6) | 42.4 (17.5) |

[a] Cumulative training time is hours per year times years of participation.

[b] Contrast with the <500 hours/year training group; $P = 0.0003$.

[c] Contrast with the <500 hours/year training group; $P = 0.0246$.

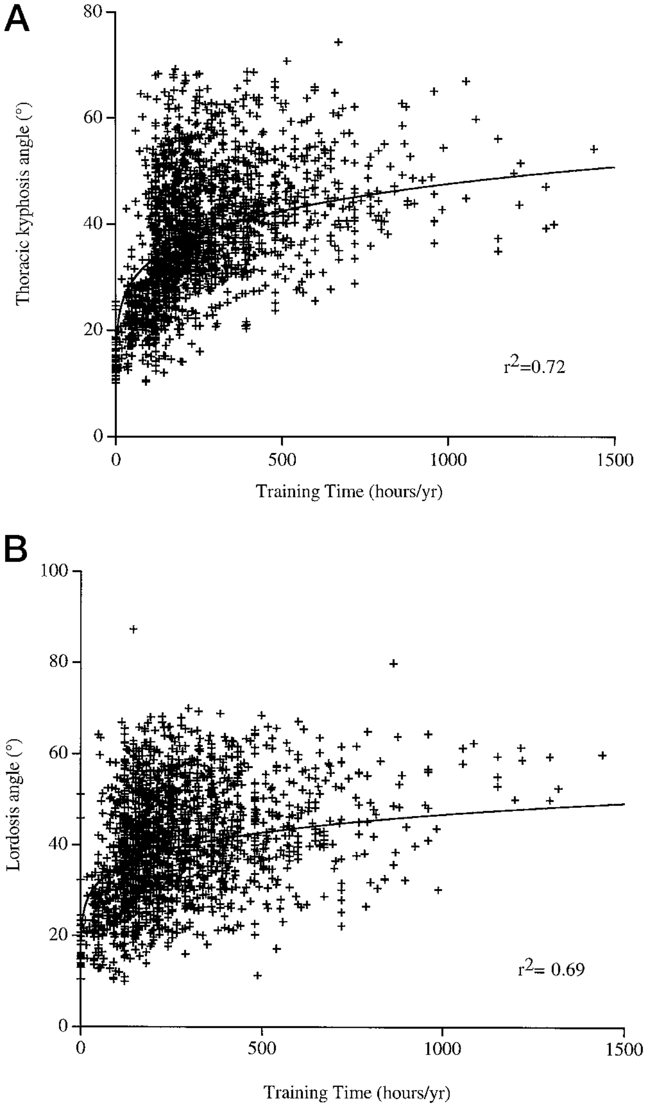

**Figure 2.** Scatter plots depicting the relationship between cumulative training exposure (hours/year) and thoracic kyphosis angle (A) and lumbar lordosis angle (B) for the entire data set. The best-fit exponential regression line is shown.

TABLE 4
Mean (SD) Thoracic Kyphosis and Lumbar Lordosis Angles Stratified by Sport

| Sport | No. of children | Thoracic angle (deg) | Lumbar angle (deg) |
|---|---|---|---|
| Control group | 57 | 16.1 (10.4) | 17.6 (15.6) |
| Track | 23 | 29.5 (10.1)[a] | 33.5 (17.0)[a] |
| Volleyball | 48 | 29.9 (13.9)[a] | 37.4 (21.7)[a] |
| Football | 180 | 39.8 (16.2)[b] | 46.2 (20.2)[a,c] |
| Gymnastics | 33 | 42.4 (13.4)[b] | 52.1 (16.7)[a,b,c] |
| Hockey | 189 | 38.1 (11.7)[b] | 44.5 (14.8)[a,b] |
| Swimming | 335 | 40.8 (13.0)[b] | 44.0 (16.5)[a,b] |
| Wrestling | 879 | 39.5 (12.2)[b] | 42.4 (16.2)[a,b] |
| Total | 1744 | 38.5 (13.6) | 42.4 (17.5) |

[a] Significant compared with the control group at $P < 0.0001$.
[b] Significant compared with track and volleyball at $P \leq 0.001$; significant compared with the control group at $P < 0.0001$.
[c] Significant compared with track and volleyball at $P \leq 0.05$.
[d] Significant compared with hockey, swimming, and wrestling at $P \leq 0.02$.

curves when adolescents were stratified by their primary sport (Table 4). Both the thoracic and lumbar angles were significantly lower ($P < 0.0001$) in the sedentary control group when compared with each of the athletic groups. The sports of football, gymnastics, hockey, swimming, and wrestling had significantly greater angles of thoracic ($P < 0.001$) and lumbar ($P < 0.05$) curvature when compared with the sports of track and volleyball. The children in gymnastics demonstrated the largest spine curvature in both the thoracic (42°) and lumbar (52°) regions.

*Weight Training Effects.* The number of hours of weight training was not associated with the increased curvature of the immature spine, in either the thoracic or lumbar spine regions (Table 5). The thoracic spine sagittal angle was 1.5° greater in children with more than 3 hours/week of upper body weight training compared with those children who did no upper body weight training. Similarly, average lumbar sagittal angle was 1.0° greater in children who trained their lower body with weights over 3 hours/week compared with children who did no weight training.

TABLE 5
Mean (SD) Thoracic Kyphosis and Lumbar Lordosis Angles Versus Annual Weight Lifting

| Body area | No. | Thoracic angle (deg) | Lumbar angle (deg) |
|---|---|---|---|
| Upper body weight lifting (hours/week) | | | |
| 0 | 563 | 38.1 (14.3) | 42.3 (18.3) |
| 0.01 to .99 | 268 | 38.1 (12.4) | 43.2 (17.2) |
| 1.00 to 1.99 | 306 | 39.2 (13.3) | 42.1 (16.9) |
| 2.00 to 2.99 | 267 | 37.8 (12.8) | 41.9 (17.0) |
| ≥3.00 | 336 | 39.6 (14.0) | 42.6 (17.2) |
| Total | 1740 | 38.5 (13.6)[a] | 42.4 (17.5)[b] |
| Lower body weight lifting (hours/week) | | | |
| 0 | 630 | 38.3 (14.1) | 42.2 (18.1) |
| 0.01 to .99 | 335 | 38.4 (12.4) | 42.6 (16.7) |
| 1.00 to 1.99 | 308 | 38.6 (13.8) | 41.9 (17.0) |
| 2.00 to 2.99 | 221 | 38.3 (12.6) | 42.9 (17.1) |
| ≥3.00 | 246 | 39.4 (14.4) | 43.2 (17.9) |
| Total | 1740 | 38.6 (13.6)[c] | 42.4 (17.5)[d] |

[a] Univariate one-way ANOVA; $P = 0.3250$.
[b] Univariate one-way ANOVA; $P = 0.9163$.
[c] Univariate one-way ANOVA; $P = 0.8885$.
[d] Univariate one-way ANOVA; $P = 0.9064$.

### Prediction of Sagittal Curvatures

No strong predictive variables emerged (that is, age, sex, height, weight, anthropometric measurements, hamstring muscle tightness, training time, years in sport, and upper or lower body weight lifting) as a measure of thoracic or lumbar surface angle when multiple regression analyses were performed.

## DISCUSSION

Of primary importance was our finding that a significant increase in spinal curvature was associated with cumulative training exposure in this sample of adolescent athletes. While the curvatures of the athletes were generally in the normal range, gymnasts were most affected, followed by those participating in American football, hockey, swimming, and wrestling (Table 4). Second, swimming did not produce the frequency of hyperkyphosis originally hypothesized. Third, the mechanisms responsible for maintaining spinal curvature in the immature spine of training athletes appear resilient because a 300% increase in training hours was associated with just a 5° increase in spinal curvature (Table 2). Last, exercise appears to be needed for normal spinal curvature development because the sedentary control subjects had 2.5-fold smaller curves than the gymnasts.

Clinically accepted radiographic values of thoracic kyphosis range from 20° to 40° in growing children,[5,44] a measurement that can depend on how far cephalad the end vertebra is visualized in a lateral radiograph. Nonradiographic methods of measuring thoracic kyphosis typically yield systematically larger angles (7° greater in this study). Previous nonradiographic methods have resulted in estimations of an average thoracic kyphosis angle of 40°,[43] which is consistent with the 38.5° average angle measured in the present study (Table 2). The mean thoracic and lumbar curves of most of the athletes reported in this study still fell within the range of normal values reported by several investigators.[13,17,31,38,42,43] However, it is noteworthy that the nonathletic control subjects had significantly smaller thoracic and lumbar angles. This finding suggests that a certain amount of physical activity is required for the development of normal curves.

A working definition of hyperkyphosis is an angle of kyphosis that exceeds the population mean kyphosis angle plus two standard deviations. In our study this threshold was 65° (equivalent to a radiographic value of 58°). Assuming a normal distribution and this definition of twice the standard deviation, we would expect 2% of athletes to develop hyperkyphosis by exceeding 65°. Clearly, given the similarity of variance across groups (Tables 2 and 3), the larger the training exposure and the larger the mean thoracic curve, the greater the percentage of group members expected to develop hyperkyphosis because of the

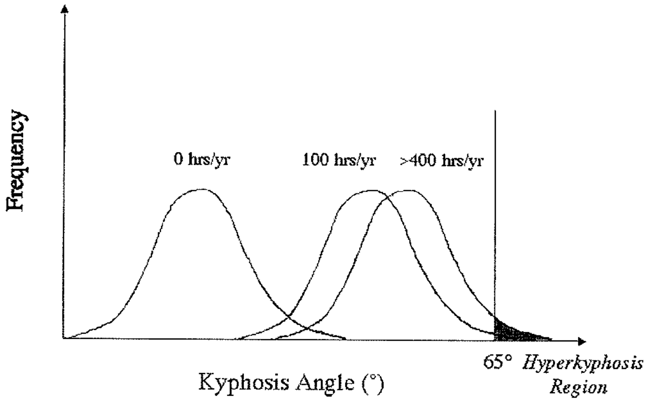

**Figure 3.** Predicted normal distributions of kyphosis angle (in degrees) based on the mean (SD) values recorded for the three groups of children: sedentary (0 training hours per year), moderate training (100 to 300 training hours per year), and intense training (over 400 training hours per year). The shaded tail region indicates that the probability of developing hyperkyphosis (defined as greater than 65°) is increased in the intense training group.

"right-shift" of the curve distribution (Fig. 3). In addition to the cosmetic problems presented, hyperkyphosis in adulthood is of clinical concern because of its known association with back pain and fatigue. Christie et al.,[9] Ohlen et al.,[30] Roncarati and McMullen,[33] and Salminen et al.[36,37] have all reported on the association between larger degrees of kyphosis or lordosis and increased frequency of low back pain. The larger the kyphosis, the larger the flexion moment from superincumbent body weight, and the greater the compression load induced on the midthoracic spine by the extensor muscles.[40] Hence, there is a theoretical association between hyperkyphosis and greater-than-normal thoracic spine loading, even during quiet upright stance. How the spine responds to such increased loading is unknown.

At competitive levels, athletes in sports like gymnastics frequently train 6 to 8 hours/day, 5 to 6 days/week, even during adolescence.[6,10] In swimming, increasing the distance swum during workouts is often considered the key to further achievement. The attitude of "If swimming 15,000 yards/day does not produce the desired results, then swimming 16,000 or 17,000 yards/day must be the answer" is not uncommon among coaches and athletes. If progressive resistance training (weights) is also perceived to be a need, the potential exists for musculoskeletal overload in the immature developing athlete. This approach to training is driven in part by the knowledge that in sports such as swimming and gymnastics, the chance of achieving an elite level is determined during adolescence. Unfortunately, immature bone is more sensitive to cyclic loading than mature bone.[8,20]

Physical activity is beneficial for proper bone growth and maturation.[39] In fact, animal studies have shown that increasing strain magnitude in bone initiates a dose-dependent elevation of bone mass.[35] Moderate exercise has also been shown to have both positive and negative effects on axial appendicular bone mechanical properties[20] and mineral composition.[16,28] Strenuous exercise, however, can have deleterious effects on immature bone structure and its mechanical integrity.[7,14,24,26] The negative effects of excessive repetitive strain have been demonstrated on the distal radii of female gymnasts[7] and also on the growth plates of vertebrae in rats.[32] Clearly, strenuous physical activity has the potential to cause abnormalities in the growth of the immature spine.

In highly competitive sports, the spine of the growing athlete may be vulnerable because it is the conduit for transferring mechanical power between the upper and lower extremities during rapid and forceful movements. Consequently, it is subjected to large three-dimensional bending moments in flexion, extension, and axial rotation, with concomitantly large compression and shear forces (see "Introduction"). The following evidence shows that long-term exposure to such forces appears to correlate with altered spinal development.

Hellstrom et al.[19] performed a radiographic review of the thoracic and lumbar spine in 143 athletes (wrestlers, gymnasts, soccer, and tennis players) and 30 control subjects. Abnormalities in the vertebral ring apophysis occurred exclusively in athletes, with male gymnasts and wrestlers demonstrating the highest rate of pathologic change (from T-6 to S-1). Disk height reduction, Schmorl's nodes, and abnormal vertebral configurations were overly represented in the athletic group. Disk height reduction is associated with exposure to higher-than-normal compressive loading situations.[41] In an ex vivo study of 95 subjects between 15 and 95 years of age, Goh et al.[15] found that thoracic kyphosis (measured as the Cobb angle between T-4 and T-9) was better predicted by vertebral structure ($r = 0.64$) than by disk structure ($r = 0.50$). Manns et al.,[25] on the other hand, reported that the degree of thoracic kyphosis may be more related to the physical integrity of the disk than to the shape of the vertebral bodies. In either case, these studies suggest that loss of disk height, particularly anteriorly, is associated with an increase in thoracic kyphosis. Therefore, some of the increase in spinal curvature observed in the present study might be due to loss of disk height, which would tend to reduce the length of the anterior column of the spine, thereby increasing thoracic kyphosis and lumbar lordosis. Whether such changes are reversible is unknown. Certainly, bone growth disturbances can occur as a result of asymmetric vertebral loading,[1,5] and these have the potential to affect vertebral structure and thereby sagittal curvature.

The limbus vertebral abnormalities reported by Hellstrom et al.[19] are indicative of disk herniation and were seen only in athletes where spinal muscle activity is expected to be excessive. These changes in vertebral architecture, as well as the spondylolytic defects noted by Rossi and Dragoni[34] and Jackson et al.,[22] can be indicative of trauma or overload.[4,18,23,27] These factors, along with the evidence provided by Revel et al.[32] that the vertebral growth plates of immature spines subjected to intense physical activity can exhibit significant pathologic alterations, suggest that there are limits to safe spinal load exposure and loading history, beyond which pathologic changes are induced.

Limitations of the methods used in this study include the use of a convenience sample of children in lieu of randomized sampling techniques, and the cross-sectional study design used in lieu of a longitudinal study. Surface measures of kyphosis and lordosis generally correlate with radiographic measures, with a correlation coefficient value of 0.7.[43] As such, they give a reasonable indication of trends in spine shape, especially in the thoracic spine. There is no reason to suspect that the method of surface measurement biased the curvature angles associated with increased training time. The fact that both thoracic kyphosis and lumbar lordosis increased with training exposure times argues against the apparent increase in curvature being due to localized growth of the spinous processes in the midthoracic region and at the cranial and caudal ends of the lumbar region. A further limitation of the present study was that no objective measure of the magnitude of the spine loads involved during training and competition was available. Therefore, it was not possible to correlate the risk of development of increased kyphosis, for example, with the exposure to high levels of spine loading. However, when exposure was documented in terms of the self-reported training times (Huston et al., unpublished data, 1998), a measure with demonstrated reliability, the data do suggest that as exposure time increased, so did the degree of spinal curvature in the immature athlete. Last, we cannot rule out the possibility that self-selection might have contributed to the association found between training exposure and sagittal curvature.

## SUMMARY

These results suggest an association between increased thoracic kyphosis and lumbar lordosis angles and exposure to athletic training. Children participating in rigorous sports had a higher risk of becoming hyperkyphotic than those not participating in sports. These data also suggest that lack of physical activity predisposes a healthy child toward hypokyphosis.

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