Mid-femur geometry and biomechanical properties in 15- to 18-yr-old female athletes

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ABSTRACT

DUNCAN, C. S., C. J. R. BLIMKIE, A. KEMP, W. HIGGS, C. T. COWELL, H. WOODHEAD, J. N. BRIODY, and R. HOWMAN-GILES. Mid-femur geometry and biomechanical properties in 15- to 18-yr-old female athletes. Med. Sci. Sports Exerc., Vol. 34, No. 4, pp. 673–681, 2002. Purpose: Right-leg mid-femur geometry and biomechanical indices of bone strength were compared among elite cyclists (CYC), runners (RUN), swimmers (SWIM), triathletes (TRI), and controls (C)—10 subjects per group. Methods: Bone cross-sectional areas (CSA), volumes (Vol), and cross-sectional moments of inertia (CSMI) were assessed by magnetic resonance imaging (MRI), and cortical volumetric bone density (volBMD) was determined as the quotient of DXA-derived bone mineral content (BMC) and MRI-derived cortical bone volume. Bone strength index (BSI) was calculated as the product of cortical volBMD and CSMI. Results: RUN had higher ($P < 0.05$) size- (femur length and body mass) adjusted (ANCOVA) cortical CSA than C, SWIM, and CYC; and higher size, age, and years of sport-specific training- (YST) adjusted cortical CSA than SWIM and CYC. TRI had higher ($P < 0.05$) size-adjusted CSA than SWIM. SWIM and CYC had significantly larger ($P < 0.05$) size-adjusted medullary cavity CSA than RUN and TRI, and the difference between CYC and RUN persisted after additional adjustment for age and YST. RUN had significantly ($P < 0.05$) greater size-adjusted CSMI and BSI than C, SWIM, and CYC; and higher size, age, and YST-adjusted CSMI and BSI than SWIM and CYC. Mid-femur areal bone mineral density (BMD) was significantly ($P < 0.05$) higher for RUN compared with CYC only, but there were no other differences among groups for BMC, bone volumes, or volumetric total or cortical BMD. Conclusions: Running, a weight-bearing exercise, is associated with more favorable geometric and biomechanical characteristics in relation to bone strength, compared with the weight supported activities of swimming and cycling. Differences may reflect skeletal adaptations to the specific mechanical-loading patterns inherent in these sports. Key Words: ELITE FEMALE ATHLETES, BMD AND CONTENT, MID-FEMUR CROSS-SECTIONAL AREAS, MOMENT OF INERTIA AND VOLUMES, BONE STRENGTH INDEX, WEIGHT-BEARING AND WEIGHT SUPPORTED ACTIVITY, MRI

The influence of physical activity on bone mass, content (BMC), and density (BMD) has been extensively investigated in both growing animals (27,28) and young children (2,5,10). The results of these studies suggest that increased mechanical loading has a positive influence on bone mineral status when the nature, magnitude, and duration of exercise are adequate. These adaptations also appear to be greater in the developing (5), compared with the mature, skeleton (7). Increasing physical activity during childhood has therefore been proposed as a primary strategy for optimizing peak bone mass (2,5), an identified predictor of fracture risk in later adult life (20).

To date, most of the physical activity studies of children and adolescents have focused on bone mineral mass or density as the surrogate measures of in vivo bone strength (2,4,5,29). These are clinically valid measures in the context of osteoporosis, as bone mass and density correlate significantly with fracture force in in vitro studies and are significant predictors of fracture risk in adult humans (3,20).

However, the physical relationship between bone density and propensity to fracture under conditions of controlled loading is quite variable, with a large proportion of unexplained variance (21–88%) between bone density and bone strength (11). Additionally, there is considerable overlap in BMD between subjects presenting with either osteoporotic or nonosteoporotic fractures (e.g., stress fractures) and those who are fracture free (6). These findings suggest that other factors besides bone mineral status, including perhaps bone geometry, biomechanical, and material properties, may play an important role in determining bone strength and functional competency at all stages of the life cycle in humans.

The influence of exercise on these nonmineral properties of bone has not been extensively investigated in children (<19 yr of age). The paucity of information on geometric and biomechanical adaptations to exercise in this population stems mostly from technological limitations in measuring these parameters accurately and with minimal health risk. Studies utilizing computed tomography (QCT or pQCT) expose children to undesirable levels of radiation, and DXA, because of its uni-planar nature, may have limited accuracy and reliability in measuring internal dimensions and biomechanical properties, and is incapable of providing 3-D analysis of long-bone geometry.
A new approach was used recently (11), which combined measures of bone mineral (cortical voLBMd) and biomechanical (CSMI) properties derived from pQCT, to estimate in vivo bone strength (bone strength index; BSI) of the rat femur. BSI correlated more strongly with actual fracture load than either BMD or CSMI, suggesting that this might be a more useful predictor of fracture risk than currently used indices. We (30) have recently developed a similar approach using nonionizing MRI to measure gross geometry and biomechanical properties of the mid-femur in children, and in combination with regional BMC measures from DXA, estimates of in vivo bone strength. This is the first study that we are aware of that has combined these technologies to compare in vivo bone geometry and biomechanical characteristics among athletes from sports with substantially different mechanical-loading patterns. This approach provides a useful noninvasive research model for examining biological adaptability of the long bones to myriad loading conditions across multiple fronts (e.g., bone density, geometry, and biomechanical characteristics) in humans. Whether this approach can be extended to other sites and proves clinically useful (e.g., in the diagnosis of osteoporosis) remains to be determined.

The purpose of this study therefore, was to compare long-bone (femur) total and cortical volumetric BMD, geometry, biomechanical, and estimated bone-strength characteristics of elite teenage female athletes from sports with substantially different mechanical-loading patterns. Bone geometry and biomechanical characteristics derived from MRI, and BMC from DXA were combined to estimate true volumetric bone density and in vivo bone strength index, similar to the approach used by Ferretti et al. (11). A cross-sectional study design, incorporating elite female athletes was used that compared triathletes to athletes who specialized in either swimming, cycling, or running. Triathlon, a new Olympic sport comprised of swimming, cycling, and running events involves both weight-bearing and nonweight-bearing exercise and an unusual load distribution pattern. With this model, we are able to compare differences in bone geometry and biomechanical characteristics between weight-bearing (running) and nonweight-bearing (cycling and swimming) sports, with a sport that incorporates both types of loading conditions (triathlon). We hypothesized that runners with relatively high-volume weight-bearing loads would have increased gross-bone geometry and biomechanical properties compared with all other groups, that triathletes would be intermediate between the runners and the other groups (because their sport includes an element of weight-bearing, albeit at lower volume), and that there would be no difference between controls and the nonweight-bearing athletes, the swimmers and cyclists.

MATERIALS AND METHODS

Study participants. Fifty female subjects, aged 15–18 yr were recruited for this study. Groups were comprised of swimmers, cyclists, runners, triathletes, and nonathletic controls (N = 10/group). Subjects comprised a subsample of volunteers from a larger study (9), who were able to commit to an additional hour of testing for MRI scanning. All athletes specialized in endurance events and were either state- or national-level representatives. Athletes participated in at least 8-wk$^{-1}$ of training and/or competition during the previous year. Furthermore, two cyclists, swimmers, and runners, and one triathlete performed supplemental strength training ranging from 30 to 60 min, and 1 to 3 times per week. Because there were no within-group differences (values were within the 95% confidence intervals) for any of the dependent variables between subjects who strength trained and those who did not, subjects who did supplemental strength training were retained in their original groups for subsequent data analysis. Controls were involved in less than 2 h-wk$^{-1}$ of physical activity and had never been involved in elite competitive sport. All subjects were Caucasian, and girls were postmenarchal by at least 1 yr, having had eight or more menstrual cycles during the previous 12 months.

This study was approved jointly by the Human Ethics Committee of the University of Sydney and The New Children’s Hospital, Sydney. An investigator explained the procedures and requirements, and then each participant gave written informed consent.

Procedures. Participants were required to make one visit to our laboratory for a period of 3 h. During this time, bone geometry, BMD, anthropometry, general health, and physical activity were assessed. All procedures were conducted at The Children’s Hospital, Westmead, and The Children’s Hospital Institute of Sports Medicine, which adjoins the hospital. Measurements were completed within 1 month of the respective sports’ national championships, to coincide with peak training loads.

Bone morphology. Bone geometry of the mid-section of the right femur was measured by MRI using a 1.5-Tesla Philips ACS-NT MRI (The Netherlands) scanner with a manufacturer supplied body coil. The mid-third section was identified from an initial scout scan in the coronal plane of the full length of the femur, and was measured as the distance from the head of the femur to the base of the medial femoral condyle (Fig. 1a). Subjects were required to remove all metal and to relax in a supine position in the magnet aperture with their leg firmly supported in a custom built holding device for approximately 40 min. Images were acquired with a proton density weighted 2-D Turbo spin echo sequence (TE/TR/= 15 ms/1600 ms) for both the scout and acquisition images. Contiguous transverse images (slice thickness = 6 mm, FOV = 250 mm, in plane pixel resolution = 488 µm$^2$) perpendicular to the long axis of the femur were made of the mid-third section, proceeding in a distal to proximal direction. Images were burned to CD-ROM in DICOM format and then analyzed off-line on a dedicated computer system.

Measures of bone geometry were obtained using the ANALYZE® software program (Mayo Foundation, Rochester: MN, version 7.0) on a Windows NT platform. Images were imported from CD-ROM in DICOM format, and converted into ANALYZE format before analysis. The image was then analyzed using the region of interest function, in
3-D mode. The image was increased by a size factor of 1.5, and gray scaling was manipulated for optimal viewing and differentiation of bone tissue compartments. The total (TCSA), cortical (CCSA), and medullary cavity (MCSA) cross-sectional areas (minus the border of subcortical trabecula spiculae) were measured for each slice on the proximal surface over the mid-third length of the femur, using the auto trace function. Volumetric measurements were calculated as the summed products of measured CSAs and slice thicknesses over the mid-third region. The outcome variables were mid-third femoral total (volTOT), medullary cavity (volMC), and cortical bone volumes (volCORT). All measurements were completed by the same investigator, and the short-term reliability (repeated measures of the same scans) was excellent with correlations ranging between \( r = 0.95 \) and \( r = 0.99 \) for the CSAs and \( r = 0.98 \) and \( r = 0.99 \) for the volumes. Short-term intraobserver repeatability of MRI measures, made on separate scans over several days, was also excellent with coefficients of variation in our center between 0.3% and 2.6%. MRI-determined morphological measurements of mid-femur CSAs and volumes were compared with digitized photographic images of sectioned slices, and water displacement of the entire mid-third section of venison femora, respectively. The MRI technique was very accurate with differences between techniques ranging from 1.6% and 3.5% (30).

**Biomechanical variables.** Cross-sectional moments of inertia (CSMI) were calculated using the Scion® software package (Frederick, MD: Version-Beta 3B) and a customised algorithm software program (Fig. 1B). MRI images were imported from the ANALYZE software program and analyzed in DICOM format. These analyses were performed on the distal, mid-, and proximal slices by using a constant gray scale with a threshold range of 230–255. The Scion program differentiated the CSMI in both the local axis system and principal axis system. The local axis system was defined in the plane of the MRI with the centroid as the origin and the principal axis system as the local axis system rotated by the CSMI principal angle. The CSMI is a measure of the cross-sectional shape of the bone around the centroid and is used to determine the bending and torsional characteristics of the bone. CSMI was calculated as the sum of products of pixel areas of cortical bone and the distance squared from each pixel to the horizontal and vertical axes that passed through the center of the cross-sectional mass, for the principal x and y moments, respectively. To calculate the most representative and average CSMI over the entire mid-third region, we summed the higher (principal) of the x or y CSMI at the proximal, mid-, and distal sites and then divided this value by 3. These averaged principle values for three sites were highly correlated to the average value measured across all sites for the mid-third region (\( r = 0.99 \)).

**BMD.** Total body areal BMC (BMC \( \cdot g \)) and density (BMD \( \cdot g/cm^2 \)) were measured by dual-energy x-ray absorptiometry (DXA), using a Lunar scanner (Model DPX, software version 3.6-pencil beam; Lunar Corp, Madison, WI) and standard operating procedures. Precision (CV) for the DXA measures was better than 1.2%. BMC of the mid-third region of the right femur was determined using the region of interest function on the total body scan. Femur length was determined as the distance from the head of the femur to the base of the medial femoral condyle, using the ruler function. A region of interest box was then applied over the mid-third section, ensuring tissue in all four corners. Mid-third femur length from DXA was highly correlated with mid-femur length derived from MRI (\( r = 0.95 \)).
A total body phantom (constructed of aluminum strips and rice bags mounted together—as recommended by Lunar Corp.) was used for quality control during the study period. The CV was 1.5% for mid-femur BMC.

The same investigator completed and analyzed all scans using standard analysis protocols. The percent body fat and lean tissue mass (g) were also obtained from the total body scan. The CV was 4.9% for lean tissue mass (LTM). Participants wore light clothing without zippers or buttons and removed all jewelry for the scanning procedures.

**Bone strength index.** The bone strength index of the entire mid-third region of the femur was determined by using a previously published equation: bone strength index (BSI) = CSMI \times \text{Volumetric Cortical BMD} \times 11. The CSMI was obtained as previously described in the biomechanical variables of the Materials and Methods section. The volumetric cortical BMD was derived as the quotient of DXA-derived mid-femoral BMC divided by the MRI-derived mid-femoral cortical bone volume (volCORT). BSI is a measure of the combined influences of bone mineral status and the distribution of this mineral within the bone organ, to bone strength.

**Normalization for size.** In addition to mechanical loading, measures of bone morphology and biomechanical indices may also be influenced by interindividual variation in both bone size and body mass. All measures of absolute CSAs, CSMI, and BSI were therefore adjusted (ANCOVA) for the covariates body mass and femur length (from MRI), to account for these potential confounding size influences. Body mass rather than lean body mass was used as the adjustment for body size, because differences among groups for the dependent variables were identical, regardless of which of these variables was used, and because the gravitational influence on the skeleton during weight-bearing activity is determined by the mass of the subject, independent of its composition.

**Dietary intake.** Participants were given written and verbal instructions regarding accurate and thorough completion of a 3-d diet history. All foods and beverages were recorded for 2 weekdays and 1 day on the weekend. This diary was returned to the investigators and the data analyzed using the Serve (Sydney, Australia) dietary analysis program, to ascertain average daily total energy and calcium intakes.

**Physical activity, training, and medical histories.** A physical activity questionnaire (NSW Schools Physical Activity Questionnaire, 1998) was completed on the day of testing to determine the activity levels of controls. This questionnaire solicited information on the frequency, type, and duration of activities over the previous year. Athletes were required to record their training history for a period of 2 wk after testing. Years of total and sport-specific (YST) training (e.g., swimming, running, cycling) as well as weekly average total training hours, including supplemental forms of training, were recorded. Athletes were given verbal and written instructions on how to complete this diary. A medical history questionnaire was used to identify menstrual status, cigarette consumption, and medication usage. The questionnaire was completed at the time of testing with the aid of an investigator.

**Statistical analysis.** A one-way analysis of variance (ANOVA) was used to identify differences among groups for all raw data. Post hoc analysis was performed only for variables with a significant main effect in ANOVA. Bone geometry and biomechanical variables were also adjusted for possible size influences (body mass and femur length) by using ANCOVA. Additionally, to account for the possible influence of differences in age, and YST, all measures of size-adjusted bone morphology (CSAs) and biomechanical indices (CSMI and BSI) were also adjusted using ANCOVA, with age and YST as covariates. Due to the expense of, and limited access to MRI, the sample size in this study was relatively small. Accepting these constraints, we have used the relatively low stringency LSD post hoc test to determine differences among groups. Observed statistical power was above 0.80 for all bone geometry and biomechanical variables except total CSA, with a power of 0.75. The statistical software program SPSS version 8.0 (Chicago, IL) was used for all data analysis, and differences were considered significant if $P < 0.05$.

**RESULTS**

The descriptive variables are presented in Table 1. Runners had a significantly greater number of years postmenarche than cyclists and trained significantly fewer hours per week...
week than all other sport groups. Runners specialized in their sport significantly longer than triathletes, and swimmers had specialized in their sport significantly longer than both triathletes and cyclists. All sport groups had significantly larger lean tissue mass (LTM) than controls.

There were no significant differences in dietary calcium intake (controls 671 mg ± 170 mg, swimmers 988 mg ± 270 mg, cyclists 873 mg ± 254 mg, runners 984 mg ± 536 mg, and triathletes 681 mg ± 413 mg) among groups. Likewise, average daily energy intakes were similar ($P > 0.05$) across groups, ranging from 7109 ± 1352 to 9806 ± 2418 kJ (means ± SD).

The absolute values for BMC, bone volumes, areal BMD, and volumetric BMD of the mid-third femur are summarized in Table 2. Runners had significantly higher areal BMD than cyclists, but there were no other significant differences among groups for this variable. There were no significant differences among groups for BMC, bone volumes, or volumetric BMD.

Absolute values for the bone geometry and biomechanical variables are reported in Table 3 (upper panel) for reference purposes only. Size-adjusted bone morphology results are presented in the lower panel of Table 3. There were no significant differences among groups for total CSA after adjusting for size, but runners had significantly larger cortical CSA than controls, swimmers, and cyclists but not triathletes. Triathletes had higher ($P < 0.05$) size-adjusted cortical CSA than swimmers. Swimmers and cyclists had significantly larger size-adjusted medullary cavity CSAs than runners and triathletes but not the controls. There were no differences among groups for mid-femur total CSA after additional adjustments for age and YST (Fig. 2), but runners had significantly higher adjusted cortical CSA than the swimmers and cyclists but not the controls or triathletes. Medullary cavity CSA was significantly ($P < 0.05$) larger in cyclists compared with runners even after the additional adjustment for age and YST, but there were no other significant differences for this variable among the other groups.

The size-adjusted CSMIs are presented in the lower panel of Table 3. Runners had the highest of all values, and these were significantly ($P < 0.05$) greater than controls, swimmers, and cyclists but not the triathletes. Although having the second highest average values, there were no significant differences for size-adjusted CSMI between the triathletes and any other group. Runners had significantly higher ($P < 0.05$) CSMI than swimmers and cyclists, but not the controls and triathletes, after additional adjustments for age and YST (Fig. 3A). There were no significant differences among the other groups for CSMI adjusted for size, age, and YST.

The bone strength index (BSI) results adjusted for size are summarized in Table 3. Runners had significantly ($P < 0.05$) higher BSI than controls, swimmers, and cyclists but not the triathletes. There were no significant differences for size-adjusted BSI among the other groups. Runners persisted with significantly higher BSI compared with the swimmers and cyclists even after additional adjustments for age and YST (Fig. 3B). Triathletes had the second highest adjusted BSI of all groups, next to the runners, but values were not significantly different from any other group.

**DISCUSSION**

This study examined differences in mid-femoral volumetric BMD, bone geometry, biomechanical, and bone strength indices in cohorts of elite teenage female athletes representing sports with variable mechanical-loading characteristics. There is abundant literature describing the relationship between areal BMD and physical activity (2,4,5,10,15,18,29) in humans but rather limited information about skeletal geometric and biomechanical adaptations associated with, or resulting from myriad mechanical-loading conditions that characterize sports participation. There have been several studies of exercise-associated differences in gross bone geometry in adult humans (1,6,17,21,23,25), but to our knowledge only three studies have investigated this relationship in children (5,10,26). There have been no attempts to describe these latter relationships in the late teenage years in female subjects, which is surprising, given that this is a period characterized by extensive modeling at both the periosestal and endocortical bone surfaces (12), resulting in extensive changes in bone size and shape.

The results of this study indicated that certain indices of gross bone geometry, specifically, total CSA, did not differ among groups after adjustment for size (body mass and femur length) or size, age, and YST influences. By contrast, however, athletes involved in the weight-supported activities of swimming and cycling had significantly higher size-adjusted medullary cavity CSA and lower cortical CSA compared with the two weight-bearing sports, running and triathlon. There are no published data of mid-femur geometry in athletes that we are aware of, against which to compare our findings. In an earlier study (25), adult male runners training at similar mileage had significantly higher weight normalized total CSA of the tibia and fibula combined (determined by

### TABLE 2. Mid-third femur BMC, BMD, and volumes (unadjusted raw data).

<table>
<thead>
<tr>
<th>Group</th>
<th>Controls</th>
<th>Swimmers</th>
<th>Cyclists</th>
<th>Runners</th>
<th>Triathletes</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMC (g)</td>
<td>69.7 (15.9)</td>
<td>79.7 (16.5)</td>
<td>76.6 (13.2)</td>
<td>89.6 (20.6)</td>
<td>82.6 (8.8)</td>
</tr>
<tr>
<td>ArealBMD (g·cm⁻²)</td>
<td>1.6 (0.07)</td>
<td>1.55 (0.21)</td>
<td>1.43 (0.11)</td>
<td>1.64 (0.15)</td>
<td>1.56 (0.15)</td>
</tr>
<tr>
<td>Total bone volume (cm³)</td>
<td>77.6 (15.7)</td>
<td>81.7 (15.7)</td>
<td>79.3 (10.8)</td>
<td>82.9 (12.9)</td>
<td>76.4 (6.2)</td>
</tr>
<tr>
<td>Cortical bone volume (cm³)</td>
<td>51.2 (6.9)</td>
<td>52.5 (12.1)</td>
<td>52.3 (6.7)</td>
<td>58.6 (8.0)</td>
<td>55.1 (3.9)</td>
</tr>
<tr>
<td>Volumetric total BMD (g·cm⁻³)</td>
<td>0.91 (0.2)</td>
<td>0.98 (0.17)</td>
<td>0.99 (0.10)</td>
<td>1.1 (0.15)</td>
<td>1.1 (0.06)</td>
</tr>
<tr>
<td>Volumetric cortical BMD (g·cm⁻³)</td>
<td>1.3 (0.15)</td>
<td>1.5 (0.21)</td>
<td>1.51 (0.10)</td>
<td>1.50 (0.23)</td>
<td>1.51 (0.08)</td>
</tr>
</tbody>
</table>

Values are mean ± SD. Significant differences among groups are indicated by alphabetical superscripts. *Significantly greater than cyclists ($P < 0.05$).
TABLE 3. Absolute and size-adjusted† (ANCOVA) bone morphology and biomechanical variables.

<table>
<thead>
<tr>
<th></th>
<th>Controls</th>
<th>Swimmers</th>
<th>Cyclists</th>
<th>Runners</th>
<th>Triathletes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute values</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Total CSA (mm²)</td>
<td>478.00 (51.00)</td>
<td>518.34 (57.01)</td>
<td>524.12 (63.14)</td>
<td>553.13 (68.11)</td>
<td>506.01 (31.32)</td>
</tr>
<tr>
<td>Medullary CSA (mm²)</td>
<td>112.00 (26.25)</td>
<td>145.01 (48.11)</td>
<td>143.11 (27.00)</td>
<td>111.01 (39.10)</td>
<td>115.00 (21.00)</td>
</tr>
<tr>
<td>Cortical CSA (mm²)</td>
<td>340.50 (39.40)</td>
<td>337.31 (46.00)</td>
<td>346.01 (43.00)</td>
<td>394.40 (47.24)</td>
<td>369.30 (36.00)</td>
</tr>
<tr>
<td>CSMI (mm²)</td>
<td>30714.0 (16629.0)</td>
<td>32665.0 (15651.3)</td>
<td>3082.0 (12513.1)</td>
<td>57105.2 (23929.0)</td>
<td>43563.0 (25242.2)</td>
</tr>
<tr>
<td>BSI (g·cm⁻³ × mm⁴)</td>
<td>38619.3 (19529.0)</td>
<td>45225.1 (20326.4)</td>
<td>40268.2 (19746.0)</td>
<td>89436.0 (54282.4)</td>
<td>54465.1 (32053.2)</td>
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<tr>
<td>Size-adjusted values</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total CSA (mm²)</td>
<td>496.00 (47.00)</td>
<td>517.20 (45.35)</td>
<td>523.40 (46.00)</td>
<td>536.00 (47.34)</td>
<td>508.10 (46.00)</td>
</tr>
<tr>
<td>Medullary CSA (mm²)</td>
<td>116.00 (35.00)</td>
<td>144.01 (34.01)</td>
<td>144.00 (34.02)</td>
<td>107.01 (35.12)</td>
<td>112.00 (34.01)</td>
</tr>
<tr>
<td>Cortical CSA (mm²)</td>
<td>347.00 (37.00)</td>
<td>336.43 (36.04)</td>
<td>342.41 (36.20)</td>
<td>388.00 (37.31)</td>
<td>372.00 (35.82)</td>
</tr>
<tr>
<td>CSMI (mm²)</td>
<td>35334.0 (18837.0)</td>
<td>32253.0 (18189.0)</td>
<td>31850.0 (18404.1)</td>
<td>53733.4 (18989.0)</td>
<td>43258.1 (18230.0)</td>
</tr>
<tr>
<td>BSI (g·cm⁻³ × mm⁴)</td>
<td>44738.0 (31331.4)</td>
<td>43231.1 (31881.2)</td>
<td>42525.0 (30503.4)</td>
<td>82246.1 (35009.0)</td>
<td>53546.1 (31840.2)</td>
</tr>
</tbody>
</table>

Values are mean ± SD
† Body mass and femur length were used as covariates for size adjusted measures.
‡ Significantly greater than controls (P < 0.05).
§ Significantly greater than swimmers (P < 0.05).
‖ Significantly greater than cyclists (P < 0.05).
¶ Significantly greater than runners (P < 0.05).
‖‖ Significantly greater than triathletes (P < 0.05).

In contrast to the study of adult male runners (25), our findings suggest that there is little if any association between total CSA and the loading patterns inherent in running in teenage female subjects. Alternatively, because runners persisted with the highest, albeit not significantly different total CSA of all sport groups, our data might also be interpreted as supporting a modest positive association between this form of weight-bearing activity and bone geometry in this population. Failure to detect significant differences after correction for size may be explained by insufficient statistical power due to relatively small sample sizes. The discrepancy between our findings and those of the adult male runners for total CSA may also be explained by differences in size-normalization approaches, measurement sites, measurement techniques, age, maturity, and training history.

Swimmers and cyclists had the greatest size-adjusted medullary cavity cross-sectional areas of all groups and significantly higher values than the runners and triathletes. Medullary cavity CSA of cyclists remained higher than runners even after an additional adjustment for differences in age and years of specialized training. These findings suggest that nonweight-bearing sports such as swimming and cycling are associated with a larger medullary cavity than a sport such as running, which includes high-volume weight-bearing loading. The medullary cavity CSA of the triathletes, who also experience weight-bearing loading, albeit at a lower volume (hours), was intermediate to that of the runners and the two nonweight-bearing sports. Swimming and cycling involve relatively less bone on bone axial compressive loading, and, therefore, the nature and anatomical distribution of the strain patterns will vary considerably in these sports, compared with activities like running and triathlon, which impose both bending and higher axial compressive strains.

The generally larger size-adjusted medullary cavity (CSA) in swimmers and cyclists with smaller cortical CSA results in a lighter bone with its mass distributed relatively distally from the centroid. These geometric properties would translate into increased strength in bending, the predominant loading condition on the femur in both swimming and cycling. These differences in internal bone dimensions may reflect differential modeling responses on the endocortical surface of the femur to the local strain conditions imposed by the different loading patterns of these sports. Our findings suggest differential adaptation, both within the various bone compartments (mostly endocortical) and among groups associated with the varied mechanical-loading conditions of the sports in this study. Additionally, and although purely speculative, these geometric adaptations may also

FIGURE 2—Summary of size, age, and years of sport-specific training (YST) adjusted measures of mid-femur A) total, B) medullary cavity, and C) cortical bone cross-sectional areas across sport groups. Data are presented as bar graphs with + SD; *r, significantly greater than runners; *s, significantly greater than swimmers; *c, significantly greater than cyclists. Significant if P < 0.05.
confer a performance advantage in swimming and cycling by minimizing the external mass to be acted upon during movement in both sports and by increasing buoyancy in swimming.

Runners had the largest size-adjusted CSMIs, and these results were significantly greater than controls and both nonweight-bearing sports. The differences between runners and the nonweight-bearing sports swimming and cycling persisted even after further adjustments were made for age and years of sport-specific training. The CSMI of the triathletes was intermediate to the runners and the other sport groups. There is scant literature on the relationship between training and skeletal CSMI in humans. Two recent studies, however, have failed to demonstrate a positive relationship between increased weight bearing and CSMI in bones of the lower limbs in children (5) and adults (19). Our results suggest a positive association between mid-femur CSMI and weight bearing, but not weight-supported activity, at least among the teenage athletes investigated in this study. The discrepancy between studies may be explained by differences in loading characteristics, bone measurement sites, age, maturity, and training histories.

The CSMI is a biomechanical variable that reflects and correlates with the strength of bone in bending (18,19). Whereas bending would be the predominant loading condition in the nonweight-bearing sports of swimming and cycling, the weight-bearing sports of running and triathlon would, in addition to relatively high bending forces, also include substantial axial-compressive loading. The observed differences in CSMI between the weight-supported and nonweight-bearing groups in our study, therefore, may reflect the differential nature of the loading conditions (e.g., differences in the absolute and relative magnitudes of bending, compressive, and torsional strains, as well as differences in muscle moments) inherent in these sports. Furthermore, these differences may reflect sport-specific training adaptations favoring optimization of bone geometry for performance enhancement in these sports.

The bone strength index (BSI) reflects the combined influences of bone mineral status and bone geometry to bone strength (11). In our study, runners had a significantly larger size-adjusted BSI than controls, swimmers, and cyclists. After additional adjustments were made for age and years of sport-specific training, runners still had significantly higher BSI than both swimmers and cyclists. The differences in BSI among athlete groups were due principally to differences in CSMI, because cortical volumetric BMD was similar among groups. Moreover, the positive results of the triathletes (second highest CSMI and BSI of all groups) provide supplementary evidence to support weight-bearing activity as a potent osteogenic stimulus. Consistent with Frost’s mechanostat theory (13), differences in BSI among the athlete groups in the present study may reflect the mechanical requirements for performance success and/or long-term adaptations to the activity-specific mechanical-loading patterns inherent in these sports.

A number of studies (22,24) have utilized various bone size adjustment procedures and reported estimated measures of volumetric BMD derived from DXA. The assumptions underlying most of the DXA-based procedures are of questionable validity, especially concerning the shape and geometry of various human long bones such as the femur. MRI has the ability to ascertain accurate bone compartment volumes, and when combined with BMC from DXA, it is possible to determine true volumetric BMD for the bone organ in its entirety (total volumetric BMD) or for the cortical compartment separately (cortical volumetric BMD) over the mid-third femoral region.

Our study failed to demonstrate any significant differences in total mid-femoral volumetric BMD among groups. There was, however, a tendency (P < 0.09) toward increased total volumetric BMD in runners and triathletes, compared with controls in the present study. These findings are consistent with other studies (5,10) that have reported positive associations between weight-bearing activities and volumetric BMD in children. Failure to detect significant differences in total volumetric BMD in our study may be explained in part by insufficient statistical power. Alternatively, as supported by our findings and discussed below, skeletal adaptations to exercise in this study appear to have been mediated mostly by changes in the distribution of mineral within the periosteal compartment, which affect predominantly the internal geometry and biomechanical properties of the bone, rather than by changes in the mineral density of bone tissue itself. Failure to detect differences in total CSA in the present study, however, does not preclude the possibility of periosteal expansion under appropriate conditions (e.g., depending on the type of exercise and age/maturity of the
Our data suggest that interpretation of the putative influence of exercise on bone adaptation may vary, depending on whether comparisons are made solely on the basis of areal and compartmentalized (e.g., cortical) volumetric BMD or concurrently with the additional consideration of differences in bone geometry and biomechanical characteristics. There were no significant differences in areal (with the exception of the difference between runners and cyclist), total volumetric, or cortical volumetric BMD among groups in the present study, suggesting a lack of association between exercise, regardless of its nature (weight-bearing or non-weight-bearing), bone mineralization, and, by inference, bone strength. By contrast, our findings clearly indicate a positive association between weight-bearing exercise and bone biomechanical indices (CSMI and BSI) that reflect differences in the distribution of mineral within the various bone compartments and increased bone strength. The higher CSMI and BSI in runners and intermediate (between runners and the other groups) levels in triathletes would provide increased resistance (bone strength) to the relatively high bending strains induced by weight-bearing during running in both sports.

Our findings also suggest that the significant difference in areal BMD between the runners and cyclists was due entirely to differences in bone size, because the difference did not persist when BMC was normalized for cortical bone volume. The DXA technique adjusts BMC for scanned bone area, not bone volume, and this limitation may misrepresent true tissue level volumetric BMD differences or changes in human exercise studies. A similar finding was also reported in a recent study (16), where the greater BMC in the dominant arm of tennis players, compared with the nondominant arm, was primarily due to differences in bone size. Additionally, the similarity in cortical volumetric BMD among groups suggests that the constituent mineral density of cortical bone tissue is largely independent of the nature of the sport-specific loading patterns inherent in the sports investigated in this study. The gross morphology of bone (especially the endocortical compartment) and its biomechanical characteristics appear to be more strongly associated with sport-specific loading patterns inherent in this study than the constituent mineral composition of the tissue itself. Whether these findings apply to other skeletal regions and to other sports remains to be determined.

Collectively, these findings suggest that caution is warranted in the interpretation of bone strength adaptations to exercise based solely on differences in areal or volumetric BMD. DXA-derived areal and volumetric bone density measures are insensitive to changes in internal bone geometry and biomechanical properties, and may not provide an accurate estimate of bone strength in human exercise studies. For a more thorough understanding of skeletal adaptations to exercise in humans, future studies should, in addition to the traditional measures of BMC and BMD, also include measurements of bone geometry and biomechanical properties. This is perhaps an even more important issue in the developing, compared with the mature, skeleton, given the dramatic changes that occur in both internal and external bone dimensions during growth in humans (12).

We have used a simple qualitative approach in this study to differentiate the mechanical-loading characteristics of the various sports in terms of the relative contributions of compressive, torsional, and bending stresses placed on the femur during specific sport activities. We were unable to quantify the actual or relative contributions of ground reaction forces and muscle moments acting on the femur, which ultimately induce the aforementioned compressive, bending, and torsional stresses during these sport activities. Given the variability in muscle force requirements among different sports, and the putative importance of muscle force in osteogenic differentiation (14), this would seem an interesting and necessary follow-up to the current investigation.

Because this is a cross-sectional study, selection bias cannot be discounted as a possible explanation for the observed differences in gross bone geometry and biomechanical outcomes among groups. It makes little biological sense, however, to suggest that participation in these competitive sports is due entirely to selection based on larger bone dimensions. If differences were due entirely to selection on this basis, then this would be evident in both nonspecific as well as site-specific skeletal adaptations. This is clearly not the case in the present study, where there were no differences in stature (a general measure of overall skeletal size) or femur length among the various groups of athletes. Furthermore, there were no differences in BMD of the skull (2.05 ± 0.15–2.17 ± 0.19 g·cm⁻² means ± SD; P < 0.05) among groups, which some investigators (8) interpret as evidence against selection bias. Collectively, these findings suggest that the observed differences in bone geometry and biomechanical characteristics in our study are more likely associated with the sport- and site-specific loading patterns inherent to these sports than to selection bias based on skeletal size. Lastly, the validity of the MRI-derived estimates of volumetric BMD are dependent on the assumption of equal cortical bone porosity among groups; at comparable stages of maturity and in conditions of good health, as was the case for all subjects in the present study, we have no reason to believe that this assumption is incorrect.

In conclusion, our results in part support our hypothesis of a positive association between running, a weight-bearing sport, and mid-femur geometry and biomechanical indices in female teenagers. These positive associations were not only evident in the runners but also in triathletes, who included only 4 h of weight-bearing (running) into their regular weekly training program. These findings suggest that weight-bearing activity is positively associated with skeletal adaptations favoring increased bone strength and that relatively few hours of additional weight-bearing activity may be sufficient to counter the influence of weight-supported activity on bone geometry and biomechanical characteristics. Weight-supported activities (swimming and
and the importance of additional measures such as bone geometry and biomechanical properties when assessing the relationship between skeletal adaptation and mechanical loading in humans.

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