ABSTRACT • OBJECTIVE: The aim of this study was to compare femoral shaft and intertrochanteric geometry in overweight and normal weight adolescent girls.

METHODS AND RESULTS: This study included 22 overweight (Body mass index (BMI) > 25 kg/m²) adolescent girls (15.4 ± 2.4 years old) and 20 maturation-matched controls (15.2 ± 1.9 years old) (BMI < 25 kg/m²). Body composition and BMD were assessed by dual-energy X-ray absorptiometry (DXA). To evaluate bone geometry, DXA scans were analyzed at the femoral shaft and the intertrochanteric region by the Hip Structure Analysis (HSA) program. Cross-sectional area (CSA), an index of axial compression strength, section modulus (Z), an index of bending strength, cross-sectional moment of inertia (CSMI), cortical thickness (CT) and buckling ratio (BR) were measured from bone mass profiles. Lean mass, body weight, fat mass and BMI were higher in overweight girls compared to controls (p < 0.001). CSA, Z, CSMI and CT were higher in overweight girls compared to controls (p < 0.05) at the two regions (femoral shaft and intertrochanteric). After adjustment for maturation index (years since menarche), CSA, Z, CSMI and CT of the intertrochanteric region and CSA of the femoral shaft were higher in overweight girls compared to controls (p < 0.05). After adjustment for either body weight, lean mass or BMI, using a one-way analysis of covariance (ANCOVA), there were no differences between the two groups (overweight and controls) regarding the HSA variables (CSA, CSMI, Z, CT and BR) at the femoral shaft and the intertrochanteric.

CONCLUSION: This study suggests that overweight adolescent girls have greater indices of bone axial and bending strength in comparison to controls at the intertrochanteric after adjustment for maturation index.
INTRODUCTION

Body weight is one of the strongest predictors of weight-bearing bone mineral density (BMD) in adults and adolescents [1-10]. BMD is a surrogate for bone strength but not a measurement of it [11]. In fact, bone strength is not only determined by the amount of bone mineral, but also by its spatial distribution with respect to the loading forces that may be encountered [11]. Interestingly, Beck et al. [12] developed a computer program to derive hip geometry from bone mineral data for an estimate of hip strength [12]. The program, called Hip Structure Analysis (HSA), was developed originally to improve the predictive value of hip bone mineral data for osteoporosis fracture risk assessment [12-13]. With this program, measurements or estimates of the mineralized bone surface cross-sectional area (CSA), the cross-sectional moment of inertia (CSMI), the section modulus (Z), the buckling ratio (BR), and cortical thickness (CT) can be obtained [12-22]. Several studies have already used HSA to describe age-related changes, ethnic and sex differences in hip strength [14-17]. Furthermore, HSA has been used to explore the effect of physical activity on bone strength in children and adolescents [20-22]. Recently, we have used this program to detect the effect of being overweight on femoral neck geometry in adolescent girls and showed that overweight adolescent girls have greater indices of bone axial and bending strength in comparison to controls at the femoral neck [8]. In this study, we aimed at verifying whether such differences in bone strength are present at the femoral shaft and the intertrochanteric region in the same population.

MATERIAL AND METHODS

Subjects and study design

The study participants were recruited from four private schools in Beirut, Lebanon. Inclusion criteria were being post-menarchal (at least one year of regular menstrual cycles), adolescent, sedentary (practicing less than 2 h of physical activity per week and not involved in impact sports) girls from 12 to 20 years of age with no diagnosis of comorbidities and no history of fracture. The girls were nonsmokers and had no history of major orthopaedic problems or other disorders known to affect bone metabolism. Moreover, girls participating in this study were not pregnant and had not taken hormonal contraceptives for the past 6 months. In this study, the number of years since menarche was considered as a maturation index (MI). Girls were divided into a group of overweight (BMI > 25 kg/m²; n = 22) and a group of control girls (BMI < 25 kg/m²; n = 20). These two groups were matched for physical activity level. This study did not include extremely lean (BMI < 16 kg/m²) girls or extremely obese (BMI > 40 kg/m²) girls. Informed written consents were obtained from the children and their parents.

This study was approved by the University of Balamand Ethics Committee.

Anthropometric measurements

Height (cm) was measured in the upright position to the nearest 1 mm with a Seca standard stadiometer. Body weight (kg) was measured on a Taurus mechanic scale with a precision of 100 g. The girls were weighed wearing only underclothes. BMI was calculated as body weight divided by height squared (kg/m²). Body composition (lean mass, fat mass, body fat percentage) was assessed by dual-energy DXA (Hologic QDR-4500W; Waltham, MA).

Bone mass measurements

Bone mineral content (BMC, in g) and density (BMD, in g/cm³) were determined for each individual. The DXA measurements were completed at the total hip (TH) and at the femoral neck (FN) using the instrument previously described (Hologic QDR-4500W; Waltham, MA). The Hologic APEX software, version 2 (1986–2007, Hologic Inc.) was used to analyze the DXA scans on the Hologic machine. In our laboratory, the coefficients of variation were < 1.5% for BMD in adults [23]. The same certified technician performed all analyses using the same technique for all measurements.

Hip structure analysis (HSA)

The proximal femur densitometry scans were analyzed for geometric properties of bone structure using the Hip Structure Analysis (HSA) software program developed by Beck et al. [12, 14]. The HSA technique calculates dimensions of bone cross-sections at specific locations across the proximal femur using bone mass images generated by absorptiometry scanners. In brief, the HSA program measures bone mineral density and geometry of cross-sections using distributions of mineral mass traversing the bone axis, averaged for precision over five parallel lines (5 mm) across the bone axis. The intertrochanteric and the femoral shaft regions were analyzed in this study (Figure 1). Bone cross-sectional area

![Figure 1. Hip image from a Hologic DXA scanner showing positions of thin analysis regions across the femur at the neck, intertrochanteric and femoral shaft. On the left are shown typical bone mass profiles used in measurements of geometric properties.](image-url)
(CSA; cm²) and section modulus (Z; cm³) were determined directly from the bone profile at the intertrochanteric and the femoral shaft regions using algorithms described previously [14-17]. CSA is equivalent to the amount of bone surface area in the cross-section after excluding soft tissue space and is proportional to conventional bone mineral content in the corresponding cross-section. In mechanical terms, CSA is an indicator of resistance to loads directed along the bone axis. Section modulus (Z) is an indicator of strength of the bone to resist bending and torsion [14-17]. Estimates of average cortical thickness (CT; cm) were calculated by modeling the cortex as concentric circular (femoral shaft) or elliptical (intertrochanteric) annuli [14-17]. The algorithm assumes that 70% and 100% of the measured CSA is in the cortex for the intertrochanteric and the femoral shaft regions respectively [14-17]. The intertrochanter model also assumes that the anteroposterior outer diameter is the outer diameter of the shaft region measured in the scan plane [14-17]. Buckling ratio (BR), a mechanical index of wall stability in thin-walled tubes, was calculated as the distance from the center of mass to the medial or lateral cortex (whichever distance was larger) divided by the estimated average cortical thickness [14-17]. High values of BR can approximate conditions in osteoporotic bone in which the cortex has become structurally unstable [14-17]. The CSMI (cm³)² is the cross-sectional moment of inertia and is derived from the integral of the bone mass weighed by the square of distance from the center of mass. The CSMI is relevant for bending in the plane of the DEXA image [14-15]. Repeated bone densitometry scans that could permit an assessment of HSA precision were not collected in this study, but precision error (CV %) for HSA variables at the intertrochanteric and the femoral shaft regions by scanner manufacturer has been published by Khoo et al. [24] and Nelson et al. [17].

**Daily calcium intake**

The estimation of the daily calcium intake was based on a frequency questionnaire [25]. Selection of items was based on the food composition diet, frequency of use, and relative importance of food items as a calcium source. The questionnaire totaled 30 food items and included the following: milk and dairy products; calcium-enriched items such as yoghurt, cheese and chocolate; eggs, meat, fish, cereals, bread, vegetables and fruits. Adequacy of calcium in the subjects was assessed using the adequate intake guidelines of 1300 mg of calcium.

**Statistical analysis**

Basic data are presented as mean ± standard deviation (SD) (Tables I & II). Comparisons between the overweight and the control group were made after checking for Gaussian distribution. If Gaussian distribution was found, parametric unpaired t tests were used. In other cases, Mann-Whitney U tests were used. Associations between clinical characteristics, BMD and HSA variables were given as Pearson correlation coefficients. Multiple linear regression analysis models were used to test the relationship between CSA with lean and fat mass, as well as Z with lean and fat mass. HSA variables were compared after adjustment for total body weight, lean mass, fat mass, BMI, BMD and maturation index (MI) using a one-way analysis of covariance (ANCOVA). The difference was considered statistically significant at p < 0.05. Data were analyzed using NCSS (2001).

**RESULTS**

**Clinical characteristics and bone mineral density of the subjects**

Clinical characteristics of adolescent girls are displayed in Table I. Age, MI, height and daily calcium intake were not different between the two groups. The mean BMI in the control group was 21.5 and the main BMI in the overweight group was 28.5. Overweight girls had significantly higher total body weight, lean mass, fat mass, BMI, BMD and maturation index (MI) using a one-way analysis of covariance (ANCOVA). The difference was considered statistically significant at p < 0.05. Data were analyzed using NCSS (2001).

**Absolute HSA variables**

At the intertrochanteric region, overweight girls had higher CSA (p < 0.01), CSMI (p < 0.05), Z (p < 0.01), CT (p < 0.05) and lower BR (p < 0.05) when compared to controls (Table II).

At the femoral shaft region, overweight girls had higher CSA (p < 0.05), CSMI (p < 0.05), Z (p < 0.05) and CT (p < 0.05) when compared to controls (Table II).
Associations between clinical characteristics, bone mineral density and crude HSA variables at the intertrochanteric region
Age and maturation index were not significantly associated with HSA variables. Body weight, lean mass, fat mass, BMI, TH BMD and FN BMD were all positively correlated to CSA, CSMI, Z and CT (p < 0.001) and negatively correlated to BR (p < 0.05) (Table III).

Fat mass was not positively related to CSA or Z after adjusting for lean mass. Lean mass was positively correlated to CSA and to Z even after adjusting for fat mass (p < 0.001). Daily calcium intake was not related to HSA variables.

Associations between clinical characteristics, bone mineral density and crude HSA variables at the femoral shaft
Age and maturation index were not significantly associated with HSA variables. Body weight, lean mass, fat mass, BMI, TH BMD and FN BMD were all positively correlated to CSA, CSMI, Z and CT (p < 0.001) and negatively correlated to BR (p < 0.05) (Table IV).

Fat mass was not positively related to CSA or Z after adjusting for lean mass. Lean mass was positively correlated to CSA and to Z even after adjusting for fat mass (p < 0.01; p < 0.05 respectively). Daily calcium intake was not related to HSA variables.

Adjusted HSA variables at the intertrochanteric region
When HSA variables were adjusted for either weight, lean mass, BMI or fat mass, CSA, CSMI, Z, CT and BR were not significantly different between the two groups. When HSA variables were adjusted for TH BMD or FN BMD, CSA, CSMI, Z, CT and BR were not significantly different between the two groups. Finally, when HSA variables were adjusted for maturation index, overweight girls displayed higher values of CSA, CSMI, Z and CT in comparison to control girls (p < 0.05).

Adjusted HSA at the femoral shaft region
When HSA variables were adjusted for either weight, lean mass or BMI, CSA, CSMI, Z, CT and BR were not significantly different between the two groups. When HSA variables were adjusted for fat mass, control girls displayed higher values of Z in comparison to overweight girls (1.91 ± 0.05 vs. 1.68 ± 0.05 respectively). When HSA variables were adjusted for TH BMD or FN BMD, CSA, CSMI, Z, CT and BR were not significantly different between the two groups. Finally, when HSA variables were adjusted for maturation index, overweight girls displayed higher values of CSA in comparison to control girls (p < 0.05).

### TABLE II:
**HIP STRUCTURE ANALYSIS VARIABLES IN OVERWEIGHT AND CONTROL ADOLESCENT GIRLS**

<table>
<thead>
<tr>
<th>Variables</th>
<th>Overweight (n = 22)</th>
<th>Controls (n = 20)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSA (cm²)</td>
<td>4.59 ± 0.65**</td>
<td>4.03 ± 0.52</td>
</tr>
<tr>
<td>CSMI (cm²)²</td>
<td>10.41 ± 2.05*</td>
<td>8.88 ± 1.96</td>
</tr>
<tr>
<td>Z (cm²)</td>
<td>3.65 ± 0.80**</td>
<td>3.10 ± 0.62</td>
</tr>
<tr>
<td>CT (cm)</td>
<td>0.389 ± 0.051*</td>
<td>0.350 ± 0.042</td>
</tr>
<tr>
<td>BR</td>
<td>7.43 ± 1.06*</td>
<td>8.29 ± 1.35</td>
</tr>
<tr>
<td><strong>FEMORAL SHAFT</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSA (cm²)</td>
<td>3.72 ± 0.51*</td>
<td>3.34 ± 0.40</td>
</tr>
<tr>
<td>CSMI (cm²)²</td>
<td>2.79 ± 0.59*</td>
<td>2.43 ± 0.56</td>
</tr>
<tr>
<td>Z (cm²)</td>
<td>1.91 ± 0.33*</td>
<td>1.68 ± 0.28</td>
</tr>
<tr>
<td>CT (cm)</td>
<td>0.514 ± 0.071*</td>
<td>0.468 ± 0.062</td>
</tr>
<tr>
<td>BR</td>
<td>2.89 ± 0.43</td>
<td>3.11 ± 0.51</td>
</tr>
</tbody>
</table>

Values are means ± SD

**CSA:** cross sectional area  **CSMI:** cross-sectional moment of inertia  **Z:** section modulus  **CT:** cortical thickness  **BR:** buckling ratio

* p < 0.05  ** p < 0.01  *** p < 0.001

### TABLE III
**CORRELATIONS (r) BETWEEN CLINICAL CHARACTERISTICS, BONE MINERAL DENSITY AND HSA VARIABLES AT THE INTERTROCHANTERIC REGION**

<table>
<thead>
<tr>
<th>Variables</th>
<th>CSA (cm²)</th>
<th>CSMI (cm²)²</th>
<th>Z (cm²)</th>
<th>CT (cm)</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>- 0.03</td>
<td>0.07</td>
<td>0.11</td>
<td>- 0.18</td>
<td>0.26</td>
</tr>
<tr>
<td>MI (years)</td>
<td>0.14</td>
<td>0.17</td>
<td>0.20</td>
<td>- 0.001</td>
<td>0.16</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>0.71***</td>
<td>0.70***</td>
<td>0.74***</td>
<td>0.56***</td>
<td>- 0.36*</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>0.46**</td>
<td>0.65***</td>
<td>0.67***</td>
<td>0.31*</td>
<td>- 0.09</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>0.68***</td>
<td>0.58***</td>
<td>0.62***</td>
<td>0.53***</td>
<td>- 0.41**</td>
</tr>
<tr>
<td>Lean mass (kg)</td>
<td>0.78***</td>
<td>0.70***</td>
<td>0.72***</td>
<td>0.56***</td>
<td>- 0.35*</td>
</tr>
<tr>
<td>Fat mass (kg)</td>
<td>0.64***</td>
<td>0.63***</td>
<td>0.69***</td>
<td>0.52***</td>
<td>- 0.40**</td>
</tr>
<tr>
<td>TH BMD (g/cm²)</td>
<td>0.86***</td>
<td>0.59***</td>
<td>0.63***</td>
<td>0.87***</td>
<td>- 0.76**</td>
</tr>
<tr>
<td>FN BMD (g/cm²)</td>
<td>0.90***</td>
<td>0.70***</td>
<td>0.74***</td>
<td>0.86***</td>
<td>- 0.72***</td>
</tr>
</tbody>
</table>

**HSA:** hip structure analysis  **CT:** cortical thickness  **MI:** maturation index (years since menarche)  **BR:** buckling ratio  **MID:** bone mineral density  **BMID:** bone mineral density  **TH:** total hip  **FIND:** femoral neck

* p < 0.05  ** p < 0.01  *** p < 0.001
DISCUSSION

In this study comparing 22 overweight adolescent girls to 20 normal weight adolescent girls, being overweight was associated with significantly greater indices of bone axial and bending strength at intertrochanteric region after adjustment for maturation index.

Several previous studies aimed at exploring the effects of obesity or overweight on bone mineral content and BMD in children and adolescents [1, 3-6, 26-30]. However, the effect of being overweight on bone mass in this period of life is not completely elucidated. The conflicting results of the studies may be related to differing approaches to the assessment of two-dimensional projected DXA bone measures relative to age, bone size, and body size [4]. In addition, the relation between fat mass and BMD is largely influenced by sex [1, 31]. Bone strength is not only determined by BMD, but also by bone geometry (the way that mineral is distributed) [11]. In this study, we aimed at exploring the effect of being overweight on bone strength indices at the femoral shaft and the intertrochanteric region using the HSA program developed by Beck et al. [12]. Our results showed that overweight girls had greater absolute indices of bone axial and bending strength in comparison to controls at the femoral shaft and the intertrochanteric region. These results are in accordance with those of Petit et al. [32]. Hence, this study suggests a positive influence of being overweight on bone strength in adolescent girls. Furthermore, HSA variables were not significantly different between the two groups after adjustment for lean mass or weight. These results reinforce the hypothesis which states that bone geometry is appropriately adapted to lean mass in adolescents [32]. Interestingly, fat mass was also a negative determinant of BR. This result is clinically important because BR is a stronger determinant of CSA and Z than fat mass related to CSA, CSMI, Z and CT; however, lean mass was a stronger determinant of CSA and Z than fat mass.

Age and maturation index were not positively associated with HSA variables. In fact, the rate of increase in BMD decreases rapidly after the menarche [20, 33]. Harel et al. [34] reported that the correlations between age on one hand and hip BMD and femoral neck BMD on the other hand disappeared after adjusting for BMI and maturation in 389 healthy postmenarchal adolescent girls. Jackowski et al. [33] showed in a longitudinal study conducted on adolescent girls that the age of peak CSA velocity at the femoral shaft was 12.1 and the age of peak Z velocity at the same region was 12.2. In our study, the lack of correlations between age and maturation index on one hand and CSA and Z on the other hand may be explained by the large variance in BMI and age as well as by the small number of subjects.

Total hip and femoral neck BMD were positively related to CSA, CSMI, Z and CT and negatively related to BR at the two regions (intertrochanteric and femoral shaft). This result seems logical since it is well established that BMD is a strong predictor of bone strength [35].

Weight, BMI, lean mass and fat mass were positively related to CSA, CSMI, Z and CT; however, lean mass was a stronger determinant of CSA and Z than fat mass. In reality, bone adapts its strength primarily to dynamic rather than static load [4, 32].

In our study group, daily calcium intake (764 mg) was below the daily requirements in this age group (1300 mg) [36-38]. These results are in line with those of several studies which measured DCI in Lebanese adolescents [36-38]. Also, we showed a lack of correlation between DCI and HSA variables. These results confirm those of [9]. Indeed, it is well known that increasing fat mass may lead to hyperinsulinemia and a decreased production of sex hormone-binding globulin in the liver [9]. These phenomena result in increased free concentrations of sex hormones, resulting in reduced osteoclast activity and possibly increased osteoblast activity, leading to increased bone mass and probably bone strength [8-9].

**TABLE IV**

<table>
<thead>
<tr>
<th>CORRELATIONS (r) BETWEEN CLINICAL CHARACTERISTICS, BONE MINERAL DENSITY AND HSA VARIABLES AT THE FEMORAL SHAFT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Age</strong> (years)</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>0.10</td>
</tr>
<tr>
<td>0.20</td>
</tr>
<tr>
<td>0.76***</td>
</tr>
<tr>
<td>0.62**</td>
</tr>
<tr>
<td>0.66***</td>
</tr>
<tr>
<td>0.75***</td>
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<tr>
<td>0.70***</td>
</tr>
<tr>
<td>0.84***</td>
</tr>
<tr>
<td>0.70***</td>
</tr>
</tbody>
</table>

HSA: hip structure analysis
CT: cortical thickness
TH: total hip
CSA: cross sectional area
CSMI: cross-sectional moment of inertia
Z: section modulus
BR: buckling ratio
MI: maturation index (years since menarche)
BMD: bone mineral density
FN: femoral neck
BMI: body mass index

* $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$
two reports in adolescents [31, 36].

Some limitations of this study deserve comment. The cross-sectional nature of the study is a limitation because it cannot evaluate the confounder variables. The second limitation is the two-dimensional nature of DXA [39-40]. Furthermore, vitamin D status and Tanner stages were not assessed in this study. Additionally, there are well-known difficulties in assessing diet using self-reported questionnaires [41]. For instance, food-frequency questionnaires provide a limited list of foods and do not allow specific ingredients to be entered for analysis [41]. Furthermore, the hip (including total hip and proximal femur) is not an ideal site for measurement of BMD in growing children due to significant variability in skeletal development and lack of reproducible regions of interest [42]. Finally, one assumption in the HSA algorithm is that bones are fully mineralized, which may not be the case in adolescents [39-40, 43]. The effect of an overestimate of mineralization can influence “true” CSA and Z values [32, 39-40].

In conclusion, this study conducted on a group of adolescent girls shows that being overweight is associated with greater absolute indices of bone axial and bending strength at the femoral shaft and the intertrochanteric region. However, after adjustment for either weight, BMI or lean mass, there are no differences between overweight and control girls regarding the HSA variables at the femoral shaft and the intertrochanteric region.

ACKNOWLEDGMENTS

This study was supported by a grant from the research council of the University of Balamand, Lebanon.

The authors state that they have no conflicts of interest.

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