BONE MEASUREMENTS BY PERIPHERAL QUANTITATIVE COMPUTED TOMOGRAPHY (pQCT) IN CHILDREN WITH CEREBRAL PALSY
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Objective To use peripheral quantitative computed tomography (pQCT) to determine bone measurements in patients with cerebral palsy (CP) age 3 to 20 years and compare them with control subjects.

Study design A total of 13 (5 male) patients with CP, along with 2 sex- and age-matched controls for each, were included in a mixed-model analysis with matched pairs as random effects for pQCT bone measurements of the 20% distal tibia.

Results Tibia length was similar in the CP and control groups (P = .57). Weight was marginally higher in the control group (P = .06). Cortical bone mineral content (BMC), area, thickness, polar strength-strain index (pSSI), and periosteal and endosteal circumferences were greater in the control group (P < .05 for all). Relationships between bone measurements and weight showed that cortical BMC, area, periosteal circumference, and pSSI were greater at higher weights in the control group (group-by-weight interaction, P < .05 for all). Cortical thickness was greater in the control group and was correlated with weight. Cortical volumetric bone mineral density (vBMD) was greater with higher weights in the CP group (group-by-weight interaction, P = .03).

Conclusions Bone strength, as indicated by pSSI, is compromised in children with CP due to smaller and thinner bones, not due to lower cortical bone density. (J Pediatr 2005;147:791-6)

Fractures are prevalent in children with cerebral palsy (CP), with the femur the most common site, followed by the tibia. Repeated fractures diminish the quality of life and add to the care requirements of these children. CP is increasing in prevalence, and fractures continue to be a challenge for patients and clinicians.

Areal bone mineral density (aBMD) measurements by dual-energy X-ray absorptiometry (DXA) of the lateral distal femur, developed specifically for use in CP patients, as well as standard measurements of the spine and proximal femur by DXA, have been used to assess bone quality. Several studies in CP show a relationship between bone measures and weight-bearing ability. In a study of 139 children with spastic CP, aBMD z-scores of the proximal femur and spine were lower in nonambulators than in normal ambulators. Another study in children with moderate to severe CP found lower lateral distal femur and spine aBMD z-scores in children with gross motor functional classification 5 (more motor impairment) than in children with gross motor functional classification 3 (less motor impairment). Weight-bearing physical activity has been shown to increase total proximal bone mineral content (BMC) and femoral neck BMC in children with CP who participated in an 8-month exercise program compared with those who maintained their usual activity.

Relationships between bone-loading and bone measures also have been shown in other populations. For example, side-to-side differences in periosteal apposition among racquet-sport players show greater increases in the impact-loaded side. Eser et al recently reported bone changes in geometry and volumetric bone mineral density (vBMD)
using peripheral quantitative computed tomography (pQCT) in adults with spinal cord injuries. They found that total cross-sectional area of the diaphyses of the femur and tibia did not change postinjury, but the cortical cross-sectional area decreased with time, indicating that the loss in area is due to endosteal resorption. The walls of the bones became thinner, but not less dense.

### Table. Anthropometric and Bone Parameters by Group (Mean ± SD)

<table>
<thead>
<tr>
<th></th>
<th>CP</th>
<th>Control</th>
<th>p-valuea</th>
</tr>
</thead>
<tbody>
<tr>
<td>N (male)</td>
<td>13 (5)</td>
<td>26 (10)</td>
<td></td>
</tr>
<tr>
<td>Age (yr)</td>
<td>10.2 ± 5.5</td>
<td>10.3 ± 5.3</td>
<td>0.96</td>
</tr>
<tr>
<td>Tibia Length (mm)</td>
<td>289 ± 66</td>
<td>284 ± 69</td>
<td>0.57</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>30.6 ± 15.5</td>
<td>36.2 ± 18.0</td>
<td>0.06</td>
</tr>
<tr>
<td>Cortical BMCb</td>
<td>59 ± 36</td>
<td>120 ± 63</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Cortical vBMDc</td>
<td>985 ± 106</td>
<td>1014 ± 83</td>
<td>0.09</td>
</tr>
<tr>
<td>Cortical Area (mm²)</td>
<td>57 ± 31</td>
<td>115 ± 54</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Cortical Thickness (mm)</td>
<td>1.4 ± 0.7</td>
<td>2.1 ± 0.8</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Periosteal Circumference (mm)</td>
<td>45.5 ± 5.9</td>
<td>59.5 ± 9.8</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Endosteal Circumference (mm)</td>
<td>36.7 ± 6.0</td>
<td>46.2 ± 7.1</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>pSSId (mm³)</td>
<td>267 ± 129</td>
<td>747 ± 427</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>

a p-value from mixed model analysis.
b BMC = bone mineral content.
c vBMD = volumetric bone mineral density.
d polar Stress-Strain Index.

**Figure 1.** Cortical area by weight. Δ CP; ○ control. Group-by-weight interaction, P < .001.

**Figure 2.** Periosteal circumference by weight. Δ CP; ○ control. Group-by-weight interaction, P = .02.

**Figure 3.** Endosteal circumference by weight. Δ CP; ○ control. No group-by-weight interaction. Group P < .001; no main effect of weight.

pQCT technology images a cross-sectional view of the limb and provides measures of bone size and geometry not attainable with DXA. The purpose of the current study was to use pQCT in children with CP and compare the findings with those from sex- and age-matched control subjects. Our hypothesis was that the bones of children with CP would
have smaller periosteal circumferences and thinner cortical shells than those of the control group, but that cortical vBMD would not differ between the groups. Therefore, bone strength as measured by the polar strength-strain index (pSSI) from pQCT imaging will be lower in children with CP and compromised due to smaller bone size, not decreased cortical density.

**METHODS**

Participants were recruited from a long-term residential care facility. Two sex- and age-matched (± 6 months) control subjects for each case were randomly selected from an existing database of healthy children obtained from the same geographic region. The protocol was approved by the institutional review boards at South Dakota State University and the University of South Dakota. Informed consent was signed by a parent if the child was not of adult age and also if the child was of adult age but the parent had legal guardianship. Otherwise, informed consent was signed by the participant. Age of participants ranged from 2.6 to 20.8 years (mean age, 10.3 years). All subjects with CP except 1 were nonambulatory, though the therapy program for most subjects included a standing program for 2 to 5 hours/week. pQCT scans were attempted on 15 of the 18 participants with CP who returned consents. Two participants were physically unable to position in the scanner, 1 had rods in both lower legs, and 2 had uncontrollable spasms at the time of the scan. Therefore, 13 (5 male) participants with CP (10 spastic quadriplegic, 1 spastic triplegic, 1 spastic hemiplegic, and 1 hypotonic quadriplegic), along with 2 sex- and age-matched controls for each case, were included in the final analysis.

Scans of the 20% distal tibia were obtained using a 6-detector XCT2000 bone densitometer (Norland Stratec Medical Systems, White Plains, NY). Our coefficients of variation (CV%) from duplicate scans at this site in children age 5 to 11 years ranged from 0.48% for periosteal circumference to 2.29% for cortical thickness, and those in adults ranged...
from 0.51% for periosteal circumference to 1.17% for cortical thickness, as reported previously. The length of the tibia from the medial knee joint line to the medial malleolus was measured using a segmometer (Rosscraft, Blain, Wash), and 20% of the length was then measured and marked from the distal end. The marked site was scanned without the use of a scout view. Settings to obtain the scans and analysis modes for all outcomes except the pSSI were as reported previously.11 The pSSI was analyzed using cort mode 1 and a threshold of 280 mg/cm³, as described previously.13

Adjustments to accommodate participants with CP while scanning included an acrylic splint to support the leg and a rolled towel to provide padded protection to the leg in case of spasm. Sedation was not used. The children with CP were scanned while sitting in their wheelchairs or, for the smaller children, with a staff person holding them. All other scanning procedures were comparable to those for the normative study group.

In the normative group, weight in light clothing was measured to the nearest 0.1 kg using a digital scale (Seca 770, Hamburg, Germany). In the CP group, weights were measured with a Healthometer ProPlus Stretcher/Lift scale (Pelstar LLC, Bridgeview, Ill).

Statistical analysis was performed using JMP IN 5.1 software (SAS Institute, Cary, NC). A mixed-model approach was used to analyze the data and assess group differences. To account for matching, the identification variable for matched case and its 2 controls was entered into the model as a random effect. The significance of the group-by-weight interaction term was determined, to identify whether the relationship between the bone measurements and weight was similar between groups. Tibia length was added to the model as a covariate to control for the scaling of cortical dimensions to bone length. Bone measurements included cortical BMC (mg/mm), cortical vBMD (mg/cm³), cortical area (mm²), cortical thickness (mm), periosteal circumference (mm), endosteal circumference (mm), and pSSI (mm³).

**RESULTS**

Means and standard deviations for anthropometric and bone measurements by group and P values from matched-pairs analysis are given in Table. Cortical BMC, cortical area, cortical thickness, periosteal circumference, endosteal circumference, and pSSI differed by group (all P < .05), whereas tibia length and cortical vBMD did not differ. Weight was marginally greater in the control group than in the CP group. Group-by-weight interactions were significant (P ≤ .05) in mixed models for cortical area, periosteal circumference, cortical BMC, and pSSI. Model outcomes are shown graphically in Figures 1 to 7. Cortical area, periosteal circumference, cortical BMC, and pSSI were greater with higher weight in the control group than in the CP group. Cortical thickness was greater in the control group and was greater at higher weights. Endosteal circumference was greater in the control group, but did not change with higher weight. Cortical vBMD was greater with higher weights in the CP group (group-by-weight interaction, P = .03). The relationship between cortical vBMD and cortical thickness is shown in Figure 8 (group-by-cortical thickness interaction, P = .01). Cortical vBMD was higher in the CP group at higher cortical thickness.

![Figure 7](image1.png)  
**Figure 7.** Cortical density by weight. ▲, CP; □, control. Group-by-weight interaction, P = .03.

![Figure 8](image2.png)  
**Figure 8.** Cortical density by cortical thickness. ▲, CP; □, control. Group-by-cortical thickness interaction, P = .01.
In patients with CP, standard measurements for bone density and geometric bone measurements are limited because of joint contractures, bony deformities from fractures or surgical procedures, metallic implants, positioning confines, and uncontrollable movements that invalidate the scans. pQCT methods are not immune to these challenges. In general, pQCT imaging can be used to measure peripheral bones and obtain trabecular bone measurements at an ultra-distal site while cortical bone measurements are acquired from the shaft of the bone. Because trabecular bone changes are dramatic between the endplate of the bone and 10% from the distal end, a scout view scan is used to set a reference line at the endplate, then the computer calculates and moves the scanner to the exact slice location. The scout view, although adding accuracy to the measurement, takes more time, and any movement between the scout view and slice imaging can invalidate the scan. A cortical site, such as the 20% distal tibia, can be acquired without a scout view. From a practical standpoint, a site involving less scanning time and greater probability of obtaining acceptable scans would seem to be advantageous when working with patients with CP. Our previous studies have shown significant changes in bone measures at the 20% distal tibia site with bone-loading exercises, and we have shown significant changes in bone measures at the 20% distal tibia site when working with patients with CP. Our previous studies obtaining acceptable scans would seem to be advantageous when working with patients with CP. From a practical standpoint, the scan. A cortical site, such as the 20% distal tibia, can be acquired without a scout view. From a practical standpoint, a site involving less scanning time and greater probability of obtaining acceptable scans would seem to be advantageous when working with patients with CP. Our previous studies have shown significant changes in bone measures at the 20% distal tibia site with bone-loading exercises, and we have published centile curves for bone measures from healthy children at this site. For these reasons, we focused on the 20% distal tibia site for this initial study in patients with CP. We have established criteria for acceptable pQCT scans at our institution and, in our effort to use these methods in children with CP, obtained successful scans on 13 of the 15 patients (87%). However, when interpreting these data, it is important to note that we did not obtain scans on the most severe cases.

An unexpected finding was that the tibia length of the children with CP was not on average less than that of their sex- and age-matched controls. This was unexpected because children with severe CP are well known to have diminished linear growth. This finding can be explained in part by the fact that the growth and nutritional status of this cohort were somewhat better than is typical of this population. The mean height and weight z-scores in this cohort were −1.4 and −0.9, respectively. In a recent multicenter study of growth involving more than 200 children with moderate to severe CP, the mean height z-score was −2.9 and mean weight z-score was −2.1. Subjects in the multicenter study lived at home, and perhaps growth is better in a residential center setting with professional care providers. It is important to note that pronounced deficits in cortical thickness and periosteal circumference were observed even in this cohort with growth and nutritional status generally considered “very good” for children with severe CP.

Weight-bearing activity has been shown to increase estimated volumetric BMD and total proximal femur and femoral neck BMC in children with CP. In our study, there were only marginal differences in weight; however, the patients’ load-bearing abilities were severely compromised. Our data show that with increasing weight there were greater increases in measures of bone size (cortical area and periosteal circumference) in the weight-bearing control group compared with the compromised weight-bearing CP group. Cortical thickness also was greater in the control group, and pSSI was greater with increasing weight in the control group.

The pSSI, an indicator of bone strength, is calculated considering both geometric properties (bone size) and material properties (bone density) of the bone. Measurements of cortical vBMD, a material property of bone, are affected by cortical thickness readings using pQCT due to the partial volume effect. We previously reported that cortical vBMD is underestimated when the cortical thickness measures < 2 mm. In the present study, we found that children with CP appear to have greater cortical vBMD than control subjects at higher cortical thicknesses. Therefore, bone strength as indicated by pSSI is compromised in children with CP due to smaller and thinner bones, not due to lower cortical vBMD.

Our pQCT measures showing decreased periosteal circumference and greater vBMD at higher cortical thickness in patients with CP can be related to principles of bone biology, namely modeling and remodeling. A recent review relating the principles of bone biology with available diagnostic methods indicates that bone geometry measures by pQCT can be used as surrogates to estimate modeling and remodeling rates in developing bone. Children with CP may theoretically have higher vBMD measures because of decreased cortical bone remodeling; this is particularly true in older children. Cortical porosity is increased during periods of high modeling and remodeling, which would be expected with bone-loading activities during growth. Because patients with CP are not bearing weight, it is likely that bone modeling–remodeling is decreased, leading to reduced periosteal circumference and increased vBMD (decreased cortical porosity). We thank the participants, parents, and hospital staff for their support for our research. Special thanks to Dan Schiferl for his input on modifications and positioning devices to aid in scanning.

REFERENCES

8. Chad KE, Bailey DA, McKay HA, Zello GA, Snyder RE. The effect of a weight-bearing physical activity program on bone mineral content and...


