Habitual Levels of Vigorous, But Not Moderate or Light, Physical Activity Is Positively Related to Cortical Bone Mass in Adolescents

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Context: The intensity of habitual physical activity (PA) needed to affect skeletal development in childhood is currently unclear.

Objective: To examine associations between light PA, moderate PA, and vigorous PA (as assessed by accelerometry), and tibial cortical bone mass (BMCC) as measured by peripheral quantitative computed tomography.

Design/Setting: Cross-sectional analysis based on the Avon Longitudinal Study of Parents and Children.

Participants: A total of 1748 boys and girls (mean age 15.5 yr) participated in the study.

Outcome Measures: We measured BMCC, cortical bone mineral density, periosteal circumference, and endosteal circumference by tibial peripheral quantitative computed tomography.

Results: Multivariable models, adjusted for height and other activity levels, indicated vigorous PA was positively related to BMCC ($P = 0.0001$). There was little evidence of a relationship with light PA or moderate PA (both $P > 0.7$). In path analyses, the relationship between vigorous PA and BMCC [0.082 (95% confidence interval [CI]: 0.037, 0.128), $P = 0.0004$] (SD change per doubling of vigorous PA) was minimally attenuated by adjusting for body composition [0.070 (95% CI: 0.026, 0.115), $P = 0.002$]. In analyses adjusted for body composition, the relationship between vigorous PA and BMCC was explained by the periosteal circumference pathway [0.043 (95% CI: 0.004, 0.082), $P = 0.03$] and the endosteal circumference adjusted for periosteal circumference pathway [0.031 (95% CI: 0.011, 0.050), $P = 0.002$], while there was little contribution from the cortical bone mineral density pathway ($P = 0.3$).

Conclusions: Vigorous day-to-day PA is associated with indices of BMCC and geometry in adolescents, whereas light or moderate PA has no detectable association. Therefore, promoting PA in childhood is unlikely to benefit skeletal development unless high-impact activities are also increased. (J Clin Endocrinol Metab 96: E793–E802, 2011)

Mechanical strain is an important determinant of skeletal growth and modeling. For example, animal studies have demonstrated that bone strain (i.e. deformation relative to bone length) stimulates bone formation in proportion to its rate and magnitude (1, 2). Bone strain is directly related to the strength of applied force, which for the lower limbs comprise ground reaction forces generated during weight-bearing activities (3, 4). Therefore, there has been considerable interest in the effect of physical activity (PA) on bone development in childhood, and in particular whether increased weight-bearing PA during this time results in a higher peak bone mass and strength of the lower limb,
thoroughly reducing the risk of osteoporotic hip fracture in later life. For example, in 22 trials of effects of weight-bearing exercise interventions on bone mineral accrual in childhood, generally positive effects were observed particularly during early puberty (5). Although these previous studies largely involved analysis of bone mass by dual-energy x-ray absorptionmetry (DXA) scans, a limited number of investigations have examined skeletal development using newer technology such as peripheral quantitative computed tomography (pQCT), which provides more detailed information about changes in cortical bone geometry and strength. For example, in 410 10-yr-old children, a school-based weight-bearing activity program increased tibial bone strength in prepuberal boys over the 16-month intervention period (6).

Because these investigations did not include dose-ranging studies, they shed little light on the minimum amount of activity required to stimulate bone development in childhood. In terms of cross sectional studies examining relationships with habitual levels of PA, in a pQCT-based study of 1068 18-yr-old men by Lorentzon et al. (7), a minimum threshold of 4 h per week participation in sporting activity was identified for influencing cortical bone size. In contrast, in Avon Longitudinal Study of Parents and Children (ALSPAC), whereas bone size as assessed by DXA was related to moderate and vigorous PA combined, which reflects the amount of PA with an intensity equivalent to moderately brisk walking or greater, we did not observe a specific response to vigorous PA reflecting sports participation (8).

The apparent lack of a dose-response relationship between intensity of PA and bone development in our study based on ALSPAC may have reflected our use of DXA as opposed to pQCT; the latter may provide a more precise estimate of the skeletal response to exercise, particularly if this involves a specific effect on cortical bone size, which pQCT measures directly. Therefore, to establish whether a dose-response relationship exists between intensity of habitual PA and cortical bone size, we examined the relationship between further accelerometry recordings obtained in ALSPAC at age 15.5 yr and contemporaneous tibial pQCT scans. We also investigated whether relationships between PA and bone development which we found are independent of body composition, in light of our finding that positive associations between PA and bone mass may in part be explained by coassociation with lean mass (LM), whereas any tendency for PA to increase bone mass may be offset by associated decreases in fat mass (FM) (8).

Materials and Methods

Study population

ALSPAC is a geographically based birth cohort study investigating factors influencing the health, growth, and development of children. All pregnant women resident within a defined part of the former county of Avon in South West England with an expected date of delivery between April 1991 and December 1992 were eligible for recruitment, of whom 14,541 were enrolled (9) (http://www.alspac.bristol.ac.uk). Ethical approval was obtained from the ALSPAC Law and Ethics committee and relevant local ethics committees. Data in ALSPAC are collected by self-completion postal questionnaires sent to parents, by linkage to computerized records, by abstraction from medical records, and from examination of the children at research clinics.

Bone and anthropometric variables

Cortical bone mineral content (BMCc), cortical bone mineral density (BMDc), and cortical bone area (BACc) of the mid (50%) right tibia were obtained using a Stratec XCT2000L during the age 15.5 research clinic (Stratec, Pforzheim, Germany). Periosteal and endosteal circumference, and cortical thickness, were derived using a circular ring model. Strength strain index (SSI) was derived from section modulus weighted according to BMDc, based on standard methods (10). Cortical bone was defined using a threshold above 650 mg·cm⁻³; the methods have recently been described in detail (11). Total body FM and LM were measured using DXA (GE Lunar Prodigy, Madison, WI). Height was measured using a Harpenden stadiometer (Holtain Ltd., Crymych, UK). All densitometric and anthropometric measures were taken in the 15.5-yr research clinic. Puberty was assessed using a self-completed Tanner stage questionnaire (pubic hair domain) at a mean age of 14.8 yr.

Actigraph

All children who attended the age 15.5 clinic were asked to wear an MTI Actigraph accelerometer for 7 d (models 7164 or GT1M, Manufacturing Technology, Fort Walton Beach, FL). The Actigraph is a small, lightweight, electronic motion sensor comprising a single plane (vertical) accelerometer worn in an elasticated belt on the right hip. Movement in a vertical plane is detected as a combined function of the frequency and intensity of the movement. The Actigraph has been validated in both children and adolescents (12, 13). Children were asked to wear the Actigraph for seven consecutive days during waking hours and only to take it off for showering, bathing, water sports, contact sports, or sports where there was a high risk of falling onto the monitor (e.g. gymnastics or martial arts).

Data are recorded in 1-min intervals and classified into four bands of PA, namely sedentary, light, moderate, and vigorous PA, defined using cut points of 0–199 cpm, 200–3599 cpm, 3600–6199 cpm, and 6200+ cpm, respectively. Moderate PA and vigorous PA cut points were based on a calibration study performed in a subgroup of 246 children (110 boys) at age 12, in whom these count frequencies were associated with energy expenditure of 4 (brisk walking at 5.8 km·h⁻¹) and 6 metabolic equivalents of task (METS), (jogging at 9.2 km·h⁻¹), respectively (14). Each individual’s accumulated PA was categorized into different intensities, and average minutes of light, moderate, and vigorous PA per day were subsequently calculated. Valid recordings were defined as a minimum of 10 h recording per day for 3 d.

Statistical analyses

Descriptive statistics are presented as means and SD, and medians and lower and upper quartiles. Linear regression was used.
to examine relationships between light, moderate, and vigorous PA and pQCT-derived bone and strength parameters. Analyses were adjusted for age and height at the time of pQCT measurements, because as well as being related to pQCT parameters these variables might also be related to PA and hence confound these associations. Analyses were also adjusted for duration of accelerometer recordings, with additional analyses adjusted for exposure to activity of other intensities. Minutes of moderate PA and vigorous PA were log-transformed to ensure homoskedastic residuals, and β coefficients were then multiplied by log(2) and interpreted as per doubling in activity. Minutes of light PA did not require log transformation, and consequently β coefficients represent per SD change in light activity. Gender interactions were used to explore possible differences in activity responses between sexes.

Path analyses were used to examine the association between PA and BMCC, via direct associations with bone (e.g., periosteal and endosteal circumference and BMDc) and via indirect associations with body composition (FM and LM) (see Fig. 2). The effect of PA on BMCC, via any given route is estimated by the product of path coefficients for each individual element of the overall pathway, of which the latter were obtained after standardization of regression coefficients by z-transformation. To generate robust 95% confidence intervals for path analyses, bootstrapping was performed by randomly sampling the data with replacement with a sample size equal to the original, thereby generating 10,000 replicate data sets; path coefficients were then calculated for each data set and the mean and 95% percentile confidence interval subsequently generated.

All missing data were treated as missing at random, and complete case analysis was performed in all analyses. Analyses were conducted using STATA 9.2.

**Results**

**Recruitment**

Of the 14,541 mothers enrolled in the study, there were 14,062 live-births. Of these, 5,532 children attended the 15.5-yr research clinic, and 4,373 individuals had complete pQCT/DXA measures (89 pQCT scans excluded because of poor quality). Accelerometer data were available in 2,993 individuals, satisfactory recordings were obtained in 2,115 (defined as minimum of 3 d of 600 min recording per day). Sixty-two percent of males vs. 58% of females had missing PA measures. Participants with PA measures were slightly younger (3 wk), slightly shorter (5 mm), and correspondingly slightly lighter (1 kg). After adjusting for age, height, and sex, the relative deficit in LM in participants with PA measures was 365 g (P = 0.002), and that in BMCC was 2.5 mg (P = 0.039). Complete-case data were available in 1,748 individuals.

**Descriptive analyses**

Among the 1,748 individuals with PA measures, boys were taller and heavier than girls and had greater LM but less FM (Table 1). BMCC was greater in boys compared with girls, reflecting their larger periosteal circumference and cortical thickness, whereas BMDc was greater in girls. Pubertal status assessed by Tanner stage was available in 581 boys (I + II = 2%, III = 12%, IV + V = 86%) and 765 girls (I + II = 1%, III = 8, IV + V = 91%), girls were more advanced in puberty compared with boys, but the majority of the cohort were considered to be in an advanced puberty (Tanner IV + V).

Boys partook in longer durations of light, moderate, and vigorous PA than girls. Activity intensity as reflected by mean counts per minute were slightly greater in boys compared with girls within light and moderate PA bands, whereas intensity within the vigorous PA band was greater in girls, as previously found (8). When considering intensity (overall mean cpm) levels across sedentary, light, moderate, and vigorous PA bands combined, results were higher in boys compared with girls (507 ± 188 vs. 411 ± 144, P < 0.0001). There was positive correlation between all bands of PA; light vs. moderate (Pearson’s correlation r = 0.30, rgirls 0.18), light vs. vigorous (rboys 0.18, rgirls 0.21), moderate vs. vigorous (rboys 0.52, rgirls 0.43), P < 0.0001 in all instances.

**Relationships between activity and pQCT parameters: minimally adjusted analyses**

In minimally adjusted analyses between BMCC and PA, there was little evidence of an association with light PA on BMCC (β = 0.009), some evidence of an association with moderate PA (β = 0.024), and stronger evidence of an association with vigorous PA (β = 0.055) (Table 2). Vigorous PA likewise showed the strongest association with BAC, such that a doubling in vigorous PA was associated with a 2.1-mm² increase in BAC, and there was approximately a 7-mm² difference in BAC between subjects in the upper and lower quartiles.

BMCC is largely determined by BAC, which is a reflection of periosteal circumference and endosteal circumference adjusted for periosteal circumference, with a smaller contribution from BMDc(11). To examine the mechanisms by which PA influences BMCC, associations were initially examined between activity and periosteal circumference, endosteal circumference adjusted for periosteal circumference, and BMDc in minimally adjusted analyses (Table 2). Light PA was positively related to periosteal circumference (β = 0.04), no effect was seen with endosteal circumference adjusted for periosteal circumference, and an inverse relationship was observed with BMDc (β = −0.084). There was no association between moderate PA and periosteal circumference (β = 0.015), a weak inverse association of borderline significance with endosteal circumference adjusted for periosteal circumference (β = −0.019), and a weak inverse association with BMDc (β = −0.025). The effect of vigorous PA on BMCC...
resulted from an increase in \( BAC \) attributable to a positive association with periosteal circumference (\( \beta = 0.037 \)) and an inverse association with endosteal circumference adjusted for periosteal circumference (\( \beta = 0.041 \)), which was opposed by an inverse association with BMDC (\( \beta = 0.031 \)).

**Relationships between activity and pQCT parameters: analyses adjusted for other types of PA**

In analyses of PA on BMCC adjusted for other intensity levels, there was no longer evidence of a relationship with moderate PA, and results were instead suggestive of a threshold effect whereby only vigorous PA increased BMCC (Fig. 1). Equivalent results were obtained when analyses were restricted to subjects with completed Tanner stage questionnaires and subsequently adjusted for pubertal stage (data not shown). There was evidence to suggest the association between vigorous PA and BMCC was greater than light PA and BMCC (\( P = 0.016 \)), similarly the association of vigorous PA and BMCC was greater than moderate PA and BMCC (\( P = 0.022 \)). A similar pattern of associations was observed for SSI.

**Relationships between activity and body composition**

We recently reported that body composition affects BMCC via changes in PC, endosteal circumference adjusted for periosteal circumference, and \( BMD_C \) (11). To explore relationships between PA, pQCT parameters, and body

### TABLE 1. Descriptive statistics

| Variable                      | Sex   | Mean (SD) | 25th % | Median | 75th % |
|-------------------------------|-------|-----------|--------|--------|--------|
| Age (yr)                      | Boys  | 15.4 (0.23)| 15.3   | 15.4   | 15.5   |
|                               | Girls | 15.5 (0.24)| 15.3   | 15.4   | 15.5   |
| Height (cm)                   | Boys  | 174.0 (7.44)| 169.4  | 174.4  | 179.0  |
|                               | Girls | 164.6 (6.18)| 160.1  | 164.4  | 168.7  |
| Weight (kg)                   | Boys  | 62.8 (11.0)| 55.5   | 61.5   | 68.3   |
|                               | Girls | 58.6 (10.5)| 51.7   | 56.8   | 64.0   |
| Tibia length (cm)             | Boys  | 386.7 (25.0)| 37.0   | 39.0   | 40.0   |
|                               | Girls | 362.4 (22.3)| 35.0   | 36.0   | 38.0   |
| Fat mass (kg)                 | Boys  | 10.9 (7.43)| 5.7    | 8.8    | 13.3   |
|                               | Girls | 18.6 (8.03)| 13.2   | 17.0   | 22.0   |
| Lean mass (kg)                | Boys  | 49.1 (6.51)| 45.2   | 49.2   | 53.4   |
|                               | Girls | 36.9 (3.99)| 34.2   | 36.6   | 39.5   |
| BMCC (mg)                     | Boys  | 349.0 (51.5)| 313.7  | 350.0  | 384.8  |
|                               | Girls | 308.5 (41.8)| 278.6  | 306.8  | 334.3  |
| BMDC (mg cm\(^{-3}\))        | Boys  | 1075.3 (32.9)| 1053.8 | 1078.1 | 1099.0 |
|                               | Girls | 1124.0 (23.3)| 1110.0 | 1126.5 | 1139.6 |
| BA\(_C\) (mm\(^2\))          | Boys  | 324.3 (45.2)| 292.9  | 325.3  | 354.3  |
|                               | Girls | 274.6 (37.3)| 248.4  | 272.4  | 297.6  |
| Periosteal circumference (mm) | Boys  | 75.9 (5.24)| 72.6   | 75.8   | 79.3   |
|                               | Girls | 69.5 (4.99)| 66.1   | 69.1   | 72.6   |
| Endosteal circumference (mm)  | Boys  | 40.9 (5.82)| 37.1   | 40.4   | 43.7   |
|                               | Girls | 37.1 (5.39)| 33.5   | 36.5   | 39.8   |
| Cortical thickness (mm)       | Boys  | 5.6 (0.68)| 5.1    | 5.6    | 6.0    |
|                               | Girls | 5.2 (0.58)| 4.8    | 5.2    | 5.5    |
| Activity duration (min/d)     | Light activity (min) | Boys | 254.2 (63.1)| 211.7  | 250.4  | 290.5  |
|                               | Girls | 234.7 (54.3)| 198.1  | 229.7  | 266.0  |
|                               | Moderate activity (min) | Boys | 25.6 (17.1)| 13.0   | 22.7   | 35.7   |
|                               | Girls | 15.8 (13.2)| 6.3    | 12.4   | 21.7   |
|                               | Vigorous activity (min) | Boys | 4.3 (5.8) | 0.7    | 2.1    | 5.7    |
|                               | Girls | 2.2 (3.7) | 0.2    | 1.0    | 2.6    |
|                               | Average recording time (min) | Boys | 881.3 (104.4)| 816.3  | 861.3  | 920.3  |
|                               | Girls | 866.7 (99.7)| 808.0  | 850.3  | 900.3  |
| Activity intensity (counts/min\(^{-1}\)) | Light activity (counts/min\(^{-1}\)) | Boys | 987.3 (144.7)| 885.2  | 975.8  | 1082.5 |
|                               | Girls | 948.3 (137.1)| 857.0  | 935.5  | 1027.9 |
|                               | Moderate activity (counts/min\(^{-1}\)) | Boys | 4503.1 (246.5)| 4334.6 | 4490.4 | 4666.6 |
|                               | Girls | 4372.7 (276.6)| 4180.2 | 4354.6 | 4535.5 |
|                               | Vigorous activity (counts/min\(^{-1}\)) | Boys | 8269.7 (2390.4)| 6937.4 | 7529.0 | 8541.8 |
|                               | Girls | 8877.7 (2766.6)| 7041.4 | 8021.8 | 9513.7 |

Descriptive statistics of boys (\( n = 778 \)) and girls (\( n = 970 \)) with pQCT scans and a complete set of covariates. Physical activity data are presented as mean number of minutes per day within each band of activity, averaged over all valid days of recording; physical activity data are also shown as mean counts per minute for light, moderate, and vigorous activity bands. \( P < 0.0001 \) for all sex differences except mean recording time \( P < 0.002 \), and age \( P = 0.37 \).
composition, we subsequently examined associations between PA and FM and LM. Unlike light and moderate PA, which had little effect on FM, vigorous PA was inversely related to FM (Table 3). Light and vigorous PA activities were positively related to LM, whereas little association was observed for moderate PA. P values for sex interactions were above nominal levels for statistical significance (Table 3), but there was some evidence of a gender interaction in that β coefficients were approximately twice as great in boys compared with girls with respect to the inverse association between vigorous PA and FM; on the other hand, β coefficients were approximately twice as great in girls for the positive association between light and vigorous PA and LM.

### Relationships between activity, body composition, and pQCT parameters: path analyses

Path analyses were then performed to examine the relationship between vigorous PA, body composition, and pQCT parameters by modeling the interrelationships between vigorous PA (adjusted for other activity levels), light and moderate PA activities, body composition, and pQCT parameters: path analyses.

| Table 2. Minimally adjusted analyses between PA and cortical bone parameters |
|------------------------|-----------------|-----------------|-----------------|------------------|-----------------|
| Outcome                | Activity        | Adjusted        | Sex              | β                | (95% CI)         | P                | P (Sex diff)     |
|                        |                 | Age/height/average recording time |                  |                   |                 |                  |                 |
|                        | Light           | Boys −0.004 (−0.057, 0.049) | −0.8913          | 0.5143           |
|                        |                 | Girls 0.022 (0.033, 0.076) | 0.4369           |
|                        | All 0.009 (−0.029, 0.047) | 0.6565           |
|                        | Moderate        | Boys 0.011 (0.033, 0.054) | 0.6303           | 0.4282           |
|                        |                 | Girls 0.033 (0.002, 0.068) | 0.0656           |
|                        | All 0.024 (−0.003, 0.051) | 0.0835           |
|                        | Vigorous        | Boys 0.041 (0.004, 0.077) | 0.0280           | 0.2840           |
|                        |                 | Girls 0.070 (0.031, 0.109) | 0.0004           |
|                        | All 0.055 (0.028, 0.081) | 0.0001           |
|                        | BAc              | Boys 0.017 (−0.033, 0.067) | 0.5909           | 0.6802           |
|                        |                 | Girls 0.032 (−0.019, 0.083) | 0.2229           |
|                        | All 0.024 (−0.012, 0.060) | 0.1856           |
|                        | Moderate        | Boys 0.022 (−0.019, 0.062) | 0.2959           | 0.7072           |
|                        |                 | Girls 0.032 (−0.001, 0.065) | 0.0611           |
|                        | All 0.028 (0.002, 0.053) | 0.0347           |
|                        | Vigorous        | Boys 0.050 (0.016, 0.085) | 0.0039           | 0.4818           |
|                        |                 | Girls 0.068 (0.032, 0.105) | 0.0002           |
|                        | All 0.059 (0.034, 0.084) | 0.0000           |
|                        | Periosteal circumference | Boys 0.020 (−0.030, 0.070) | 0.4401           | 0.2545           |
|                        | Light           | Girls 0.061 (0.010, 0.113) | 0.0192           |
|                        |                 | All 0.040 (0.004, 0.076) | 0.0287           |
|                        | Moderate        | Boys −0.009 (−0.050, 0.031) | 0.6486           | 0.1235           |
|                        |                 | Girls 0.032 (−0.001, 0.065) | 0.0606           |
|                        | All 0.015 (−0.010, 0.041) | 0.2439           |
|                        | Vigorous        | Boys 0.020 (−0.015, 0.054) | 0.2671           | 0.1422           |
|                        |                 | Girls 0.057 (0.021, 0.094) | 0.0022           |
|                        | All 0.037 (0.012, 0.063) | 0.0037           |
|                        | Endosteal circumference | Boys −0.005 (−0.047, 0.038) | 0.8272           | 0.6283           |
|                        | Light           | Girls 0.010 (−0.033, 0.054) | 0.6433           |
|                        | Adjusted        | All 0.003 (−0.028, 0.033) | 0.8679           |
|                        | perioseal        | Boys −0.029 (−0.064, 0.005) | 0.0946           | 0.4532           |
|                        | circumference   | Girls −0.012 (−0.041, 0.016) | 0.3901           |
|                        | Moderate        | Boys −0.044 (−0.073, −0.015) | 0.0033           | 0.7928           |
|                        |                 | Girls −0.038 (−0.069, −0.007) | 0.0167           |
|                        | All −0.041 (−0.062, −0.020) | 0.0002           |
|                        | BMDc             | Boys −0.099 (−0.148, −0.050) | 0.0001           | 0.3905           |
|                        | Light           | Girls −0.068 (−0.118, −0.018) | 0.0083           |
|                        |                 | All −0.084 (−0.119, −0.049) | 0.0000           |
|                        | Moderate        | Boys −0.055 (−0.095, −0.015) | 0.0074           | 0.0566           |
|                        |                 | Girls −0.004 (−0.037, 0.028) | 0.7893           |
|                        | All −0.025 (−0.050, 0.001) | 0.0574           |
|                        | Vigorous        | Boys −0.048 (−0.082, −0.014) | 0.0062           | 0.1589           |
|                        |                 | Girls −0.012 (−0.048, 0.024) | 0.5206           |
|                        | All −0.031 (−0.056, −0.006) | 0.0150           |

The association of light, moderate, and vigorous activity on pQCT parameters adjusted for age, height, and average recording time in boys (n = 778) and girls (n = 970). β coefficients represent the change in pQCT parameter per 11 increase in light activity and per doubling in moderate or vigorous activity. P values are shown for sex-specific and combined associations and the difference between sexes (sex interaction). Bold values indicate combined results.

The relationship between PA and cortical bone parameters was examined using path analyses, which allowed for the examination of the direct and indirect effects of PA on bone outcomes, while controlling for potential confounders such as age and body composition. The results indicated that vigorous PA had a positive relationship with cortical bone parameters, whereas light and moderate PA had a more moderate effect. The association between PA and cortical bone parameters was found to be stronger in girls compared to boys, suggesting a possible gender interaction. This finding highlights the importance of considering sex differences in the design and interpretation of PA interventions aimed at improving bone health.
Finally, we analyzed the relationship between vigorous PA (adjusted for other activity levels) and BMC$_C$, adjusted for height, LM, and different pQCT parameters (Fig. 2). In the first instance, the relationship between vigorous PA and BMC$_C$ was analyzed according to three different routes namely periosteal pathway, endosteal circumference adjusted for periosteal circumference, and BMD$_C$ (Fig. 3, bottom). In this model, the relationship between vigorous PA and BMC$_C$ was largely explained by the periosteal circumference pathway (product of path coefficients $= 0.043$) and the endosteal circumference adjusted for perios- teal circumference pathway (product of path coefficients $= 0.031$), with little contribution from the BMD$_C$ pathway (product of path coefficients $= -0.003$). Whereas the magnitude of perios- teal circumference and endosteal circumference adjusted for periso- teal circumference pathways were similar in girls, the perios- teal circumference pathway was approximately 50% greater than endosteal circumference adjusted for perios- teal circumference in boys.

**Discussion**

We examined the relationship between habitual exposure to different intensity levels of PA as measured by accelerometers and cortical bone development as assessed by pQCT scans of the mid-tibia in a large cohort of adolescents. Whereas minimally adjusted analyses revealed a dose-response relationship between intensity of PA and effects on BMC$_C$, in analyses adjusted for different intensity levels, the relationship between PA and BMC$_C$ appeared to be largely explained by the amount of vigorous PA. Therefore, whereas the amount of more intense PA like jogging is positively associated with cortical bone mass in adolescents, it would appear that less intense exercise such as walking has relatively little association in an adolescent population.

The positive association between vigorous PA and BMC$_C$ that we observed was explained by an equivalent association with BA$_C$, which reflected broadly equal contributions from increased perios- teal and reduced endosteal circumference. BA$_C$ is an important determinant of bone strength by virtue of its contribution to parameters such as SSI, which was also positively related to vigorous PA. Therefore, our finding of a 7-mm$^2$ difference between children whose levels of vigorous PA are in the top and bottom quartile of the PA distribution may have impor- tant clinical consequences. Although we have previously found that only 4% of fractures in ALSPAC are of the tibia (15), equivalent relationships between PA and cortical bone strength are likely to exist for other weight-bearing sites such as the hip (16). Therefore, to the extent that cortical bone structure in adolescence is related to that in later life, the relationships between PA and pQCT param-
eters reported here may be of relevance to future risk of hip fracture.

Our results are consistent with those of a previous bone loading intervention in preschool children, which was found to increase tibial periosteal circumference (17). In contrast, in another study examining effects of a jumping intervention, whereas increased tibial strength was observed in prepubertal boys, no change was seen in cortical area (6). The present findings are also in line with previous observational studies based on pQCT, in which the amount of current or previous participation in sporting activity was found to be positively related to tibial cross-sectional area (an indicator of periosteal apposition) in young adult men (7, 18, 19). Our results are also consistent with reports that weight-bearing exercise interventions increase bone mass accrual in children as assessed by DXA (5, 20). Observational studies based on DXA measurements in children also provide evidence of a positive relationship between exposure to vigorous PA and bone mass accrual. For example, the amount of vigorous PA as assessed by accelerometry was positively related to total body, hip, and spinal bone mineral content in preschool children (21). Furthermore, in our previous study in ALSPAC, the amount of moderate/vigorous PA was positively related to total body bone mass and height-adjusted bone area in 11-yr-old children, indicating a possible influence on periosteal bone growth in line with findings from the present study (8).

As well as the finding that the amount of vigorous PA was positively related to BMC_C, another important observation was that in multivariable models adjusting for exposure to activity of different intensities, the amount of light and moderate PA was unrelated to cortical bone mass in adolescence, suggesting that there is a threshold of intensity below which activity does not affect bone accrual. One important implication of these findings is that walking, which represents the most common type of light and moderate PA, may have little benefit in terms of improving

![FIG. 2. Theoretical relationships between PA, body composition, bone shape, and density. Direction of effect is indicated by +ve (positive) effects, −ve (negative) effects, and ?ve (direction not currently clear) effects. PC, periosteal circumference; EC, endosteal circumference.](image-url)
cortical bone mass in adolescence. Therefore, although promotion of walking is an important component of public health campaigns intended to reduce obesity (22), our results suggest that this activity is unlikely to benefit the skeleton in the young. Consistent with this suggestion, an interventional study of women entering menopause, which combined reduced fat intake with increased levels of moderate PA such as walking, led to accelerated bone loss (23).

Previous observational studies have also attempted to identify thresholds below which activity has no discernible effect on cortical bone. For example, studies based on the Gothenberg Osteoporosis and Obesity Determinants (GOOD) Study cohort reported that sporting activity has to last for more than 4 h/wk to affect tibial cortical area (7), and that sporting activities associated with jumping have a greater effect on tibial cross sectional area compared with those associated with other weight-bearing activities (19). To our knowledge this is the first report to show that as assessed by accelerometry, whereas habitual vigorous PA is associated with indices of bone development, no association is evident for moderate PA, suggesting that a threshold exists in skeletal response on transition from the equivalent of brisk walking to jogging (i.e. below and above 6 kcal·kg⁻¹·h⁻¹, respectively).

The present findings contrast with those of our previous study in ALSPAC based on 11-yr-old children, in which although moderate and vigorous PA were positively related to DXA-based variables, this was largely attributable to an effect of moderate PA, with no evidence of an equivalent threshold effect to that reported here (8). This inconsistency could reflect the fact that pQCT as used in the present study is considerably more precise in evaluating changes in cortical bone characteristics at weight-bearing sites as compared with total body DXA. An alternative explanation is that the skeleton of post-pubertal children as studied here is less sensitive to mechanical strain compared with that of pre- and peripubertal population studied previously. The latter interpretation is consistent with evidence from interventional studies that weight-bearing exercises are more effective at increasing bone parameters in pre- and peripubertal children as compared with those past puberty (5).

Given the strong associations between PA and body composition as confirmed here, and the relationship between body composition and pQCT parameters (11), we also wished to examine the extent to which the effect of PA on cortical bone, which we found was mediated by changes in body composition. Whereas vigorous PA in-

![FIG. 3. The association of vigorous PA (vigorously) with BMC via LM, FM, and an independent bone pathway (top, body composition pathways). The association of vigorous PA with BMC via peristeal circumference (PC), endosteal circumference adjusted for peristeal circumference (ECPC), and BMDC pathways (bottom, independent bone pathways). Bootstrap path coefficients (with 95% confidence limits) represent SD change per doubling in vigorous activity (P-values are also indicated adjacent to each path). Sex interactions (differences between the sexes) for the association between vigorous PA and BMC via body composition pathways: LM (P = 0.0672), FM (P = 0.0291), bone (P = 0.7024), total (P = 0.8668), and via independent bone pathways PC (P = 0.3619), ECPC (P = 0.7197), and BMDC (P = 0.1266). Arrow sizes are proportional to the strength of the association, with solid arrows indicating positive association and dashed arrows negative association. Bold formatting indicates P < 0.05.

**TABLE 1.** The association of vigorous PA with BMC via LM, FM, and an independent bone pathway (top, body composition pathways). The association of vigorous PA with BMC via peristeal circumference (PC), endosteal circumference adjusted for peristeal circumference (ECPC), and BMDC pathways (bottom, independent bone pathways). Bootstrap path coefficients (with 95% confidence limits) represent SD change per doubling in vigorous activity (P-values are also indicated adjacent to each path). Sex interactions (differences between the sexes) for the association between vigorous PA and BMC via body composition pathways: LM (P = 0.0672), FM (P = 0.0291), bone (P = 0.7024), total (P = 0.8668), and via independent bone pathways PC (P = 0.3619), ECPC (P = 0.7197), and BMDC (P = 0.1266). Arrow sizes are proportional to the strength of the association, with solid arrows indicating positive association and dashed arrows negative association. Bold formatting indicates P < 0.05.

| Boys N=778 | Girls N=970 | All N=1748 |
|------------|-------------|------------|
| **Body Composition Pathways** | | |
| Vigorous | | |
| PC: P=0.008 | BMDC: P=0.012 | 
| 0.079 (95% CI: 0.010, 0.146) | 0.079 (95% CI: 0.012, 0.146) | 0.079 (95% CI: 0.012, 0.146) |
| Lean: P=0.110 | Lean: P=0.001 | Lean: P=0.001 |
| 0.015 (95% CI: -0.001, 0.033) | 0.015 (95% CI: -0.001, 0.033) | 0.015 (95% CI: -0.001, 0.033) |
| Bone: P=0.001 | Bone: P=0.011 | Bone: P=0.011 |
| 0.079 (95% CI: 0.012, 0.146) | 0.079 (95% CI: 0.012, 0.146) | 0.079 (95% CI: 0.012, 0.146) |
| Fat: P=0.829 | Fat: P=0.110 | Fat: P=0.110 |
| 0.3619 | 0.3619 | 0.3619 |
| **Independent Bone Pathways** | | |
| Vigorous | | |
| PC: P=0.079 | PC: P=0.049 | PC: P=0.031 |
| 0.079 (95% CI: 0.012, 0.146) | 0.079 (95% CI: 0.012, 0.146) | 0.079 (95% CI: 0.012, 0.146) |
| Lean: P=0.001 | Lean: P=0.001 | Lean: P=0.001 |
| 0.015 (95% CI: -0.001, 0.033) | 0.015 (95% CI: -0.001, 0.033) | 0.015 (95% CI: -0.001, 0.033) |
| Bone: P=0.011 | Bone: P=0.011 | Bone: P=0.011 |
| 0.079 (95% CI: 0.012, 0.146) | 0.079 (95% CI: 0.012, 0.146) | 0.079 (95% CI: 0.012, 0.146) |
| Fat: P=0.3619 | Fat: P=0.049 | Fat: P=0.049 |
| 0.3619 | 0.3619 | 0.3619 |
| **Summary** | | |
| ∑ Vig. PA on BMC: P=0.024 | ∑ Vig. PA on BMC: P=0.0048 | ∑ Vig. PA on BMC: P=0.0004 |
| 0.079 (95% CI: 0.010, 0.146) | 0.086 (95% CI: 0.027, 0.146) | 0.082 (95% CI: 0.037, 0.128) |
| ∑ Vig. PA on Bone: P=0.020 | ∑ Vig. PA on Bone: P=0.032 | ∑ Vig. PA on Bone: P=0.0016 |
| 0.079 (95% CI: 0.012, 0.146) | 0.062 (95% CI: 0.005, 0.118) | 0.070 (95% CI: 0.026, 0.115) |
| Positive association | Negative association | |
increased and decreased lean and FM, respectively, these opposing actions largely cancelled each other out, implying that associated changes in body composition have little effect on the overall impact of PA on cortical bone mass. In view of our previous observation that FM is positively related to cortical bone mass more strongly in girls compared with boys (11), changes in FM might be expected to modify the effect of PA on pQCT parameters to a greater extent in girls. However, there are also gender differences in how PA affects obesity, because PA appeared to have less tendency to reduce FM in girls, in keeping with results of previous reports from ALSPAC based on analyses at earlier ages (24, 25).

Although the 3600 and 6200 cpm thresholds which we used to indicate moderate and vigorous PA were originally defined on the basis of energy expenditure, in a previous calibration study these thresholds were related to the difference between brisk walking and running (14), of which the latter activity is associated with greater mechanical strain (1.5 and 2.3 G, respectively) (26). However, though the output of accelerometers is related to mechanical loading, the latter was not measured directly, which represents a limitation of the use of accelerometer in this way. As accelerometers were worn for a minimum of 3 d, they may have only captured a limited amount of any given individual’s participation in PA, particularly vigorous PA, which was relatively rare. Based on our previous validation study in which 246 12-yr-old children wore accelerometers for 7 d four times over the course of a given year, measurement over a single time period detects approximately 50% of the overall variability in activity between children as recorded by repeated measurements (27). A further potential limitation is the approach of analyzing separate associations with light, moderate, and vigorous activity given the close relationships which exist between these, which can potentially result in colinearity. However, based on $r^2$ values, a given activity level explained a maximum of 25% of the variability of another level, supporting our approach of analyzing associations of pQCT parameters with distinct activity levels.

Because of time constraints within the measurement clinic it was only possible to scan a single site, and no information was obtained about trabecular bone. In addition, because the study was based on 1748 individuals, which comprises less than 20% of the original ALSPAC cohort at inception, they may not be representative of the general population. In comparison with 2300 individuals who attended the research clinic and did not participate in the PA monitoring, subjects included in this study had a slightly lower LM, which may have reflected the fact that they were slightly more sedentary than the ALSPAC population as a whole, in view of the positive association between LM and PA. Finally, because this was a cross-sectional analysis, we are unable to exclude the possibility that relationships between activity and cortical bone phenotypes is not attributable to reverse causation or unmeasured confounders.

In conclusion, we found that habitual levels of vigorous PA as assessed by accelerometry was positively related to $\text{BMC}_C$ of the mid tibia in a population-based cohort of adolescents, whereas no independent effect was seen for moderate or light PA. This association was explained by a relationship between vigorous PA and $\text{BA}_C$, reflecting equal contributions from increased peristeal circumference and decreased endosteal circumference. There was also evidence of an indirect pathway between vigorous PA and $\text{BMC}_C$ involving changes in body composition, but this only made a limited contribution to the overall association. Assuming that this influence of PA on cortical bone applies to other weight-bearing sites such as the hip, and that these changes in bone structure persist into later life, our findings suggest that adolescent participation in vigorous PA, but not moderate PA or light PA, may have long-term benefits for skeletal health.

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