

Measuring Children's Vertical Ground Reaction Forces with Accelerometry During Walking, Running, and Jumping: The Iowa Bone Development Study

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Ground reaction forces (GRF) are associated with bone hypertrophy; therefore, they are important to understanding physical activity's role in children's bone health. In this study, we examined the ability of accelerometry to predict vertical GRF in 40 children (mean age 8.6 yr) during slow walking, brisk walking, running, and jumping. Correlation coefficients between accelerometry-derived movement counts and GRF were moderate to high and significant during walking and running, but not during jumping. Given a large proportion of children's daily physical activity involves ambulation, accelerometry should be useful as a research method in bone-related research. However, this method underestimates GRF during jumping, an important physical activity for bone modeling and remodeling.

Introduction

To date, the best understood link between physical activity and children's health status has been cardiovascular, specifically physical activity's impact on the metabolic pathways that improve cardiovascular profiles (3,18). Energy expenditure is the assumed biological mechanism, though specifics involving the frequency, intensity, and duration are still being examined and defined (13). Researchers interested in children's cardiovascular health outcomes, as well as researchers interested in other health outcomes thought to be influenced by metabolic pathways, have developed methodologies that measure physical activity in such a way to provide an estimate of energy expenditure (e.g., $\text{Kcal} \cdot \text{min}^{-1}$). These methods vary from simple questionnaires to electronic monitors to elaborate closed-system metabolic chambers. Of course, these different techniques directly measure different characteristics of physical activity. Generally, whatever is directly measured by a

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particular technique is calibrated to energy expenditure in a laboratory setting. This latter step provides biological meaning to data collected in field settings.

Increasingly, accelerometers have become popular as an assessment technique for measuring children's physical activity. Accelerometers measure accelerations in one or more planes and sum these data, termed movement counts, over a specified time period. Pediatric studies comparing accelerometry to criterion measures of energy expenditure have shown accelerometers to be reliable and valid (5,23). Consequently, several large-scale epidemiological studies examining cardiovascular health outcomes in children now use accelerometry to measure physical activity (e.g., the European Youth Heart Study). Accelerometry is also being used in epidemiologic studies examining bone-related outcomes (e.g., the Iowa Bone Development Study and the South Dakota Children's Health Study). In these bone studies, it is assumed that mechanical overload, rather than metabolic overload, is the mechanism through which physical activity influences bone development (11,22). Mechanical overload occurs when active load forces (the pull on bone from muscle contractions) and impact load forces (incurred during weight-bearing physical activities) cause strain or deformations of bone greater than needed for steady-state remodeling (6,7). This phenomenon is known as Wolf's Law (6,7). Impact load forces can be estimated by measuring ground reaction forces (GRF), which are produced when falling body mass generates force during weight-bearing physical activity. In this descriptive report, we examine the association between accelerometry-derived movement counts and GRF during children's walking, running, and jumping.

Methods

Sample

The study was approved by the University of Iowa Institutional Review Board (Human Subjects). Forty children ranging in age from 6 to 11 yr were recruited from a University of Iowa newsletter. Parents signed informed consent forms on behalf of their children. There were 19 boys and 21 girls. The mean age of the children was 8.6 – 1.7 yr. Prior to the exercise session, the children were weighed to the nearest 0.1 kg and height was measured to the nearest 0.5 cm. Mean body mass was 33.3 – 9.4 kg and mean height was 137.5 – 11.9 cm.

Instrumentation

The CSA accelerometer (model 7164, Shalimar, FL) is a uni-axial accelerometer that measures vertical movement using an internal piezoceramic cantilever beam. The beam creates a charge proportional to the magnitude of movement. This monitor is designed to measure accelerations ranging in magnitude from 0.05 to 2 G's. Movement counts are accumulated and stored over a specified time period. For our study, the time period was 15 s. The accelerometer is small (5.0 x 3.8 x 1.5 cm) and lightweight (42 g). When positioned over the hip, it directly measures the second derivative of the displacement of the hip. The manufacturer calibrated the accelerometer prior to use.

Walking and running vertical GRF (N) and stride lengths (cm) were measured using an instrumented treadmill system (Gaitway, Kistler Inc., Amherst, NY)

(25). The system includes two-recessed Kistler piezoelectric force plates embedded in the treadmill platform (i.e., one plate mounted in front of the other). Validity correlation coefficients of 0.98 have been reported between GRF and stride length measured with the Gaitway treadmill and criterion measures using (traditional) over ground systems (25). GRF were measured during jumping using a force plate (Type 9286, Kistler Inc. Amherst, NY) recessed into the laboratory floor. Prior to each subject, force plates for the treadmill and floor were reset to zero.

Protocol

The accelerometer was attached at the waist over the mid-axillary line of the right hip. A heart rate monitor transmitter (Polar, Accurex Plus, Port Washington, NY) was attached at the chest. The children were familiarized with the treadmill and jumping blocks and allowed to practice at the speeds and jumping height used during the session. The exercise session consisted of four 3-minute trials (two treadmill walking, one treadmill running, and one jumping). Each subject walked at $4.0 \text{ km} \cdot \text{hr}^{-1}$ and $5.6 \text{ km} \cdot \text{hr}^{-1}$ and ran at $8.0 \text{ km} \cdot \text{hr}^{-1}$. Treadmill velocities were presented in increasing order. The children then performed drop jumping by stepping up to a height of 30.5 cm and jumping down at a self-selected cadence.

The findings of McNair et al. (16) support the use of instructions to draw the subjects' attention to desired performance and to help reduce inter- and intra-subject variability. Therefore, the children were asked to jump using only a slight knee bend and to land with knees extended, but not locked, and with the whole foot contacting the force plate at landing (4,10,16,17). This jumping strategy and landing is typical of gymnastics, basketball, and volleyball (4). GRF time curves were examined to ensure consistency in jumping strategy and that the children landed with both feet contacting the forceplate simultaneously (14). Children rested 1 to 2 minutes between each trial.

Data Collection

During the third minute of the walking and running trials, peak vertical GRF experienced over total contact time was calculated and averaged over fifteen strides (mean peak vertical GRF). The children then jumped, and the peak vertical GRF experienced over total contact time for each step was calculated and averaged over 15 successfully performed jumps (mean peak vertical GRF). Force plates in the treadmill allowed us to separate foot contact and calculate GRF for individual legs (2,14,25). Similarly, we would have required the children to land on two separate force plates during jumping. However, we felt that this approach would distract the children and reduce the likelihood that they would perform consistent jumps. Therefore, we used one force plate and required the children to land entirely on the plate. We assumed that each leg incurred exactly half of the total measured ground reaction force (8). Accelerometry data collection was synchronized to GRF data collection. Heart rate was recorded during the last 5 s of each trial.

Statistical Analysis

Analyses were conducted to examine the distributional properties of the variables. Means and standard deviations were calculated. T-tests were used to examine possible gender differences. Intra-class correlation coefficients among the 15-s

accelerometry epochs during each trial were calculated. One-minute epochs (the sum of the four 15-s epochs) were used for all subsequent accelerometry data analysis. One-way analysis of variance with repeated measures and Bonferroni post-hoc analysis was used to examine mean movement counts by trial. Pearson correlation coefficients among age, weight, height, movement counts, stride length, and GRF were also calculated for each trial. This analysis was repeated using partial correlation coefficients in which the influence of body weight (described in N) was removed. Trial-specific forward stepwise multiple linear regression models were constructed using mean peak vertical GRF (N) as dependent variables. Body weight, height, age, stride length, and movement counts served as predictor variables. Thirty children were randomly assigned to a developmental group and the remaining ten children to a validation group. The trials were then pooled and the GENMOD procedure of SAS (V.8) was used to construct a Generalized Estimating Equation for prediction of GRF based on the significant variables in our trial-dependent regression analyses. The GRF prediction equation calculated using the developmental group was cross-validated using the validation group. Generalized estimating equation procedures do not compute an estimate of explained variance; however, we used a crude estimate of variance (that ignores correlations within individuals) defined as $1 - (\text{SSR}/\text{SST})$, where SSR is the sum of squared residuals (observed-predicted)², and SST is the sum of squared total (observed-overall mean)².

Results

Descriptive data are presented in Table 1. Boys and girls did not differ in age, body weight, height, heart rate, movement counts, or stride length. GRF did not differ by gender during walking and running; however, there was a gender difference in GRF during jumping. The boys incurred a mean ground reaction force of 3.8 times body weight while the mean ground reaction force for girls was 3.2 times body weight. This result suggests that boys were using a different jumping strategy than girls. The peak GRF (N) averaged over fifteen strides or fifteen jumps were 391, 472, 757, and 1118 for the slow walking ($4 \text{ km} \cdot \text{hr}^{-1}$), brisk walking ($5.6 \text{ km} \cdot \text{hr}^{-1}$), running ($8.0 \text{ km} \cdot \text{hr}^{-1}$), and jumping (32 cm), respectively. When expressed as a multiple of body weight, the peak GRF were 1.2 times body weight for slow walking, 1.5 times body weight for brisk walking, 2.3 times body weight for running, and 3.5 times body weight for jumping for boys and girls combined. The mean ground reaction force standard deviation for the 15 within-subject measures during each trial was very small for walking and running. The mean ground reaction force standard deviation was greater during the jumping trial. These within-subject standard deviations were 0.08, 0.11, 0.16, and 0.70 (slow walking, brisk walking, running, and jumping, respectively). The coefficients of variation ranged from 2 to 6%.

Table 2 presents the within-trial means, standard deviations, and the average measure intraclass correlation for the four 15-s movement count epochs per trial. These correlations were all very high, although the intraclass correlations during steady-state walking and running were higher (0.98–0.99) than the intra-class correlation during jumping (0.91).

Pearson correlations and partial correlations adjusted for body weight are presented in Table 3. Heart rate was not associated with unadjusted nor adjusted

Table 1 Means and Standard Deviations for Each Exercise Trial

	Heart rate (b · min ⁻¹)	Movement count (ct · min ⁻¹)	Stride length (cm)	Ground reaction forces (N)	Ground reaction forces multiples of body weight
Walking 4.0 km · hr ⁻¹	121 (10)	2113 (609)	106 (5.5)	391 (109)	1.2 (0.09)
Walking 5.6 km · hr ⁻¹	138 (12)	3810 (1059)	130.5 (8.3)	472 (115)	1.5 (0.16)
Running 8.0 km · hr ⁻¹	182 (10)	6542 (1648)	152 (11.2)	757 (216)	2.3 (0.30)
Jumping 30.5 cm	140 (12)	4276 (837)	NA	1118 (326)	3.5 (0.68)

Note. $n = 40$ except trial 1 accelerometry data where $n = 39$ and all heart rate data where $n = 39$.

Table 2 Means, Standard Deviations, and Average Measure Intraclass Correlation Coefficients for 15-s Movement Counts During Last Minute of Each Trial

	15-s movement count	15-s movement count	15-s movement count	15-s movement count	Intra-class correlation (4-Epochs)	95 th CI
Walking 4.0 km · hr ⁻¹	541 (173)	519 (150)	528 (153)	525 (150)	0.98	0.97–0.99
Walking 5.6 km · hr ⁻¹	949 (263)	962 (306)	942 (253)	957 (262)	0.98	0.97–0.99
Running 8.0 km · hr ⁻¹	1633 (415)	1621 (405)	1644 (428)	1644 (418)	0.99	0.98–0.99
Jumping 30.5 cm	1053 (248)	1083 (259)	1055 (211)	1085 (223)	0.91	0.85–0.95

GRF. Movement counts were moderately associated with unadjusted GRF during brisk walking and the running ($r = 0.33$ and 0.66). Movement counts were also moderately associated with adjusted GRF during slow walking, brisk walking, and running ($r = 0.38$ to 0.59), but not during jumping ($r = -.15$). These results were similar to the trial-specific regression analyses. In these analyses, GRF (N) during each trial served as the dependent variable, and age, body weight, height,

Table 3 Pearson and Partial Correlation Coefficients Sorted by Trial Between Peak Vertical Ground Reaction Forces and Age, Weight, Height, Heart Rate, Accelerometry, and Stride Length

	Walking 4.0 km · hr ⁻¹		Walking 5.6 km · hr ⁻¹		Running 8.0 km · hr ⁻¹		Jumping 30.5 cm	
	GRF	adjusted weight	GRF	adjusted weight	GRF	adjusted weight	GRF	adjusted weight
Age (yr)	0.60**	-0.27	0.54**	-0.40*	0.56**	-0.14	0.39*	-0.18
Weight (N)	0.97**	NA	0.95**	NA	0.92**	NA	0.73**	NA
Height (cm)	0.78**	0.01	0.75**	-0.08	0.70**	-0.16	0.64**	0.12
Heart rate (b · min ⁻¹)	0.07	0.03	-0.01	0.25	0.25	0.26	0.07	0.05
Movement count (count · min ⁻¹)	0.17	0.38*	0.33*	0.41*	0.66**	0.59**	-0.09	-0.15
Stride length (cm)	0.40**	0.12	0.57**	0.07	0.10	0.06	NA	NA

Key: GRF = Peak Vertical Ground Reaction Forces (N). NA = not applicable.

*Correlations significant at $p < .05$. **Correlations significant at $p < .01$.

heart rate, movement counts, and stride length were allowed to enter. Body weight and movement counts were the only significant predictors of GRF during walking and running. Body weight explained most of the variability (84% to 95%), while movement counts explained a small proportion (2 to 6%). Only body weight entered the regression equation for jumping. In this model, it explained 54% of the variability.

Because movement counts did not enter the jumping regression equation, we calculated a prediction equation pooling only the ambulatory GRF data (N). The prediction equation was: ambulatory GRF (N) = $-81.15 + 0.51$ (movement counts $\cdot \text{min}^{-1}$) + 1.32 (body weight in N). The equation was then used to compare predicted with actual GRF (average over the three types of motion—slow walking, fast walking, and running) for the 10 children serving as a validation group. Our crude estimate indicated that the model explained approximately 78% of the overall variation. The mean absolute difference between actual and predicted GRF was 37.14 (N) ($SD = 21.85$). This was a small absolute mean error (6%). The Pearson correlation between actual and predicted GRF was 0.98 ($N = 10$, $P < .0001$).

Discussion

Laboratory and clinical studies have demonstrated that the strongest relationship between physical activity and bone hypertrophy involves physical activities producing high impact load forces in unusual patterns (1,19,21,24). Bone responds to these loads by increasing mass and improving the internal structural supports at the high strain locations (15,24). This study examined the use of accelerometry for the assessment of GRF during ambulatory movement and jumping. GRF are indirect measures of high impact load of the lower body skeleton including the femur (12). By using a specially instrumented treadmill, we were able to control speed during walking and running trials, thus significantly decreasing variability and allowing us to measure GRF during steady-state movement. This approach provided a quantification of GRF during activities that are common to children's everyday life. Eventually, we hope that this work and the work of others can be used to construct a compendium to facilitate the coding of physical activities by GRF and improve our understanding of physical activity's influence on bone development during childhood.

In our study, during walking and running, accelerometry-derived movement counts increased in a linear manner as GRF increased. However, when the mode of physical activity changed from ambulation to jumping, there was a disassociation in this relationship (see Figure 1). This is problematic since jumping is a common physical activity known to influence bone hypertrophy in children. Our results suggest that accelerometry may provide an estimate of GRF, although equating movement counts to a specific level of force appears to be dependent on the mode of physical activity. More specifically, our data indicate that when compared to walking and running, uni-axial accelerometry underestimates GRF during drop jumping. It may be that uni-axial accelerometry is more sensitive to GRF incurred during up and down jumping (e.g., rope jumping). Since whole-day monitoring would include walking, running, and various forms of jumping, as well as other types of movement, it is not warranted to propose a general equation to predict GRF during daily physical activity based on our study results. However, the methods

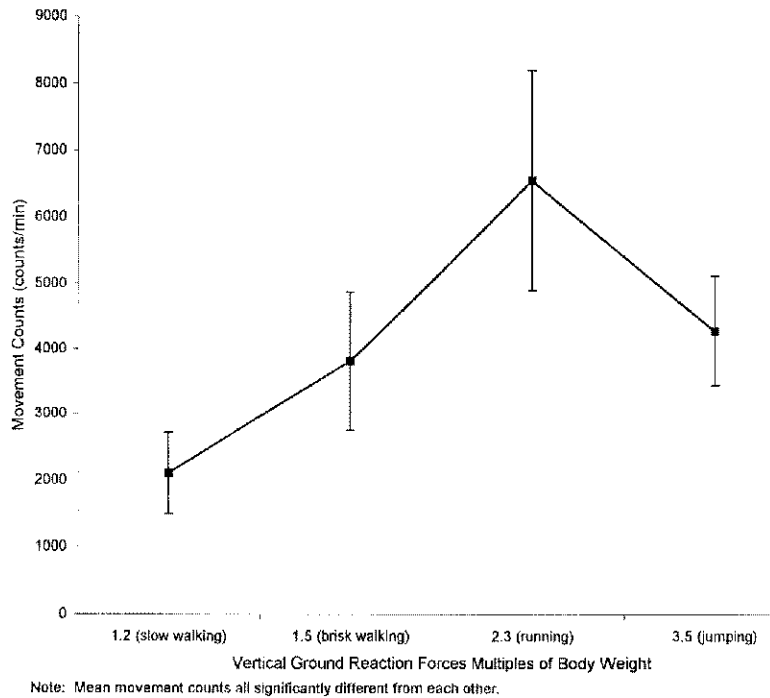


Figure 1 — Movement count means and standard deviations by vertical ground reaction forces multiples of body weight.

that we used in creating our prediction equation for walking and running may be useful to investigators examining the impact of physical activity on bone health in adults, since almost all physical activity in adults is ambulatory.

Even with these limitations, accelerometry may still be one of the best available choices for epidemiologists interested in measuring physical activity in bone-related research. Weight-bearing movement is an important bone-related dimension of physical activity that is not easily captured with other measurement techniques. When positioned over the hip, a uni-axial accelerometer directly measures the second derivative of the displacement of the hip. This measurement is closely related to weight-bearing movement. The hip, or more precisely the head of the femur, is one of the most important skeletal sites to study since it is the most debilitating site for osteoporotic fractures (21). In addition, our study indicates that accelerometry is preferable to heart rate monitoring as a measure of GRF. The association between heart rate and GRF was low (and not significant) during walking, running, and jumping. This result indicates that heart rate monitoring is unable to differentiate between differences in vertical GRF. Accelerometry is also preferable to questionnaire methods for young children who are not cognitively capable of reporting their own activity (9). Indeed, two recent papers have reported that accelerometry-derived movement counts predict bone mass and density in young children (11,22).

Physical activity is a modifiable behavior; therefore, understanding its effects on bone development is important for the construction of interventions to maximize bone mass and prevent osteoporosis. Our study and the work of others (20) have shown that acceleration is related to impact load forces. These forces are associated with bone hypertrophy. Multi-axial accelerometers may also provide a real time recording of unusual movement patterns. Unusual patterns of movement have also been associated with bone hypertrophy (19). In addition, multi-axial accelerometers may prove to be more sensitive to jumping than our uni-axial accelerometer. In the end, using laboratory studies to determine the relationship between accelerometry-derived movement counts and impact load forces and using accelerometry in field studies to measure physical activity while children participate in day-to-day routines may allow researchers to define the habitual level of physical activity needed to increase bone mass.

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