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Spectral and Bout Detection Analysis of Physical Activity Patterns in Healthy, Prepubertal Boys and Girls

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ABSTRACT Little is known about the frequency-intensity patterns of naturally occurring physical activity in children. A data set obtained previously by direct observation of physical activity in 8 girls and 7 boys (all prepubertal, ages 6–10) was analyzed with spectral analysis to detect significant frequency-intensity relationships. Pulse detection algorithms were used to characterize the number of exercise bouts, their duration and relative intensity. Spectral analysis revealed that physical activity bouts were frequent, pulsatile, and random with no significant frequencies detected during many 24-min periods of observation. An average of 83 ± 11 bouts per hour were observed in boys and 89 ± 12 bouts per hour in girls, and the mean duration of an exercise bout was 21 ± 5 sec for boys and 20 ± 4 sec for girls (NS). While high-intensity exercise bouts comprised less than 20% of the time spent in physical activity, duration of high intensity exercise bouts tended to be longer and accounted for about 40% of the energy expenditure associated with physical activity. Spontaneous physical activity in prepubertal children is characterized by frequent bouts of brief, mostly low intensity exercise, randomly interspersed with less frequent, but metabolically substantial high intensity bouts. These findings are potentially useful in assessing the impact of disease on quality of life in children, investigating the relationship between physical activity and mechanisms of growth and development, and creating new approaches for in-laboratory exercise testing in children. *Am. J. Hum. Biol.* 10:289–297, 1998. © 1998 Wiley-Liss, Inc.

The widely held but largely intuitive notion that vigorous physical activity occurs more frequently in children and adolescents than in adults is increasingly supported by scientific investigation (Cohen et al., 1992; Livingstone et al., 1992), but the nature of the *pattern* of physical activity in children has largely been ignored. Nonetheless, there are compelling reasons to believe that frequency-amplitude analysis of these patterns might yield biologically important and clinically useful information of relevance to understanding the process of growth and development.

From a practical perspective, clinical ex-

ercise tests based on naturally occurring patterns of activity in children, rather than on maximal efforts, could provide laboratory data that are more relevant to the impact of disease on real life (Martha et al., 1993). From a developmental biology perspective, there is growing evidence that physical activity directly influences the processes of growth and development by modulating

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growth hormone, IGF-I, and other anabolic agents (Cooper, 1994). GH secretory pulse-amplitude characteristics are affected by physical activity in both humans and animals (Borer et al., 1977). Moreover, the pulsatile pattern of GH secretion appears to enhance the influence of GH on mediating growth factors [like IGF-I (Maiter et al., 1988)] and on growth itself.

Frequency-amplitude analytical strategies (spectral analysis and bout detection analysis) were used to quantify patterns of naturally occurring physical activity in children. It was hypothesized that the nature of physical activity in children was not periodic and, therefore, that spectral analysis would *not* reveal particular, statistically significant patterns of activity. Moreover, since fitness is related, in part, to gender, it was hypothesized that gender dependent differences in physical activity could be found even in prepubertal subjects.

METHODS

Sample and data collection

Not unexpectedly, there are few tools specifically designed to actually record and measure the magnitude, duration, and frequency of physical activity "events" in children. A direct observational technique from this laboratory was validated with a time resolution of 3 sec for quantifying physical activity patterns in 15 prepubertal children between the ages of 6–10 years-old (8 boys) (Bailey et al., 1995). This data set was used for the analysis presented in the study. Briefly, subjects were recruited from two Los Angeles elementary schools. Fifteen subjects (8 males; 7 females), ages 6–10 years (mean, 8.3 yrs.) participated in the study. One subject was African American, two were Hispanic, and the remainder were Caucasian. All aspects of the study were reviewed and approved by the Institutional Review Board at Harbor-UCLA Medical Center.

Protocol

Since the purpose of the study was to acquire a representative sample of the full range of daily activities of the subject children, observations were performed in the full variety of settings experienced by the subjects, including in the home, at school, in the car, at friends' homes, at sports events, in the dentist office, in restaurants, and elsewhere throughout the day. The 12-hour

day was divided into four-hour time blocks, called observation periods (8:00 AM–12:00 noon, 12:00 PM–4:00 PM, and 4:00 PM–8:00 PM), and the subject child was observed wherever s/he went during an observation period. Nine, four-hour observation periods, three within each time block, were obtained for each of the 15 subjects. By design, two thirds of observations occurred on school days, one-third occurred on weekend days, holidays, or summer vacation days. Observation periods were scheduled randomly within strata according to school days and non-school days.

Each four-hour observation period was divided into consecutive 30-min time blocks. During the first 24-min of each time block, activity categories and intensity codes were recorded every three seconds. Three seconds was determined as the shortest interval possible between observation records without loss of recording accuracy. A microcassette tape recorder equipped with an earphone cued the observer every three seconds. Six-minute breaks between each 24-min time block provided observers with a brief respite and with time to review their records and rewind the tape. Each four-hour observation period thus resulted in 192 actual min of recorded observation time. The total data set for each subject consisted of about 28,800 data points.

A coding system to record the activities, based on that described by Klesges et al. (1984) was developed. Fourteen physical activity categories were established. Each category was assigned criteria for coding intensity level as low, medium, or high. The 3-sec activity-intensity codes were translated to $\dot{V}O_2$ (ml/min/kg) using data obtained in this laboratory. The activity codes and the corresponding estimated $\dot{V}O_2$ were presented previously (Bailey et al., 1995). The classification of "low" and "high intensity" exercise was based on whether the estimated $\dot{V}O_2$ was below or above an estimate of the anaerobic or lactate threshold [LT–(Wasserman et al., 1973; Cooper et al., 1984)]. Although the mechanism of the LT is still not clear, exercise performed above this level results in more profound and non-linear increases in metabolic responses to exercise (e.g., increases in catecholamines) compared with exercise performed below the LT (Cooper et al., 1989; Coggan et al., 1992). The LT is gaining acceptance as means of delineating heavy (high-intensity)

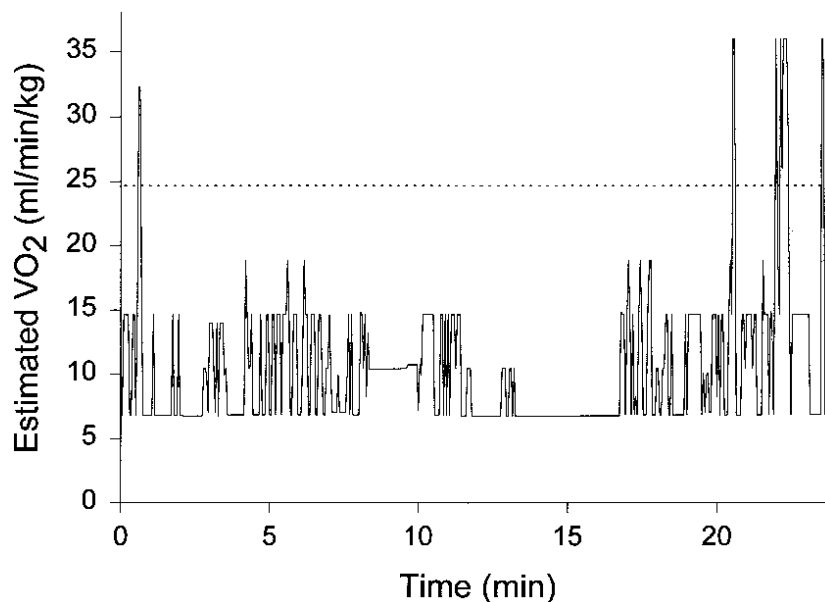


Fig. 1. Representative example of activity patterns derived from direct observation in a 7-year-old boy over a 24-min period. The dashed line represents the estimated lactate threshold.

from light to moderate (low-intensity) power output (Barstow et al., 1989). In prepubertal children, the LT is equivalent to a $\dot{V}O_2$ of about 24 ml O_2 /min/kg (Cooper et al., 1984).

Data analysis

An example of raw data from 24-min sampling periods with estimated $\dot{V}O_2$ as a function of time is shown in Figure 1. Spectral analysis was used to determine if there was any recurring pattern of activity bouts during each 24 minute period. Spectral analysis is a well-known mathematical procedure that models a time series as a sum of sine waves with periods which are integral divisors of the entire measurement period. An amplitude and phase are estimated for each frequency. Spectral analyses were performed on each of the approximate sixty 24-min data sets from each subject; then the power at each frequency was averaged for each subject. A method developed by Fisher (1929) and refined by Shimshoni (1971) was used to determine whether the amplitude of each component is larger than what would be expected from noise.

The cluster analysis program of Veldhuis et al. (1986) was also used to identify the occurrence and duration of bouts of activity. A bout of exercise was defined as an interval

in which intensity rises to a significantly greater level than background, reaches a maximum level and then decreases back to the background level. These bouts may be comprised of any combination of activities, and the key to identification of bouts of exercise is the change in levels of intensity. The cluster analysis program uses a computerized algorithm to define a bout in a series of measurements as a significant increase in a "cluster," i.e., a contiguous set of values followed by a significant decrease in a second cluster of values. The user specifies the cluster size and a significant value for comparisons. Measurement error may be specified by user or calculated from the data when there are replicate values.

The cluster algorithm was originally designed for analysis of pulsatile hormones in the circulation (Velhuis et al., 1986), but is applicable to other types of data as well. The program calculates the peak height, i.e., the maximum height of the exercise bout, and the bout width, which is the time between the start of the increase and the end of the decrease (or start of another increase). For the present analysis, each bout of exercise was characterized by its maximum intensity, and the intensity values were categorized into nine categories of width 4 ml/ O_2 /

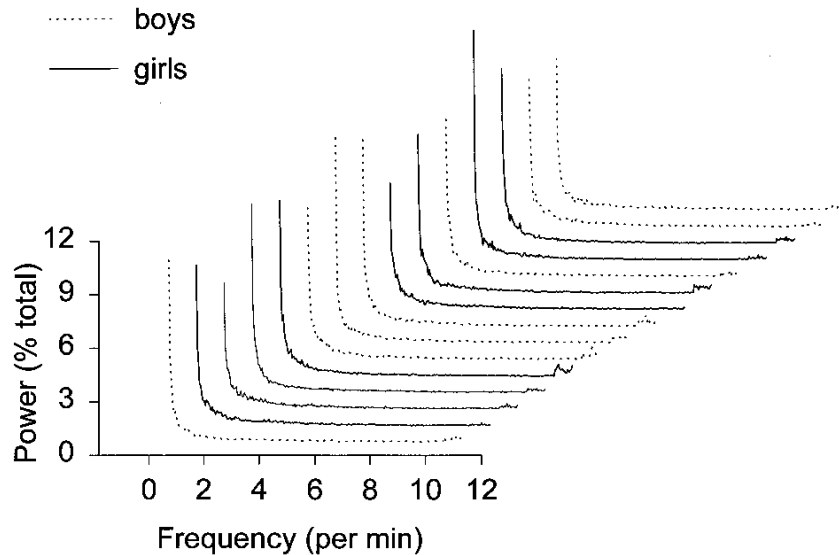


Fig. 2. Spectral analysis derived from the analysis of the approximately 60 24-min observation periods in each of the 15 subjects.

kg: 8–11, 12–15, 40–43. All of the data for each subject were then combined and the following variables for each subject at each intensity category were computed: 1) the number of bouts; 2) the average bout duration; and 3) the estimated energy expenditure as O_2 uptake (calculated as the product of bout duration and mean intensity). Comparisons between parameters for boys and girls were made using t-tests or the Wilcoxon rank sum test for non-normally distributed variables. Repeated measures ANOVA was used to determine whether or not duration of exercise bouts increased with the intensity of exercise.

RESULTS

Spectral analysis

All children exhibited a singular pattern of activity frequency (Figure 2). The only significant frequencies ($p < 0.05$) were those representing the lowest possible frequencies that could be detected in a 24-min period of observation (i.e., one bout for every 24-min). The single low frequency peak is interpreted to indicate that there was no detectable periodic pattern of activity within the 24-min; rather the activity occurred at irregular intervals. Had there been no change in physical activity levels, then the spectra would not have shown even the single dominant

peak. There were no differences in spectral frequency patterns between the boys and girls.

Cluster analysis

An average of 83 ± 11 bouts per hour of observation in boys and 89 ± 12 bouts per hour in girls were detected (NS). This corresponded to 26 ± 2 min per hour spent in physical activity bouts (as defined above) in the boys and 28 ± 3 min per hour in the girls (NS). Figure 3 shows the number of bouts per hour at each intensity level in the male and female subjects (3A and B) and for the groups as a whole (3C). Activity patterns were very consistent from subject to subject. The majority of the time was clearly spent in low intensity bouts (in boys, $81 \pm 4\%$ of the total time spent in bouts, and in girls $82 \pm 5\%$), but there were distinct "local maxima" in the low and high intensity ranges ($p < 0.05$). There were relatively few bouts noted in the immediate estimated vicinity of the LT.

The average duration of bouts of all intensities for boys was 21 ± 5 sec and for girls 20 ± 4 sec (NS). The high intensity bouts tended to have longer duration (about 15 sec for lowest intensities and 25 sec for the highest, $p < 0.05$). The time per hour spent in physical activity reveals a pattern similar

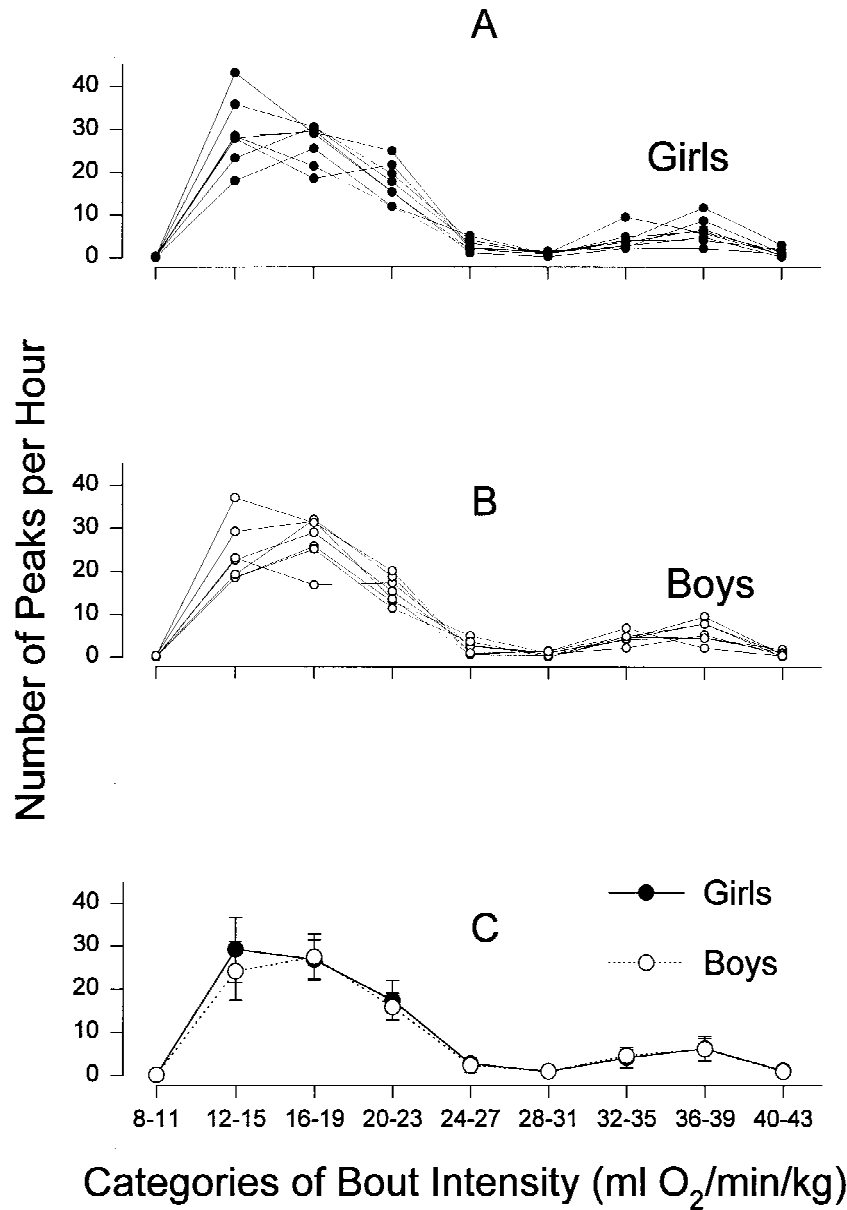


Fig. 3. Number of bouts per hour detected by cluster analysis (see text). Categories of bout intensity is shown on the x-axis. Panels A and B show data from the individual subjects. Panel C reveals the mean values for each group.

to that shown in Figure 3, although the low and high intensity level bouts are closer in magnitude.

Qualitatively different results were obtained when estimated energy expenditure of activities of different intensities were ex-

amined. Similar to the data regarding bout number and duration, two significant local maxima were noted, one in the low and one in the high intensity range. However, although high intensity bouts were fewer in number and in total time (accounting for

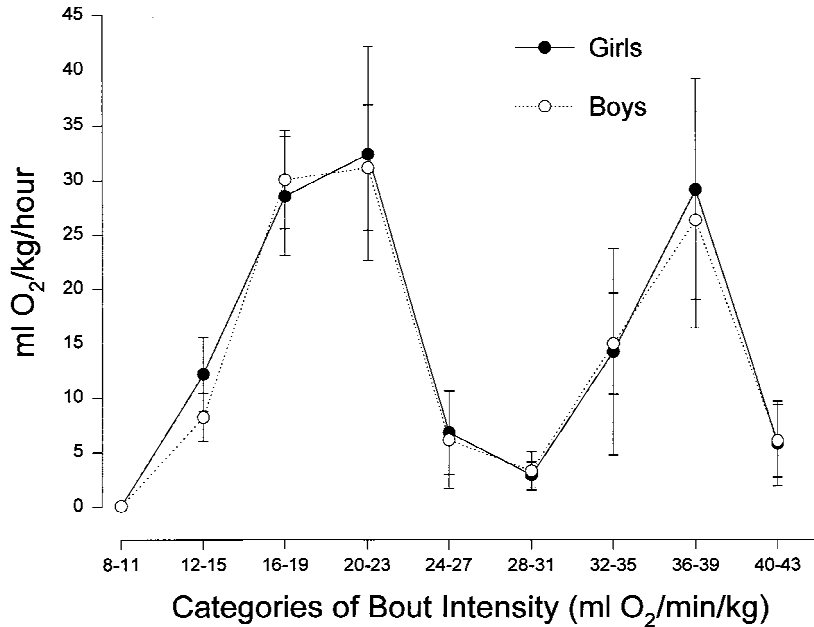


Fig. 4. Energy expenditure due to physical activity of different intensities.

less than 20% of the time spent in physical activities), the relative contribution of the high intensity exercise bouts to energy expenditure associated with physical activity bouts was high, $40 \pm 6\%$ for boys and $39 \pm 9\%$ for girls (Figure 4).

DISCUSSION

The results demonstrate that naturally occurring physical activity in prepubertal children is characterized by many brief pulses of exercise that vary greatly in intensity. Consistent with the first hypothesis, spectral analysis revealed that no particular frequency power pattern could be discerned within a 24-min period of observation in the children. However, cluster analysis demonstrated that the number of bouts of physical activity, their duration, and intensity patterns were quite consistent among the children studied. In contrast to the second hypothesis, the general patterns of physical activity were the same in this sample of boys and girls.

Some caution must be exercised in the interpretation of the spectral analysis data. These observations were limited because it would have been impossible to detect significant power-frequency patterns below one event in 24 min. This limitation is prob-

ably not important in studying healthy children because within any observation period there were usually many bouts of activity, and only 3.1% of continuous bouts were terminated by the end of the 24-min observation period (Bailey et al., 1995). However, the inability to detect lower frequency events by this method could pose substantial methodological problems when studying either adults or children with physiological impairments. In these populations, it is more likely that there will be substantial bouts of activity occurring only every hour or so and, consequently, would probably not be detected even with multiple observation periods of only 24 min.

The peak-detection algorithms highlighted and quantified the pulsatile nature of physical activity patterns among healthy children. The subjects in the present study demonstrated remarkably rapid and frequent changes in metabolic rate, most of which were in the low intensity range. While the biological importance of these relatively low levels of physical activity is not yet determined in children, a number of studies suggest that low intensity physical activity might more profoundly influence energy balance than previously appreciated. For example, "fidgeting" appears to play a

substantial role in the variation of 24-hr energy expenditure among healthy adults and children (Fontvieille et al., 1993), and it has been hypothesized that low levels of even low-intensity physical activity, like fidgeting, may play a role in obesity in children (Dietz et al., 1994).

High intensity bouts (i.e., above the LT) occurred less frequently than low intensity bouts and accounted for less than 20% of the time spent in physical activity bouts. But exercise in the high intensity range accounted for about 40% of the energy expenditure associated with physical activity. High intensity exercise is associated with profoundly different hormonal and metabolic responses than those associated with low intensity exercise. For example, catecholamines, growth hormone, and glucose clearance are known to be elevated only when exercise is performed in the high intensity range (Cooper et al., 1989; Felsing et al., 1992; Coggan et al., 1992). These data suggest a surprising consistency with which children engage naturally in brief pulses of heavy exercise. It is speculated that these episodes may play a role in modulating hormonal responses that play a role in growth and development.

As noted above, descriptive categories of exercise intensity were converted to metabolic rates (i.e., $\dot{V}O_2$) by using data obtained from the exercise laboratory. But it is certainly possible that these estimates based on the $\dot{V}O_2$ measured during steady states of exercise may not completely reflect the energy demand of bouts of activity lasting, on average, only about 20 sec. The additional metabolic cost of *prolonged* high intensity exercise is well documented (Casaburi et al., 1987), but whether or not increased metabolic costs are also found in very brief exercise is not yet known.

In the initial analysis of these data (Bailey et al., 1995), no attempt was made to determine frequency patterns of activity bouts, or to determine how different activities were linked into discrete bouts of activity. These additional analyses were performed in the present study. In the original analysis, the average duration of any *single* activity was 6 sec while using the present approaches, bout duration was about 20 sec. The difference between these values is simply that in the present analysis bouts of activity were usually composed of serially linked activities of different types (e.g., as

noted, walk, jump, run, etc.). There may be mechanistic relationships between naturally occurring patterns of physical activity and cardiorespiratory responses to exercise that can be measured in the laboratory. One hypothesis is that the number of physical activity bouts in natural conditions is related to kinetic and dynamic aspects of the cardiorespiratory response (e.g., the time required to either achieve a steady state in response to an exercise input or the time required for recovery following exercise).

The recovery for heart rate (HR) from 1-min of low-intensity exercise in children was found in this laboratory to have a time constant of about 16–20 sec (Baraldi et al., 1991). [Recovery kinetics for $\dot{V}O_2$ are a bit longer (Zanconato et al., 1991)]. In the present study, about 86 bouts per hour were found for the children studied, equivalent to about 46 sec for each bout and its recovery. Bout duration was about 20 sec, thus the time for recovery was about 26 sec. Accordingly, complete recovery (about 2–3 time constants) would be equivalent to 32–48 sec, a value reasonably close to the in-laboratory measurements of HR kinetics. Moreover, as exercise intensity increases, the recovery times also become prolonged (Zanconato et al., 1991; Baraldi et al., 1991), and this is consistent with the present observation of far fewer exercise bouts occurring in the high-intensity range.

A number of clinical observations would support the intriguing hypothesis that natural physical activity patterns are determined, in part, by kinetic features of the gas exchange and HR responses. For example, HR recovery times are much longer in adults than in children (Baraldi et al., 1991), and in most mammals, physical activity tends to decrease with age (Cohen et al., 1992). Recovery dynamics for HR and $\dot{V}O_2$ are also prolonged in children with diseases of the heart or lung (Drakonakis et al., 1974), and this is consistent with the generally reduced levels of physical activity associated with chronic disease. Conversely, HR and $\dot{V}O_2$ responses to exercise are faster in trained subjects, who, by definition, engage in greater amounts of daily physical activity (Hagberg et al., 1980; Casaburi et al., 1987). The precise mechanisms that link HR and gas exchange kinetics with naturally occurring patterns of exercise have yet to be determined.

Differences in physical activity patterns

between the boys and girls in this study sample were not observed, but caution must be used in interpreting the results of this study due to the small sample size. Previous studies of gender related influences on physical activity in young children have not been consistent. For example, McKenzie et al. (1995) reported higher activity levels among third-grade boys compared with girls using direct observation, as did Baranowski (1993) in 3–4 year-old children; but Janz et al. (1992) found no gender related differences in physical activity using HR monitoring. Levels of fitness assessed by $\dot{V}O_2\text{max}$ or the LT in this laboratory were found to be virtually the same in prepubertal children (comparable to those studied here), but substantial differences between boys and girls begin to appear in the LT and $\dot{V}O_2\text{max}$ with the onset of puberty as females appear to become less fit (Cooper et al., 1984).

Sociocultural and ethnic factors play a role in both the choice and level of children's physical activity (McKenzie et al., 1992), and these might explain the difference between the current results and those of previous studies. The sample population in the present study consisted of middle and upper-middle class children whose parents were concerned with their children's participation in programs of sports and exercise both at school and in extramural venues such as soccer teams, dance classes, etc. This factor may have attenuated other social or cultural influences which might act to diminish participation in physical activity, particularly in females.

Finally, the finding of rapidly changing, brief, predominantly low intensity bouts of exercise in naturally occurring physical activity of children may be useful in designing in-laboratory exercise tests for children. The progressive exercise test protocol in which power on a cycle ergometer or treadmill is increased until the subject reaches his or her maximal level of tolerance remains the cornerstone of most exercise tests in children and adults. These tests last 10–15 minutes, and usually about the last half of the test is performed at work rates that are above the subject's lactate or anaerobic threshold. Clearly this current mode of exercise testing does not mimic naturally occurring physical activity in children.

It is the authors' experience that many children, particularly those with diseases or disabilities, find maximal exercise testing to

be unpleasant. This leads to poor cooperation with repeated maximal tests limiting their usefulness when multiple testing over time is required. Moreover, many clinicians are uncomfortable about enthusiastically coaxing the subject (necessary for a successful maximal test) in children with underlying heart, lung, or metabolic disease.

New approaches toward exercise testing based on naturally occurring physical activity may result in tests that are more acceptable and, ultimately, clinically valuable in young patients. In addition, physical activity promotion interventions for both healthy children and those with chronic disease that are based on naturally occurring physical activity patterns may prove to be more appealing, and, therefore, more effective.

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