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The Use of Uniaxial and Triaxial Accelerometers to Measure Children's "Free-Play" Physical Activity

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In order to effectively measure the physical activity of children, objective monitoring devices must be able to quantify the intermittent and nonlinear movement of free play. The purpose of this study was to investigate the validity of the Computer Science and Applications (CSA) uniaxial accelerometer and the TriTrac-R3D triaxial accelerometer with respect to their ability to measure 8 "free-play" activities of different intensity. The activities ranged from light to very vigorous in intensity and included activities such as throwing and catching, hopscotch, and basketball. Twenty-eight children, ages 9 to 11, wore a CSA and a heart rate monitor while performing the activities. Sixteen children also wore a Tritrac. Counts from the CSA, Tritrac, and heart rates corresponding to the last 3 min of the 5 min spent at each activity were averaged and used in correlation analyses. Across all 8 activities, Tritrac counts were significantly correlated with predicted MET level ($r = 0.69$) and heart rate ($r = 0.73$). Correlations between CSA output, predicted MET level (0.43), and heart rate (0.64) were also significant but were lower than those observed for the Tritrac. These data indicate that accelerometers are an appropriate methodology for measuring children's free-play physical activities.

Introduction

Physical activity has long been viewed as an important component of a healthy lifestyle. The relationship between physical activity and several known risk factors for chronic diseases are well-documented in adults (11, 14, 15, 19, 20, 25). In children, however, the association between physical activity and health is less understood (21). The lack of conclusive findings regarding the link between physical activity and health in children can be attributed, in part, to the difficulty of measur-

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ing physical activity in this population. Instruments designed to measure physical activity in adults are frequently used with children. Because children typically engage in frequent, short bursts of activity, while adults tend to engage in sustained activity, adult-specific measurement tools may not accurately quantify the activity patterns of children.

Several methods are currently used to measure physical activity in children. Among them, self-report is used frequently. Although self-report is valid for use with adults and adolescents (24), it not recommended for use with children under age 10 because they lack the cognitive ability to accurately recall physical activity (3). Heart rate monitoring is also used to measure the daily physical activity of children. Its usefulness is limited, however, because factors other than physical activity can cause heart rate to be elevated (9, 22). Direct observation and doubly-labeled water techniques are two valid research tools for measuring physical activity in children (9, 10). Unfortunately, these methods are very costly, useful only with small samples sizes, and limited with regard to the types of information they provide. Of the tools currently used to measure physical activity in children, accelerometers appear to be the most promising.

Accelerometers are electro-mechanical devices that detect and record motion in a single or in multiple planes. Uniaxial accelerometers, such as the Computer Science and Applications (CSA) activity monitor (Shalimar, FL) measure vertical displacement by recording and storing acceleration in the vertical plane during a specified period of time. Studies have shown the CSA monitor to be both valid and reliable in estimating the energy expenditure resulting from treadmill walking and running in children (10, 13, 24). Triaxial accelerometers, such as the Tritrac-R3D (Reining International, WI), measure acceleration in three planes. Preliminary validation studies have reported high correlations ($r = 0.88$) between measurements of daily physical activity in children from uniaxial and triaxial accelerometers (26). Studies have not determined, however, whether triaxial accelerometers provided better assessments of children's free-play activity than uniaxial accelerometers.

Previous studies of physical activity in children using accelerometers have involved continuously-monitored daily physical activity or treadmill walking and running (9, 13, 24). While treadmill protocols are an important first step in establishing the validity of these monitors, accelerometers should also be validated using activities that approximate children's real-life activities. Since children are likely to engage in activities that involve bending, jumping, running, and throwing as part of their typical daily physical activity, measurement tools should be validated for use with such activities. To date, only one study has attempted to validate accelerometers for use in measuring the intensity of "free-play" activities. Eston and colleagues (8) used "unregulated play activities" (playing catch, hopscotch, and sitting and crayoning) to compare the accuracy of heart rate monitoring, triaxial accelerometry, uniaxial accelerometry, and pedometry in estimating energy expenditure. They found that the Tritrac more accurately assessed the energy expenditure of unregulated play activities than a uniaxial accelerometer, heart rate monitor, or hip pedometer. Additional studies should be conducted that include a greater variety of activities common to children and that incorporate a wider range of bodily movements. The purpose of this study, therefore, was to investigate the validity of uniaxial and triaxial accelerometers with respect to their ability to measure the intensity of children's "free-play" activities.

Methods

Subjects

The study included 28 fourth- and fifth-grade students between the ages of 9 and 11 years (mean ± *SD*: 9.7 ± 0.6 years). The majority of the subjects were white (71.4%) and female (57.1%). Mean height was 139.8 ± 6.5 cm and 142.5 ± 9.3 cm for males and females, respectively. Mean body mass was 38.3 ± 8.8 kg and 39.4 ± 10.7 kg for males and females, respectively. No significant gender differences existed for either variable. The majority (67.8%) reported having participated in at least one organized sport during the past 12 months. All subjects and their parents or guardians were informed of the benefits and risks of this study as required by the University of South Carolina School of Public Health Human Subjects Committee.

Study Design

Subjects completed a circuit of eight different free-play activities. The activities ranged from light to very vigorous in intensity and included: playing a video game, throwing and catching, walking, bench stepping, hopscotch, basketball, aerobic dance, and running. The activities were chosen because they are common children's activities that do not require a high degree of skill. The activities could also be standardized, and the energy expenditure required to engage in them could be estimated. Following a practice circuit for familiarization, each subject was assigned a starting station and moved through the circuit in a set order, spending 5 min at each activity. During the activities, all subjects wore heart rate monitors and a waist belt securing one CSA at the right hip. In addition, 16 of the 28 subjects also wore a Tritrac secured to the left hip using the waist belt. Due to the relatively high cost of the Tritrac monitors, not all subjects could wear the monitors. Those not wearing a Tritrac were given a psuedomonitor enclosed in a cloth pouch to wear instead. Average heart rate and accelerometer counts were obtained for the last 3 min of each activity.

Instrumentation

The CSA activity monitor (WAM 7164) is designed to detect vertical acceleration ranging in magnitude from 0.05 to 2.00 Gs, with frequency response in the range of 0.25 to 2.5 Hz. These parameters were chosen to allow the monitor to detect normal human motion and reject high frequency motion encountered in activities such as operating a lawn mower. The acceleration signal is filtered and summed over a user-defined time interval. The hardware used in the monitor includes an 8 bit microcontroller, with an 8 bit analog to digital converter, 8 kb of nonvolatile RAM, a low-power operational amplifier, and piezoelectric motion sensor with analog signal conditioners and filters. This hardware is housed in a plastic enclosure measuring 5.1 × 3.8 × 1.5 cm and weighing only 43 g (7). All programming operations are completed through interface with a Reader Interface Unit (RIU) connected to a personal computer serial port.

The Tritrac-R3D activity monitor measures the integrated acceleration in the horizontal, vertical, and mediolateral dimensions. The frequency response range is 0.1 Hz to 3.0 Hz, and magnitude of acceleration measured ranges from 0.05 to 6.3 Gs. The unit weighs 170.4 g and measures 10.8 × 6.8 × 3.3 cm(12). The power

source is a 9-V battery. The acceleration signal is integrated and summed over a user-defined time interval ranging from 1 to 15 min. The memory capacity is 20,790 data points. All programming operations are completed using a personal computer equipped with a Reader Interface Unit (RIU).

Heart rate was monitored using a Polar Vantage XL Heart Rate Monitor (Port Washington, NY), a wireless portable monitor that consists of a transmitter and a wrist monitor. The transmitter is 143 × 31 × 10 mm, is powered by a 160 mAh lithium battery, and attaches to the chest via an elastic chest band. The wrist monitor is similar in size to a wrist watch and is also powered by a 160 mAh lithium battery. The heart rate receiver has the capability to record and store heart rates at intervals of 5, 15, or 60 s. The stored files can be downloaded to a personal computer.

Activity Circuit

Each station was supervised by a trained research assistant who monitored the subjects to ensure that they performed the activity correctly. Each activity was assigned a MET value based on a published compendium of physical activities (1). In addition, the activities were classified as light (<3 METs), moderate (3–5 METs), vigorous (6–8 METs), and very vigorous (≥9 METs). The estimated MET levels, the intensity classification of the activity, and a brief description of the activity are provided in Table 1. Because bench stepping was not classified in the compendium, the MET value of 4.0 for this activity was estimated using the American College of Sports Medicine (ACSM) metabolic equations (2).

Data Analysis

Counts from the CSA and the Tritrac (individual axis and vector sum) were averaged to determine the mean counts per minute for each activity. Similarly, the heart rate data were averaged to determine the subject's mean heart rate corresponding to each activity. To determine the minute-to-minute stability of heart rate, CSA, and Tritrac output, intraclass correlations were calculated for each activity separately. Differences between males and females with regard to accelerometer output and average heart rate were determined using a one-way analysis of variance (ANOVA). Pearson product-moment correlations were used to establish the associations between counts from both accelerometers and predicted MET values and heart rate over all activities. Spearman rank-order correlations were calculated to determine the associations between counts from both accelerometers and the intensity classifications. Statistical significance was set at alpha level of 0.05.

Results

The intraclass correlation (ICC) statistics for each of the eight activities are shown in Table 2. High intraclass correlations suggest that activity levels remained constant at each station. High ICCs were seen for both accelerometers and heart rate in all activities. There were no differences in ICCs between the CSA and the TriTrac with the exception of those reported from the video game station. The ICCs for the video game were higher for the TriTrac than the CSA ($r = 0.96$ compared to $r = 0.59$).

Table 1 Description of Activity Circuit

Activity	MET value[a]	Intensity classification	Description of activity[b]
Video game	1.5	Light	The subjects sat in a chair and played the video game.
Throw and catch	2.5	Light	The subjects alternately threw and caught a rubber activity ball while standing 10 feet from the research assistant. A metronome was set at 60 to allow for 15 catches and 15 throws per minute (24).
Walking	3.5	Moderate	The subjects walked between two cones placed 16 m apart. Each subject was timed and instructed to maintain a pace of 11.9 s per 16 m (3 mph).
Bench stepping	4.0	Moderate	Using a 4-in. plastic step, the subjects stepped up and down at a rate of 24 steps/min.
Hopscotch	5.0	Moderate	Subjects played hopscotch using a board taped on the gymnasium floor and a small bean bag.
Basketball	6.0	Vigorous	The subjects shot a basketball at a target taped on a wall. Four marks were placed around the perimeter of the target at a distance of 8 feet from the wall. The subjects moved from mark to mark, taking a shot from each of the marks.
Aerobic dance	7.0	Vigorous	The subjects were lead by a research assistant through a choreographed aerobics routine. The routine used music and contained steps appropriate for the age of the subjects.
Running	11.0	Very Vigorous	The subjects ran through a 12-m obstacle course of cones. The subjects wove through cones spaced at 4 and 8 m.

[a]MET values based on adult studies.
[b]Full descriptions of the activities are available from the authors.

Table 2 Intraclass Correlation Coefficients for Mean Heart Rate, CSA, and TriTrac-R3D Counts Corresponding to Last 3 Min in Each Activity

Activity	HR	CSA	$TriTrac_X$	$TriTrac_Y$	$TriTrac_Z$	$TriTrac_{Sum}$
Video game	0.99	0.59	0.97	0.96	0.93	0.96
Throw and catch	0.98	0.92	0.88	0.93	0.92	0.92
Walking	0.99	0.94	0.93	0.84	0.77	0.79
Bench stepping	0.99	0.80	0.23	0.73	0.49	0.76
Hopscotch	0.97	0.92	0.62	0.87	0.88	0.74
Basketball	0.92	0.92	0.81	0.69	0.90	0.85
Aerobic dance	0.94	0.75	0.57	0.80	0.63	0.60
Running	0.95	0.71	0.63	0.91	0.89	0.90

Note. X = anteroposterior; Y = vertical; Z = mediolateral; SUM = vector sum of X, Y, Z.

Average heart rates, CSA counts, and Tritrac counts (vector sum) corresponding to each of the activities are shown in Table 3. Heart rates of males and females did not differ significantly for any of the activities except hopscotch. For both monitors, the highest and lowest number of counts per minute were recorded during aerobic dance and playing a video game, respectively. Significant gender differences were observed for the CSA and/or Tritrac output during video game playing, hopscotch, and running.

Correlations between the CSA counts, Tritrac vector sum, predicted METs, intensity classification, and heart rate are shown in Table 4. Across all eight activities, CSA counts were significantly correlated with predicted MET values (r = 0.43), intensity classification (r = 0.58), and heart rate (r = 0.64; $p < .001$). The vector sum for Tritrac counts was also significantly correlated with predicted MET values (r = 0.66), intensity classification (r = 0.73), and heart rate (r = 0.73; $p < .001$). Heart rate correlated well with both the predicted METs (r = 0.70) and the intensity classification (r = .68), while CSA and Tritrac output were highly correlated to one another (r = .86).

Correlations between the individual Tritrac vectors, CSA counts, heart rate, predicted METs, and intensity classification are shown in Table 5. For all three vectors, moderate to strong correlations were observed between activity counts and the other activity variables (0.63–0.84; $p < .001$). Of note, the correlation between the CSA and the vertical axis of the Tritrac was 0.84 ($p < .001$).

Discussion

The Tritrac and other three dimensional accelerometers were developed under the assumption that more is better. By measuring motion in more than one plane, these monitors might be better able to quantify activity than uniaxial accelerometers. Indeed, several authors have suggested that triaxial accelerometers may be more sensitive than uniaxial accelerometers to the torsional, non-vertical movements often involved in children's play (6, 8, 24). In this study, both accelerometers were significantly correlated with predicted METs, intensity classification, and heart

Table 3 Average Heart Rate, CSA Counts, and TriTrac-R3D (Vector Sum) Counts for the Total Sample and By Gender

Activity	HR (beats + min^{-1}) n	HR Mean ± *SD*	CSA (counts + min^{-1}) n	CSA Mean ± *SD*	TriTrac (counts + min^{-1}) n	TriTrac Mean ± *SD*
Video game	22	107.3 ± 13.6	28	4.3 ± 9.4	16	68.1 ± 170.9
Throw and catch	25	144.8 ± 20.7	28	1979.1 ± 1125.7	16	1021.3 ± 488.1
Walking	27	133.2 ± 13.4	28	2363.2 ± 773.2	16	1621.1 ± 239.4
Bench stepping	26	137.4 ± 15.1	28	2251.6 ± 401.6	16	1183.2 ± 198.8
Hopscotch	25	180.9 ± 16.9	28	6328.1 ± 1695.4	16	2788.8 ± 505.7
Basketball	25	191.1 ± 13.8	28	5264.8 ± 1252.2	16	2575.7 ± 438.3
Aerobic dance	28	167.2 ± 18.1	28	6639.0 ± 2705.6	16	3088.4 ± 742.5
Running	23	188.9 ± 8.3	28	3089.6 ± 950.5	16	2395.7 ± 476.9
			Females			
Video game	12	108.8 ± 9.8	16	5.7 ± 11.9 ***	7	14.8 ± 10.2 ***
Throw and catch	15	144.1 ± 21.0	16	2077.9 ± 1081.5	7	1102.1 ± 317.0
Walking	16	135.0 ± 10.5	16	2573.2 ± 810.9	7	1583.1 ± 225.1
Bench stepping	16	136.7 ± 12.2	16	2172.8 ± 386.3	7	1198.1 ± 195.1
Hopscotch	15	187.7 ± 10.7 *	16	6673.7 ± 2028.4 *	7	2806.5 ± 2775.0
Basketball	15	191.7 ± 13.6	16	4954.2 ± 1177.4	7	2566.2 ± 425.6
Aerobic dance	16	173.0 ± 14.9	16	6720.2 ± 2588.5	7	3090.2 ± 754.8
Running	15	190.2 ± 9.3	16	3112.9 ± 711.8	7	2710.2 ± 564.0 *
			Males			
Video game	10	105.5 ± 17.6	12	2.4 ± 4.2	9	109.6 ± 224.2
Throw and catch	10	145.9 ± 21.1	12	1847.3 ± 1217.4	9	958.4 ± 601.0
Walking	11	130.7 ± 16.9	12	2083.2 ± 648.9	9	1650.7 ± 259.2
Bench stepping	10	138.6 ± 19.5	12	2356.6 ± 413.9	9	1171.7 ± 212.7
Hopscotch	10	170.8 ± 19.9	12	2806.5 ± 619.8	9	2775.0 ± 436.8
Basketball	10	190.2 ± 14.8	12	5678.9 ± 1277.2	9	2583.1 ± 473.5
Aerobic dance	12	159.3 ± 19.7	12	6530.8 ± 2967.9	9	3078.2 ± 778.7
Running	8	186.5 ± 5.9	12	3058.7 ± 1234.8	9	2151.1 ± 184.4

*Male and female values significantly different ($p < .05$).
***Male and female values significantly different ($p < .001$).

rate; however, the correlations observed for the Tritrac vector sum were somewhat greater than those observed for the CSA. This observation is consistent with the idea that the triaxial accelerometer may be better suited to measure the movements characteristic of children at play.

Previous studies have compared uniaxial and triaxial accelerometers, although under different conditions. Welk and Corbin (26) reported slightly higher correlations between heart rate and counts for the Tritrac ($r = 0.58$) than the Caltrac ($r = 0.52$) during continuous monitoring of physical activity in children ages 9 to 11. It was concluded, however, that a one-dimensional accelerometer was as effective as a three-dimensional one in quantifying activity, since movement in the horizontal

Table 4 Pearson and Spearman Correlation Coefficients for CSA and TriTrac-R3D Counts, and Heart Rate, Predicted METs, and Intensity Classification

Variables	TriTrac[a]	HR[a]	METs[a]	Intensity[b]
CSA (counts + min^{-1})	0.86***	0.64***	0.43***	0.58***
$TriTrac_{sum}$ (counts + min^{-1})		0.73***	0.66***	0.73***
HR (beats + min^{-1})			0.70***	0.68***
METs				0.96***

[a]Pearson correlation; [b]Spearman correlation.
*** $p < .001$.

Table 5 Pearson and Spearman Correlation Coefficients for Each TriTrac-R3D Vector

Variables	CSA[a]	HR[a]	METs[a]	Intensity[b]
TriTrac X (counts + min^{-1})	0.82***	0.72***	0.69***	0.75***
TriTrac Y (counts + min^{-1})	0.84***	0.68***	0.64***	0.74***
TriTrac Z (counts + min^{-1})	0.82***	0.69***	0.63***	0.71***

Note. X = anteroposterior; Y = vertical; Z = mediolateral.
[a]Pearson correlation; [b]Spearman correlation.
*** $p < .001$

and sagittal planes is usually accompanied by movement in the vertical plane. Easton and colleagues (8), who studied activities children commonly engage in during free play, reported a significant difference between the CSA and the Tritrac with respect to their ability to estimate energy expenditure, with the Tritrac providing better estimates than the CSA. This study and the study by Eston et al. (8) are the first to use activities that reflect the intermittent, non-vertical movements of children's play. The findings of both suggest that a three-dimensional accelerometer may provide information not recorded by a one-dimensional monitor.

The Tritrac allows for the counts corresponding to each of the vectors to be analyzed separately. In the present study, when counts recorded in each plane were correlated with CSA output, heart rate, predicted METs, and intensity classification, the correlation coefficients were found to be moderate to strong and similar in magnitude. Eston et al. (8) reported similar findings with no differences in the correlation between any of the vectors and the vector sum and measured oxygen consumption. However, it is important to note that when CSA counts and its analogous vertical vector from the Tritrac were compared with respect to its association with the other activity variables (predicted METs, intensity classification, and heart rate), higher correlations were reported for the Tritrac. This difference suggests that the Tritrac may be a more sensitive instrument than the CSA.

The correlation between the Tritrac vector sum and predicted METs (r = 0.66) was slightly lower than correlations reported in previous adult studies (4, 17, 18). Meijer, Westerterp, Verhoeven, Koper, and Hoor (18), Matthews and Freedson (17), and Bouten et al. (5) investigated the use of triaxial accelerometers with adults. In Meijer, Westerterp, Verhoeven, Koper, and Hoor (18), the correlation between triaxial accelerometer counts and energy expenditure as measured by doubly-labeled water was $r = 0.87$ in adults ages 20 to 24. Matthews and Freedson (17) reported a correlation coefficient of $r = 0.82$ between a triaxial accelerometer and energy expenditure estimated by self-report. Bouten et al. (5) reported a correlation of $r = 0.82$ between a triaxial accelerometer and oxygen consumption during sitting, sitting and lifting arm weights, and treadmill walking. In a study involving children, Eston and colleagues (8) reported correlations between oxygen consumption and Tritrac counts of $r = 0.88$ for treadmill walk/running and $r = 0.93$ for unregulated play activities. However, because the investigators expressed oxygen consumption relative to body mass raised to the power of 0.75, it is difficult to compare results of that study with our own findings.

Heart rate monitoring can be a useful adjunct tool to assess physical activity in children provided that certain assumptions are met. Heart rates below 120 beats per minute are not considered valid predictors of exercise intensity because factors independent of physical activity, such as emotions, can cause slight elevations in heart rates (22). In addition, there must be sufficient time for the heart rate to reach "steady-state" in order for the true heart rate at a given activity to be recorded. This lag heart rate response is an important issue when using heart rate to quantify physical activity in children. There is often a rapid change from activity to activity, and heart rate monitoring alone may not be able to capture such changes. In the present study, heart rates were very stable over the 3 min indicating the steady state had been reached, with ICCs exceeding $r = 0.90$ for all activities. The heart rates also correlated well with both the intensity of the activity ($r = 0.68$) and the predicted MET level ($r = 0.70$). These results lend support to previous studies (21, 22) that have concluded that heart rates can be used as measures of physical activity given that it is sustained (>5 min) and that the activities are ≥ 3 METs in intensity.

As with many validation studies of this type, our study was limited by the lack of a "gold standard" for assessing physical activity behavior in children and youth. We assessed the relative validity of both accelerometers by examining the correlation between accelerometer output and three validation realms—published MET values, a general intensity classification, and heart rate monitoring data. While each of these measures have their own limitations, collectively they provide a measure of convergent validity. Our findings suggest that accelerometer devices such as the CSA and the Tritrac provide valid measures of children's physical activity in real life settings, with the Tritrac vector sum providing somewhat better information. Nevertheless, it is important to note that the MET values assigned to each activity and their corresponding intensity classification were based on adult data. Consequently, we cannot make any conclusions regarding the ability of the CSA or the Tritrac to predict energy expenditure in children.

In summary, the results of this study indicate that accelerometers are an appropriate methodology for measuring children's free-play physical activities. Based on differences in their respective correlations with predicted METs, relative intensity, and heart rate, it appears that the Tritrac may provide somewhat better assess-

ments of children's free-play activities than the uniaxial CSA. It should be noted, however, that across all activities, counts from both devices were highly correlated. Future studies should examine the validity of accelerometers to measure free-play activities in children using more rigorous criterion measures of physical activity such as direct observation and indirect calorimetry.

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