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Comparison of Indirect Calorimetry- and Accelerometry-Based Energy Expenditure During Children‘s Discrete Skill Performance

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ABSTRACT

Purpose: To compare children's energy expenditure (EE) levels during object projection skill performance (OPSP; e.g., kicking, throwing, striking) as assessed by hip- and wrist-worn accelerometers. Method: Forty-two children (female *n* = 20, *M*age = 8.1 ± 0.8 years) performed three, nine-minute sessions of kicking, over-arm throwing, and striking at performance intervals of 6, 12, and 30 seconds. EE was estimated using indirect calorimetry (COSMED k4b2) and accelerometers (ActiGraph GT3X+) worn on three different locations (hip, dominant-wrist, and non-dominant-wrist) using four commonly used cut-points. Bland-Altman plots were used to analyze the agreement in EE estimations between accelerometry and indirect calorimetry (METS). Chi-square goodness of fit tests were used to examine the agreement between accelerometry and indirect calorimetry. Results: Hip- and wrist-worn accelerometers underestimated EE, compared to indirect calorimetry, during all performance conditions. Skill practice at a rate of two trials per minute resulted in the equivalent of moderate PA and five trials per minute resulted in vigorous PA (as measured by indirect calorimetry), yet was only categorized as light and/or moderate activity by all measured forms of accelerometry. Conclusion: This is one of the first studies to evaluate the ability of hip- and wrist-worn accelerometers to predict PA intensity levels during OPSP in children. These data may significantly impact PA intervention measurement strategies by revealing the lack of validity in accelerometers to accurately predict PA levels during OPSP in children.

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Only 26% of U.S. children ages 6–15 years accumulate the recommended minimum of 60 minutes of moderate-to- vigorous physical activity (MVPA) every day (Katzmarzyk et al., 2016), which is needed to reduce chronic disease risk and obesity (Committee., 2018). Furthermore, updated recommendations from the Physical Activity Guidelines Advisory Committee (2018) emphasize the need to a) increase our understanding of dose-response relationships between physical activity (PA) and multiple health outcomes throughout the life- span, and b) to develop instrumentation and measure- ment that will enhance physical activity surveillance systems. Physical activities that have been promoted for the achievement of recommended levels of physical activ- ity (e.g., sports, games, leisure activities) include move- ments that are both continuous (e.g., brisk walking, jogging, or running) and discrete (e.g., kicking, throwing, or striking) in various forms (Committee., 2018). The wide range of movement types impose significant meth- odological and logistical challenges to PA assessment in children where PA can take many forms and occur in environments with various movement constraints (Butte et al., 2017; Kim, Beets, & Welk, 2012; Ridley, Ainsworth, & Olds, 2008). As a result, many forms of PA measure- ment (e.g., self-report, systematic observation, accelero- metry) have been developed to address the need to evaluate both small and large groups of children in a cost conscience manner without disrupting the natural environment of play. However, limitations exist for all current forms of PA measurement. For example, self- report assessments are limited in their accuracy due to the validity of parental recall of their child's PA behavior (Machado-Rodrigues et al., 2011) and self-assessments questionnaires are not recommended for distribution to children due to the child's lack of cognitive ability to accurately recall their PA behavior (Kohl, Fulton, & Caspersen, 2000). Difficulties in the use of systematic observation include the requirement of large amounts of researcher time to measure PA (McKenzie et al., 1991) and results may be altered due to interactions between observers and children (Bailey et al., 1995). However, objective technology driven assessments such as acceler- ometers and pedometers also have limitations. Two cur- rent limitations include a) activity levels are dependent upon the selection of cut-points developed from studies that mainly involved continuous locomotion movements or activities heavily impacted by locomotor activity and b) the choice of wear location (e.g., hip, wrist) on the parti- cipant (Crouter, Flynn, & Bassett, 2015; Kim et al., 2012; Sacko, Brazendale, et al., 2018). Universal agreement among researchers regarding cut-points and the optimal wear location for cut-points does not exist (Kim et al., 2012). Therefore, it is critical to obtain precise estimates of energy expenditure (EE) of children during all forms of PA in order to advance technology driven assessment of PA

Recently, Sacko, Brazendale, et al. (2018) demon- strated hip-worn accelerometry dramatically underesti- mates energy expenditure (EE) during the repetitive performance of object projection skills at different trial intervals in adults. Sacko et al. (2019) established that EE associated with the practice of object projection skills in children (ranging from 4.5 to 8.3 METS depending on interval condition) was equivalent to moderate and/or vigorous PA (Sacko, Brazendale, et al., 2018; Sacko et al., 2019). Thus, examining the predictive utility of accelerometry for repetitive object projection skills in children is warranted; however, algorithms and wear locations for children differ and are far more numerous than those available for adults (Brazendale et al., 2016).

Accelerometer cut-points are developed in calibration studies. In calibration studies, participants are instructed to wear accelerometers placed on specified locations on the body (e.g., hip, wrist) while executing various forms of PA. The participant would also wear a standardized device (i.e., criterion measure) used to determine energy expenditure (e.g., indirect calorimetry) (Kim et al., 2012). Algorithms are then applied to raw accelerometer "counts" (output unit of accelerometers) and the energy expenditure measured by the standardized device to transform accelerometer data into METS (metabolic- equivalence of task) (Lyden, Kozey, Staudenmeyer, & Freedson, 2011). Accelerometers worn on the hip mainly capture movement associated with the movement of an individual's center of mass, while accelerometers worn on the wrist are associated more closely with arm movement independent from the hip or lower extremity (Evenson, Catellier, Gill, Ondrak, & McMurray, 2008; Freedson, Melanson, & Sirard, 1998; Freedson, Pober, & Janz, 2005; Trost, McIver, & Pate, 2005). The two most com- monly used hip-worn accelerometer cut-points, which are derived from indirect calorimetry-assessed METS for children were developed by Evenson et al. (2008) and Freedson et al. (2005). Specifically, these cut points were based on the linear relationship between vertical accelera- tions of the body and EE (assessed by indirect calorimetry) during locomotion (Evenson et al., 2008; Freedson et al., 2005). Monitoring activity with acceler- ometers worn on the wrist has been suggested to increase accelerometer PA observation validity in children (Evenson et al., 2008; Freedson et al., 2005) due to a stronger association between wrist and upper body movement (Chandler, Brazendale, Beets, & Mealing, 2016). Researchers also have attempted to develop regres- sion techniques that could be used to unify accelerometer cut-point equations in an attempt to address inaccuracies that exist, due to in part the intermittent performance nature of discrete skill performance and differences in movement counts that are tallied when accelerometers are placed on different anatomical positions (i.e., domi- nant or non-dominant wrists) (Crouter, Clowers, & Bassett, 2006; Crouter et al., 2015). Regression models predict movement intensity levels by expressing average counts during a period of time (i.e., 5, 15, or 60 seconds) (Freedson et al., 2005; Pate, Almeida, McIver, Pfeiffer, & Dowda, 2006; Trost et al., 2005), in categorical form (i.e., sedentary, light, moderate, vigorous), or by translating counts into a universal unit such as METS. Activities that require at least 4 METS are classified as moderate intensity activity in children, while > 7 METS are classi- fied as vigorous (Butte et al., 2017).

Over the past decade, there has been a movement away from hip-worn, to wrist-worn (dominant and non- dominant) accelerometry in PA assessment studies (Chandler et al., 2016; Crouter et al., 2006; Crouter et al., 2015). This change was brought about, in part, due to the lack of validity of hip worn accelerometry to ade- quately classify PA during seated or non-locomotor activ- ities, such as video games, where wrist movement upper extremity movements may be more likely than hip move- ment during activities (Kim, Lee, Peters, Gaesser, & Welk, 2014). Advantages to the wrist location also include increased wear time compliance (van Hees et al., 2011) and the ability to assess movement during activities where hip movement may be limited in low-skilled individuals (e.g., kicking, throwing, striking) (Sacko, Brazendale, et al., 2018). Accelerometer cut-points and regression equations were recently established in children using accelerometer placement on the dominant wrist (Crouter et al., 2006; Crouter et al., 2015). A concern with using an accelerometer on the dominant hand is the possibility of an overestimation of PA, during seden- tary activities, such as drawing, coloring, and video games. In response to this assumption, Chandler et al. (2016) published cut points for accelerometers worn on the non- dominant wrist. While numerous accelerometer calibra- tion studies have been published to provide "cut-points" for the estimation of PA levels (e.g., sedentary, light, moderate, vigorous) during activities such as walking running or activities of daily living (Troiano, 2006), accu- rately quantifying PA intensities during discrete skill per- formance (e.g. kicking, throwing, and striking) remains a challenge to researchers and clinicians (Butte et al., 2017; Kim et al., 2012; Sacko, McIver, Brian, & Stodden, 2018).

Object projection skill performance and children's physical activity

Discrete movement skills, specifically object projection skill performance (OPSP), involve complex multi-joint move- ments that demand high neuromuscular involvement (Escamilla & Andrews, 2009; Gabbard, 2011; Laukkanen, Pesola, Havu, Sääkslahti, & Finni, 2014). Effortful move- ments that include multiple segments of the body, such as kicking, throwing or striking a ball, activate large muscle groups and are generally produced with high effort in many games and sports. The inherent complexity of coor- dination and control of OPSP skills requires repetitive practice and a large number of trials to develop a high level of performance. Promoting high effort levels also is a prerequisite to developing advanced levels of OPSP as the emergence of more advanced coordination patterns inher- ently includes the exploitation of neuromuscular mechan- isms that necessitate high effort eccentric/concentric muscular contractions (Cattuzzo et al., 2016; Croix & Korff, 2013; Girard, Micallef, & Millet, 2005; Langendorfer, Roberton, & Stodden, 2011; Stodden, True, Langendorfer, & Gao, 2013) that produce high ground reaction forces and power (MacWilliams, Choi, Perezous, Chao, & McFarland, 1998; Orloff et al., 2008).

Object projection skills (e.g., kicking, throwing, and striking), are an integral part of many games, sports and physical activities recommended for the accumulation of suggested levels of MVPA per week (Committee., 2018). Specifically, MET levels associated with OPSP performance have recently been calculated to be between 4.5 and 8.3 METS, during varying rates of performance trials in chil- dren (Sacko, McIver, et al., 2018). However, due to periods of relative inactivity that occur between high effort activity trial repetitions, it may be possible that commonly used hip- and wrist-worn accelerometer cut-points underesti- mate EE levels associated with OPSP (Chandler et al., 2016; Crouter et al., 2015; Sacko, Brazendale, et al., 2018; Trost et al., 2005). Thus, an important step in increasing our understanding of dose-response relationships of various activities to children's overall PA levels is to determine the accuracy of established cut-points for children's accel- erometry. The purpose of this study was to compare chil- dren's energy expenditure (EE) levels during object projection skill performance (OPSP) as assessed by indirect calorimetry and hip- and wrist-worn accelerometry.

Methods

Participants

This study is a part of a larger study; however, the data represented in the current study has never been published elsewhere. A convenient sample of 42 elementary school- aged children (*M*age: 8.0 ± 0.8 years) from a southeastern city in the United States were recruited for this study. The physical characteristics of participants are shown in Table 1. The study was approved by the University's Institutional Review Board and the ethical treatment of participants was followed. The parent/guardian of each participant com- pleted informed consent and each child provided assent before participating in the study. Participants also com- pleted a Health History Questionnaire to determine elig- ibility for participation. Disqualifying conditions included those: (a) who were under the care of a physician that excluded them from PA (e.g., heart condition, chest pain, injury, chronic illness, limb deformity) (b) who were taking prescription or non-prescription medications or used an inhaler (c) who had high blood pressure or cholesterol (d) who had a history of seizures, asthma, lung disease, vertigo, or diabetes. Parents self-identified the race/ethnicity of their children as 88% Caucasian, 8% African-American, 2% Hispanic, and 2% Asian/Pacific Islander.

Object projection skill performance procedures

For the purposes of this study children participated in three, nine-minute experimental sessions in an indoor laboratory where participants performed rounds of five kicks, five throws, and five strikes in blocked fashion, at three different trial intervals (i.e., 6, 12, and 30 second intervals). Each participant completed the three experi- mental sessions in a randomized order. Participants were instructed to perform all trials with maximum effort. The interval schedules ranged from more intense (i.e., 6 second intervals to less intense intervals (i.e., 30 second intervals) that could be expected in a different practice, training, or physical education environments. A complete description of the OPSP procedures may be found in Sacko et al. (2019).

Table 1. Physical characteristics of the participants.

	Boys (*n* = 22)	Girls (*n* = 20)	All participants (*N* = 42)
Age, years	8.1 ± 0.8	8.0 ± 0.8	8.1 ± 0.8
Height, cm	133.8 ± 3.9*	135.0 ± 4.0	134.4 ± 7.6
Body mass, kg	33.2 ± 4.3*	30.0 ± 6.6	29.1 ± 5.6
Resting METS, ml·kg^{-1}·min^{-1}	2.5 ± 0.3	2.5 ± 0.6	2.5 ± 0.5

Note. Values presented as means (SD); *n*, number of subjects; BMI, body mass index; METS, metabolic equivalent of task; *Significantly different from girls, $p < .01$.

Indirect calorimetry

Energy expenditure during skill performance was mea- sured using a criterion measure of indirect calorimetry. A COSMED K4b2 portable system for pulmonary gas exchange was used to collect expired respiratory gases on a breath-by-breath basis to measure oxygen con- sumption (VO_2 kg^{-1}·min^{-1}) and METS (Duffield, Dawson, Pinnington, & Wong, 2004; Melby, Scholl, Edwards, & Bullough, 1993; Pinnington, Wong, Tay, Green, & Dawson, 2001). METS were averaged using data collected during minutes 4–8 of each nine-minute OPSP session (Pinnington et al., 2001) of each nine-minute OPSP session (Sacko et al., 2019).

Accelerometry

Accelerometers (ActiGraph GT3X+, ActiGraph, Pensacola, FL) were worn on three locations: a) waist level at the right anterior axillary line attached to a belt,
b) posterior side of the non-dominant wrist, and c) poster- ior side of the dominant wrist. The accelerometers were synchronized with the COSMED K4b2 (indirect calorime- try) for data analysis purposes. The accelerometers were initialized using the sampling rate of 100 Hz and down- loaded in epoch lengths of 1 second. The results were downloaded using ActiLife (Pensacola, FL) software. Measurements from accelerometry were matched with the corresponding time period collected by indirect calori- metry (i.e., minutes 4–8) and used for EE prediction evaluation.

The inclusion criteria for the cut-points used within this study were accelerometer studies that: (a) reflected a sample age range included children 7–9 years of age. (b) used an appropriate biological standard (4.0 METS = moderate), (c) used an EPOCH length less than 60 s, and (d) were vali- dated in sample sizes of at least 10 per age group. The following four cut-points and their respective wear location were identified for inclusion into this study (1) Freedson et al. (2005), hip; (2) Evenson et al. (2008), hip; (3) Crouter et al. (2015), dominant wrist; and (4) Chandler et al. (2016), non-dominant wrist.

Predicted METS from accelerometer data were calcu- lated using four sets of cut points that delineated various intensities of PA (e.g., light, moderate, vigorous) and were established for children ages 7–9 for the hip (i.e., Evenson et al., 2008; Freedson et al., 2005), non-dominant wrist (i.e., Chandler et al., 2016), and dominant wrist-worn (i.e., Crouter et al., 2015) accelerometers. All data was converted to average counts min-1. Accelerometer data from the hip (i.e., Freedson et al., 2005) and from the dominant wrist using the equation developed by (Crouter et al., 2015) were transformed to METS using repression equations provided in text by the respective authors (Crouter et al., 2015; Freedson et al., 2005).

Freedson et al. (2005) Hip-worn Regression Model:

$$\text{METS} = 2.757 + (0.0015 \cdot \text{cntspermin}) - (0.08957 \cdot \text{age(yr)}) - (0.000037 \cdot \text{cntsperminute} \cdot \text{age(yr)})$$

Crouter et al. (2015) Dominant Wrist-worn Regression Model

(1) If the vertical axis counts per 5 sec are ≤ 35, energy expenditure = 1.0 child—MET
(2) If the vertical axis counts per 5 sec are > 35, energy expenditure (child-MET)

$$\text{METS} = 1.592 + (0.0039 \cdot \text{ActiGraph vertical axis counts per 5 second})$$

MET transformation could not be performed for Evenson et al. (2008) or Chandler et al. (2016) because no regression equations were provided in the respective publications. All data were classified as light, moderate, or vigorous by the cut-points that corresponded to their wear location and are presented in Table 2.

Data analysis

To examine time spent in moderate (>4.0 METS), and vigorous (>7.0 METS) PA, the minute-by-minute values for the COSMED K4b2 (criterion) and each acceler- ometer regression formula (estimate) were downloaded and used for comparison. Estimated METS (i.e., acceler- ometer) and actual METS (i.e., indirect calorimetry) were analyzed to examine the prediction accuracy of hip-worn accelerometry and wrist-worn accelerometry during OPSP. One-sample *t*-tests were conducted and used to detect differences between the COSMED K4b2 and accel- erometer regression formulas (Freedson et al., 2005; Crouter et al., 2006).

Table 2. Vertical axis cut-points associated with moderate-to-vigorous physical activity.

Cut-point	Wear location	Range of accelerometer counts-per-minute				
		Sedentary	Light	Moderate	Vigorous	Very-vigorous
Freedson et al.	Hip	0–149	150–499	500–3999	4000–7599	> 7600
Evenson et al.	Hip	0–100	101–2295	2296–4011	> 4012	N/A
Crouter et al.	Wrist (dominant)	0–420	421–4320	4321–13548	> 13560	N/A
Chandler et al.[a]	Wrist (non-dominant)	0–1932	1933–6348	6349–17532	> 17554	N/A

Note. N/A, non-applicable. All cut-points presented as measure of vertical axis. All cut-points presented in counts-per minute.
[a]Originally published as counts per 5 seconds.

Bland-Altman plots were used to analyze the agreement between accelerometry (predicted METS, Freedson et al., 1998) and indirect calorimetry (measured METS) (Bland & Altman, 1986). The agreement between accelerometry pre- dicted METS and indirect calorimetry MET values were depicted by plotting the mean difference between two measures (e.g., accelerometry estimated METS minus indirect calorimetry METS) against the mean of the two measures (e.g., accelerometry estimated METS and indirect calorimetry METS). The mean error score (solid line) and the 95% prediction intervals (dashed line) are shown gra- phically (Figure 1). An agreement between accelerometry estimated METS and indirect calorimetry METS are repre- sented by data points clustered tightly around zero. Data points above zero indicate an overestimation of METS by accelerometry while data points below zero indicate an underestimation.

To examine the prediction of validity of accelerometry to accurately categorize PA (e.g., light, moderate, vigorous) during OPSP accelerometer cut-points (Chandler et al., 2016; Crouter et al., 2015; Evenson et al., 2008; Freedson et al., 2005) were applied to the data downloaded from each session (6, 12, and 30 second intervals). Average counts-per minute from each wear location (hip, dominant-wrist, non- dominant wrist) and the corresponding categorical repre- sentation of PA (light, moderate, vigorous) from each application of cut-points (Chandler et al., 2016; Crouter et al., 2015; Evenson et al., 2008; Freedson et al., 2005) are presented in Table 2.

Next, a 3 × 3 chi-square test of goodness of fit was conducted to examine categorical PA levels derived from accelerometer cut-points PA categorical PA levels derived from METS measured using indirect calorimetry for each of the OPSP sessions. All statistical procedures were con- ducted using IBM SPSS software (Version 23.0; IBM, Armonk, NY USA) with a significance level of alpha ≤ .05.

Results

The average energy expenditure for boys and girls respec- tively were 9.3 (± 1.4; vigorous PA) and 7.2 (± 1.2; vigor- ous PA) METS during the six second intervals, 7.0 (± 1.1; vigorous PA) and 5.6 (± 1.1; moderate PA) METS during 12 second intervals and 4.8 (± 0.7; moderate PA) and 4.1 (± 0.7; moderate PA) during 30 second intervals. The categorization of exercise intensity levels (e.g., light, mod- erate, vigorous) by indirect calorimetry (METS) and accelerometry (counts per min) is presented in Table 3. One-sample *t*-tests (Table 4) indicated a statistically sig- nificant difference between hip-worn accelerometry METS calculated from regression equations (i.e., Freedson et al., 2005) and indirect calorimetry measured METS during OPSP. One-sample *t*-tests also indicated a statistically significant difference between dominant- wrist-worn accelerometry predicted METS (i.e., Crouter et al., 2015) and indirect calorimetry METS during OPSP. When accelerometer METS (calculated from regression equations) were placed in categorical levels of PA (mod- erate ≥ 4.0 METS; vigorous ≥ 7.0 METS) every interval condition (i.e., 30 s, 12 s, 6 s) were calculated as “light”. In contrast, the values indicated by indirect calorimetry were “moderate”, “moderate”, and “vigorous” during the 30 s, 12 s, and 6 second trials respectively.

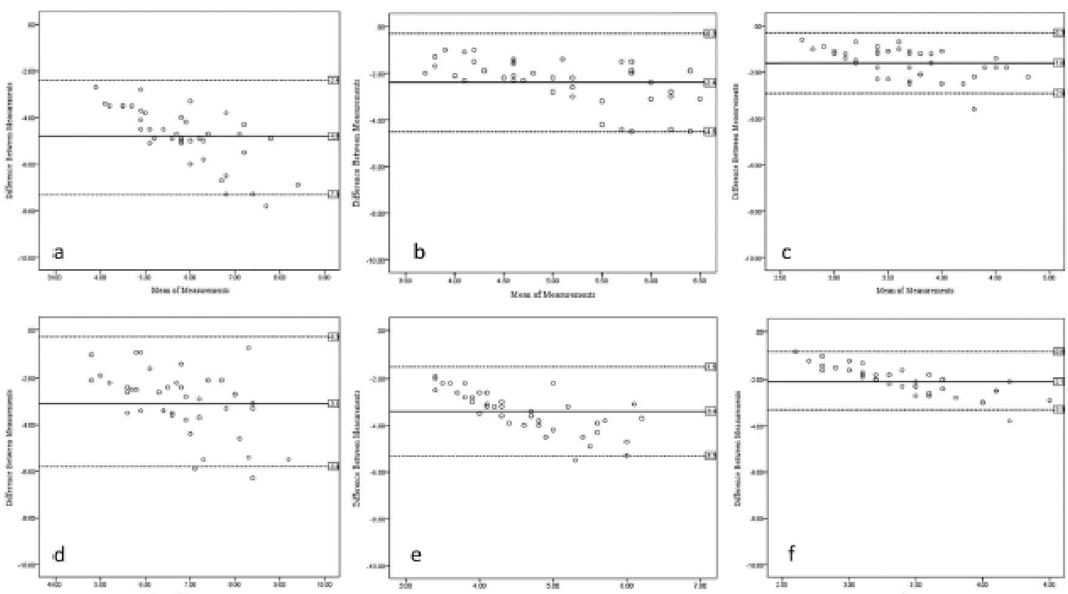

Figure 1. (*Top Row*) Bland-Altman plots depicting error scores of METS estimated by hip-worn accelerometers (Freedson MET equation) vs indirect calorimetry (criterion measure) during the (a) 6-second, (b) 12-second, and (c) 30-second interval sessions. (*Bottom Row*) Bland-Altman plots depicting error scores of METS estimated by dominant wrist-worn accelerometers (Crouter MET equation) vs indirect calorimetry (criterion measure) during the (d) 6-second, (e) 12-second, and (f) 30-second interval sessions.

Table 3. Physical activity levels as measured by indirect calorimetry and accelerometry.

	Device	Study	Location	Group	6 Second interval		12 Second interval		30 Second interval	
METS (Categorical PA, METS ± SD)	Cosmed		N/A	Total	Vigorous	8.3 ± 1.6	Moderate	6.3 ± 1.3	Moderate	4.5 ± 0.8
				Boys	Vigorous	9.3 ± 1.4	Moderate	7.0 ± 1.1	Moderate	4.8 ± 0.7
				Girls	Vigorous	7.2 ± 1.2	Moderate	5.6 ± 1.1	Moderate	4.1 ± 0.7
	ActiGraph	Freedson et al.	Hip	Total	Light	3.4 ± 0.7	Light	2.8 ± 0.5	Light	2.4 ± 0.2
				Boys	Light	3.8 ± 0.6	Light	3.1 ± 0.4	Light	2.4 ± 0.3
				Girls	Light	3.0 ± 0.5	Light	2.6 ± 0.4	Light	2.3 ± 0.2
		Crouter et al.	Wrist Dominant	Total	Moderate	5.2 ± 0.9	Light	3.9 ± 0.6	Light	2.8 ± 0.8
				Boys	Moderate	5.6 ± 0.9	Light	4.1 ± 0.5	Light	3.0 ± 0.5
				Girls	Moderate	4.7 ± 0.5	Light	3.6 ± 0.5	Light	2.7 ± 0.3
CPM (Categorical PA, counts ± SD)	ActiGraph	Freedson et al.	Hip	Total	Moderate	1186 ± 583	Moderate	681 ± 394	Light	281 ± 195
				Boys	Moderate	1490 ± 548	Moderate	861 ± 367	Light	342 ± 216
				Girls	Moderate	834 ± 402	Light	471 ± 320	Light	212 ± 145
		Evenson et al.	Hip	Total	Light	1186 ± 583	Light	681 ± 394	Light	281 ± 195
				Boys	Light	1490 ± 548	Light	861 ± 367	Light	342 ± 219
				Girls	Light	834 ± 402	Light	471 ± 320	Light	212 ± 145
		Crouter et al.	Wrist Dominant	Total	Moderate	11025 ± 2700	Moderate	6916 ± 1790	Light	3876 ± 1283
				Boys	Moderate	12232 ± 2845	Moderate	7657 ± 1573	Light	4226 ± 1471
				Girls	Moderate	9628 ± 1709	Moderate	6057 ± 1667	Light	3472 ± 900
		Chandler et al.	Wrist Non-Dominant	Total	Moderate	8609 ± 2728	Light	5614 ± 1792	Light	3379 ± 1225
				Boys	Moderate	9913 ± 2705	Moderate	6429 ± 1686	Light	3780 ± 1319
				Girls	Moderate	7099 ± 1876	Light	4670 ± 1437	Light	2914 ± 939

Note. METS, metabolic equivalence of task; PA, physical activity; CPM, counts per minute; SD, standard deviation; N/A, non-applicable.
Categorical ranges for METS; < 4.0 METS = Light, 4.0–7.0 METS = Moderate, >7.0 METS = Vigorous.
Categorical ranges for accelerometry; Freedson: 150–499 counts min^{-1} = light, 500–3999 counts min^{-1} = moderate, 4000–7599 counts min^{-1}, = vigorous; Evenson: 101–2295 counts min^{-1} = light, 2296–4011 counts min^{-1} = moderate, > 4012 counts min^{-1}, = vigorous; Crouter: 421–4320 counts min^{-1} = light, 4321–13548 counts min^{-1} = moderate, > 13,550 counts min^{-1}, = vigorous; Chandler: 1933–6348 counts min^{-1} = light, 6349–17532 counts min^{-1} = moderate, > 17,533 counts min^{-1}, = vigorous.
All data is presented as an average per minute.

Table 4. One-sample t-test difference of means, indirect calorimetry vs accelerometry.

Cut-point	Interval	*N*	Mean diff	Std. deviation	*t*	*df*	Sig. (2-tailed)	Cohens *d*	95% Confidence interval of the difference Lower	Upper
Freedson et al.	6 Second	41	5.8	1.1	34.6	40	0.001	11.0	5.5	6.2
Freedson et al.	12 Second	41	4.6	0.8	34.9	40	0.001	11.0	4.3	4.8
Freedson et al.	30 Second	41	3.4	0.5	46.7	40	0.001	15.0	3.3	3.6
Crouter et al.	6 Second	41	6.7	1.1	38.9	40	0.001	12.3	6.4	7.1
Crouter et al.	12 Second	41	5.1	0.8	38.6	40	0.001	12.2	4.8	5.3
Crouter et al.	30 Second	41	3.6	0.5	45.7	40	0.001	14.4	3.5	3.8

Note. Physical activity levels measured by indirect calorimetry and accelerometry (mean ± SD) during nine-minute sessions of object projection skill performance (30, 12, and 6 second intervals).

Hip- and wrist-worn accelerometers, as demonstrated by Bland-Altman plots (Figure 1), underestimated EE com- pared to indirect calorimetry; Hip = 30 s ($P < .001$), 12 s ($P < .001$) and 6 s ($P < .001$); Wrist = 30 s ($P < .001$), 12 s ($P < .001$) and 6 s ($P < .001$). Hip-worn accelerometers underestimated METS by 1.6, 2.4, and 4.8 METS during the 30-, 12-, and 6-second interval conditions respectively. Wrist-worn accelerometers underestimated METS by 2.1, 3.4, and 3.1 METS during the 30-, 12-, and 6-second interval conditions respectively. When calculated as cate- gorical PA levels, hip-worn accelerometers categorized movement as light in all conditions. Wrist-worn acceler- ometers categorized movement as light in during the 30- and 12-second interval conditions and moderate during the 6-second interval condition. Movement values pre- dicted by accelerometry were 0.9 METS or less above resting (2.5 ± 0.4 METS) for all skill conditions. Although EE values estimated by wrist-worn accelerometry were higher (~ 1.0 MET) than by those estimated by hip-worn accelerometry, wrist-worn accelerometry still underesti- mated PA in all interval conditions.

Accelerometer counts were applied to cut-points for each respective wear location to yield categorical levels of PA (i.e., light, moderate, vigorous) for comparison. Chi- square analysis of categorical PA levels derived by acceler- ometery underestimated the PA levels derived from the criterion measure of indirect calorimetry and acceler- ometers from all wear locations during the 6 second and 30 second interval sessions. Furthermore, Evenson et al. (2008; hip) cut-points underestimated PA levels of OPSP during all three interval conditions (i.e., 6, 12, and 30 sec- onds). Chi-square analysis from the remaining 12 second interval sessions (Chandler et al., 2016; Crouter et al., 2015; Freedson et al., 2005) indicated the following statistically significant predictive qualities of accelerometry: 1) catego- rical PA derived from Freedson et al., hip-worn cut-points for the total sample χ^2 (2, N = 42) = 9.46, $p < .01$ and for the boys χ^2 (2, N = 22) = 12.36, $p < .01$, 2) categorical PA derived from Crouter et al., dominate-wrist-worn cut- points for the total sample χ^2 (2, N = 42) = 20.77, $p < .01$ and for both boys χ^2 (2, N = 22) = 19.00, $p < .01$ and girls χ^2 (2, N = 20) = 9.82, $p < .01$, 3) and for categorical PA derived from Chandler et al., non-dominate-wrist-worn cut-points for boys $\chi\chi^2$ (2, N = 22) = 5.45, $p < .05$.

Discussion

The purpose of this study was to compare energy expen- diture (EE) levels during object projection skill perfor- mance (OPSP) as assessed by indirect calorimetry and hip- and wrist-worn accelerometry in children. Overall, accelerometry failed to accurately predict METS, as assessed by indirect calorimetry, during all object projec- tion skill intervals. Recent insight into the EE of specific intervals of OPSP in children and adults (Sacko, Brazendale, et al., 2018; Sacko et al., 2019) challenges the validity of accelerometry in its ability to accurately predict PA intensity levels of OPSP. Comparisons between indirect calorimetry and accelerometry derived PA intensity levels in this study illustrate the consistent underestimation of PA intensity levels by accelerometers worn on the hip, domi- nant wrist, and the non-dominant wrist, during OPSP at varying practice intervals. Each of the accelerometer cut- points analyzed for the purposes of this study (Chandler et al., 2016; Crouter et al., 2015; Evenson et al., 2008; Freedson et al., 2005) are commonly used in the analysis of movement. Accelerometers used in this study measured what they were designed to measure, movement accelera- tions. However, raw accelerometer data is not commonly used in the evaluation of PA levels. Instead, researchers and practitioners apply raw accelerometer data to cut-points to provide an understanding of PA levels during a given event. Data from this study illustrates that MET levels predicted from both hip- and wrist-worn accelerometry were drastically underestimated compared to METS derived from indirect calorimetry (criterion measure) during all three OPSP interval conditions (i.e. 6, 12, 30 sec). Specifically, the discrepancy in mean differences in pre- dicted MET levels between hip- and dominant-wrist-worn accelerometry and indirect calorimetry increased as the performance trial interval time decreased (i.e., 30 s < 12 < 6 s) (see Table 2). Further examination of Bland- Altman plots, illustrates the underestimation of hip- and wrist-worn accelerometry when compared to indirect calorimetry in predicting activity intensity levels (i.e., mod- erate < 4 METS and vigorous < 7 METS) (See Figures 1 & 2). While dominant-wrist-worn accelerometers predicted a higher value of METS over that of hip-worn accelerome- try, the EE values expressed in METS still did not surpass the thresholds of 4 and 7 METS needed to accurately predict PA levels as determined by the criterion measure of indirect calorimetry.

EE measured by indirect calorimetry indicated OPSP yielded "vigorous" levels of PA during the 6 second ses- sions and "moderate" during the 12 s and 30 s intervals sessions; however, hip worn cut-points based on Evenson et al. (2008) predicted only "light" activity levels during all interval conditions. Underestimating PA levels during OPSP may lead to the exclusion of ballistic skills when planning movement interventions or physical education lessons. Furthermore, all PA intensity levels categorized by cut-points (Chandler et al., 2016; Crouter et al., 2015; Evenson et al., 2008; Freedson et al., 2005) during OPSP and by wear location variations (hip, dominant-wrist, and non-dominant-wrist) underestimated actual PA levels dur- ing the 6 second (i.e., highest intensity EE condition) and the 30 second (i.e., lowest intensity EE condition) interval sessions. Thus, illustrating that the underestimation of PA intensity levels is present throughout all accelerometer testing conditions evaluated for the purposes of this study. Interestingly, chi-square analysis demonstrated cate- gorical agreement between Freedson et al. (2005) hip-worn accelerometry and indirect calorimetry, as well as between Crouter et al. (2015) dominant wrist-worn accelerometry and indirect calorimetry, for the total sample during the 12 second interval sessions. The agreement of the Freedson et al. (2005) and Crouter et al. (2015) cut-points during the 12 second interval may simply be a construct of timing (5 performance events per minute) and intensity (i.e., moderate). The accumulation of wrist and hip movements during the 12 second interval represented a value high enough to cross the threshold for moderate categorization, however, this occurred in the two cut-points with the low- est values for moderate PA. Thresholds for Freedson et al. (2005) cut-points (see Table 2) for moderate PA (>500 counts per minute—cpm) are lower than those of Evenson et al. (2008) (>2296 cpm), thus, it is not surprising that Evenson et al. (2008) cut-points failed to accurately categorize PA levels against indirect calorimetry METS during the 12 second interval condition where children averaged just 681 cpm. Surprisingly, thresholds for domi- nant-wrist (Crouter et al., 2015) cut-points for moderate PA (> 4321 cpm) are lower than those of non-dominant-wrist worn (Chandler et al., 2016) cut-points for moderate PA (> 6349 cpm). Intuitively, one would assume that the dominant wrist would yield higher movement values than the non-dominant wrist movement during OPSP as it relates to play, as the dominant wrist is primarily respon- sible for actions such as throwing, grasping, or carrying. Results from this study (see Table 3) demonstrate that average counts per minute for the dominant wrist were higher than the non-dominant wrist in all conditions. These data speak to the high degree in variability in accel- erometer cut points while also demonstrating that accelerometers underestimate PA levels during OPSP. Dominant wrist cut-points may appear to provide a more valid location for the prediction of PA levels during OPSP; however, these data suggest that their use during OPSP is not reliable for the measurement of PA intensity levels. Due to the limited use of the non-dominant wrist in children with lower skill levels, non-dominant wrist cut- points should not be considered for use in the measure- ment of PA levels during OPSP.

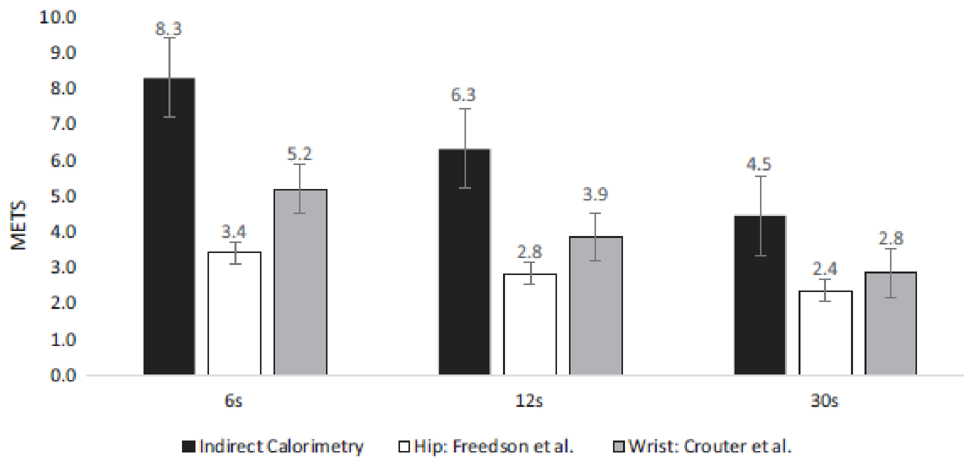

Figure 2. Indirect calorimetry (criterion measure) estimated METS (metabolic equivalent of task), Hip-worn accelerometer (Freedson et al.), and Dominant wrist-worn (Crouter et al.) acceleromter estimated METS during a nine-minute bout of running at a self-selected pace and object projection skill performance intervals (kicking, throwing, and striking) of one repetition every 6, 12, and 30 seconds.

Global findings, illustrated within these data, emphasize the lack of influence that gender has on the comparisons between indirect calorimetry-based and accelerometry- based assessment of EE and PA intensity levels reported by Sacko, Brazendale, et al. (2018). Indirect calorimetry indicated that 38 of the 42 participants achieved the 7.0 METS needed obtain a "vigorous" level of PA which demonstrates a high level of consistency in EE required by children to perform object projection skills at 6 second intervals. In contrast, hip- and wrist-worn accelerometers consistently underestimated OPSP PA intensity levels dur- ing the 6-second interval using MET prediction extrapola- tions and cut-points. This same underestimation occurred throughout the 30 second OPSP where indirect calorimetry indicated that 38 of 42 participants achieved the > 4 METS required for classification of moderate PA, yet, hip- or wrist-worn accelerometry failed to classify any participant above a "light" PA intensity level.

It is important to note that the development of Freedson et al. (2005), Evenson et al. (2008) Crouter et al. (2015) and Chandler et al. (2016) cut-points for children were all developed without using any activities that included any variation of OPSP during calibration. An important reason for the consistent and drastic under- estimation of PA intensity levels (i.e., 4.0–7.0 METS) by accelerometry during OPSP is that the volume of accel- erations associated with intermittent performances of object projection skills is far smaller than the volume of accelerations associated with a continuous activity (e.g., brisk walking, running) during an equivalent amount of time (i.e., nine-minutes). In essence, oscillations of the hips and wrists occur continuously during the locomotor activities (e.g., running), thus producing a high and con- sistent accumulation of counts that are captured by accel- erometers. In contrast, oscillations of the hip and wrists produced during the OPSP is limited by the total number of repetitions that occur during a given time period (e.g., 1 OPSP every 30 seconds = 2 performances per minute); However, high effort OPSP requires high total body neu- romuscular demand (high intensity) and thus, necessitates high levels of acute EE. It is therefore not surprising that the lower volume of accelerometer counts worn at both the hip and wrists does not demonstrate MVPA. These data also suggest that the neuromuscular demands asso- ciated with OPSP are substantially higher than repetitive cardiorespiratory activities of moderate intensity (e.g., brisk walking or running; Girard et al., 2005) and "activ- ities of daily living" that were used during the Freedson et al. (2005), Evenson et al. (2008), Crouter et al. (2015) and Chandler et al. (2016) cut-point validation studies. Accelerometers used in this study did not fail to measure what they are intended to measure (i.e., number of move- ment accelerations at different intensities during nine- minute trials), rather, they failed to capture the metabolic EE associated with the neuromuscular demand of OPSP. The high neuromuscular demand facilitated during repe- titive OPSP is promoted via the demand for high seg- mental velocities produced by concentric and eccentric neuromuscular mechanisms through the kinetic chain (Campbell, Stodden, & Nixon, 2010; Croix & Korff, 2013; Girard et al., 2005; Langendorfer et al., 2011; MacWilliams et al., 1998; Rodacki, Fowler, & Bennett, 2002; Stodden, Langendorfer, Fleisig, & Andrews, 2006). Thus, the importance of promoting activities that involve OPSP are beneficial to impact acute levels of health-enhancing PA in children and adolescence.

The use of wrist-worn accelerometers has been pro- moted over those of hip-worn accelerometers for the mea- surement of PA levels in children (Evenson et al., 2008; Freedson et al., 2005) due to the wrists association with upper body movement (Chandler et al., 2016). For exam- ple, the cut-points associated with MVPA for wrist-worn accelerometers (moderate ≥ 6360 counts min^{-1}; Chandler et al., 2016) are significantly higher than those of hip-worn accelerometers (moderate ≥ 2296 counts min^{-1}; Evenson et al., 2008) in children. Furthermore, the cut-points asso- ciated with MVPA for non-dominant-wrist-worn acceler- ometers (moderate ≥ 6360 counts min⁻1; Chandler et al., 2016) are significantly higher than those of the dominant- wrist-worn (i.e., more active limb during OPSP) acceler- ometers (moderate ≥ 4321 counts min^{-1}; Crouter et al., 2015) in children. Thus, the lack of validity in the measure- ment of EE or intensity levels during OPSP by acceler- ometers, as indicated by this study's findings, again is a result of the neuromuscular demands of OPSP and lack of OPSP specific cut-points rather than a result of the wear location.

The current study evaluated the ability of acceler- ometers placed on common wear locations (hip, domi- nant- and non-dominant wrists) and corresponding cut- points to predict EE. Recently, research by Crouter, Oody, and Bassett (2018) and Duncan, Roscoe, Faghy, Tallis, and Eyre (2019) have suggested that the wear placement of an accelerometer on the ankle may be favorable to both hip or wrist accelerometer placements during unstruc- tured PA, instep passing, or a toss and catch activity and warrants future research. In addition, the commonly used cut-points evaluated for the purposes of this study did not include repetitive OPSP during their respective validation studies, thus, it was not surprising that these cut-points failed to account for the intermittent nature of OPSP performance. As previously suggested, the evaluation of raw accelerometer data may provide the predictive valid- ity needed to produce a wearable technology that can be used by researchers and practitioners for more valid PA assessment.

The early childhood years are a critical time for the development of health-enhancing PA habits and the development of motor skills as they provide a foundation for future PA (Clark & Metcalfe, 2002; Stodden et al., 2008). Sacko et al. (2019) demonstrated that repetitive OPSP (performed during play or prac- tice) provide an alternative to continuous activities (brisk walking or running) to assist in accumulating recommended doses of MVPA associated with health- enhancing benefits. As illustrated by the data contained within this study, the repetitive practice of OPSP in physical education, sports, and PA intervention settings may be drastically undervalued in its usefulness to attain not only recommended daily levels of MVPA, but also promote long-term positive PA trajectories (Jaakkola, Yli-Piipari, Huotari, Watt, & Liukkonen, 2016; Lima et al., 2017; Robinson et al., 2015). Optimizing moderate to vigorous PA may be accom- plished if play and practice environments can facilitate trial intervals demonstrated in this study (i.e., one repetition of kicking, throwing, or striking with high effort every 6–30 seconds). Practice environments where trials are on the order of 2–5 trials per minute also allow for inter-trial instruction and feedback, which can further facilitate the learning of the skills. As recommendations for time spent in moderate to vigorous PA during K-12 physical education in the United States is a minimum of 50% of the class period (Wiecha, Hall, & Barnes, 2014). maximizing time spent in health-enhancing levels of PA may be as simple as encouraging consistent high-intensity ballistic move- ments at regular intervals during physical education lessons. Furthermore, combining OPSP in activities with continuous locomotor activities would provide even greater levels of health-enhancing PA.

This study is not without limitations. A contributing factor that may influence MET values is an individual's effort during performance. Although participants were queued to execute movements "with maximal effort" throughout each interval session, each participants interpretation of the instruction is relative to each per- former. Over 90% (38 of 42) of participants measured for the purposes of this study exhibited EE equivalent to moderate or vigorous PA during all interval conditions (8.3 ± 1.6, 6.3 ± 1.3, 4.5 ± 0.8 at 6-, 12-, and 30-sec interval conditions respectively). Finally, as EE and counts were assessed via the combination of all three skills, the relative contribution of each skill to EE and counts were not addressed. However, as kicking, throw- ing, and striking all are multi-joint ballistic skills that have similar gross neuromuscular involvement via similar kinetic chain mechanisms to produce force; individual skill performance contributions relative to EE during each skill movement should be similar (Langendorfer et al., 2011).

What does this article add?

This is one of the first studies to evaluate the ability of hip- and wrist-worn accelerometry to predict PA levels during object projection skill performance (OPSP) at different intensity intervals in children. Results demonstrated that, when compared to indirect calorimetry, hip- and wrist- worn accelerometry dramatically underestimate EE and thus, PA intensity (assessed by both METS and counts) during higher effort OPSP. The large disparity between indirect calorimetry MET levels and predicted MET levels from both hip and wrist accelerometers during OPSP suggests that accelerometry can grossly underestimate actual exercise intensity levels during many activities in which children routinely engage during physical educa- tion, recess, sports, and leisure play. This underestimation occurs even at a rate of only two performance events per minute. Thus, the potential impact of these data on measurement of children's PA should not be underesti- mated nor undervalued in terms of both acute PA levels and lifetime PA behaviors. As the development of motor competence is linked to positive trajectories of PA, health- related physical fitness and body weight status across childhood and adolescence (Cattuzzo et al., 2016; Lima et al., 2017) it seems logical to emphasize the acquisition and development of OPSP as well as locomotor skill competence in PA settings such as physical education, recess, and youth sports.

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References

Bailey, R. C., Olson, J., Pepper, S. L., Porszasz, J., Barstow, T. J., & Cooper, D. M. (1995). The level and tempo of children's physical activities: An observational study. *Medicine & Science in Sports & Exercise*, *27*(7), 1033–1041. doi:10.1249/00005768-199507000-00012

Bland, J. M., & Altman, D. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *The Lancet*, *327*(8476), 307–310. doi:10.1016/S0140-6736(86)90837-8

Brazendale, K., Beets, M. W., Bornstein, D. B., Moore, J. B., Pate, R. R., Weaver, R. G., … van Sluijs, E. M. F. (2016). Equating accelerometer estimates among youth: The Rosetta Stone 2. *Journal of Science and Medicine in Sport*, *19*(3), 242–249. doi:10.1016/j.jsams.2015.02.006

Butte, N. F., Watson, K. B., Ridley, K., Zakeri, I. F., McMurray, R. G., Pfeiffer, K. A., … Long, A. (2017). A youth compendium of physical activities: Activity codes and metabolic intensities. *Medicine and Science in Sports and Exercise*, *50*(2), 246. doi:10.1249/MSS.0000000000001430

Campbell, B. M., Stodden, D. F., & Nixon, M. K. (2010). Lower extremity muscle activation during baseball pitching. *The Journal of Strength & Conditioning Research*, *24*(4), 964–971. doi:10.1519/JSC.0b013e3181cb241b

Cattuzzo, M. T., dos Santos Henrique, R., Ré, A. H. N., de Oliveira, I. S., Melo, B. M., de Sousa Moura, M., … Stodden, D. (2016). Motor competence and health related physical fitness in youth: A systematic review. *Journal of Science and Medicine in Sport*, *19*(2), 123–129. doi:10.1016/j.jsams.2014.12.004

Chandler, J. L., Brazendale, K., Beets, M. W., & Mealing, B. A. (2016). Classification of physical activity intensities using a wrist-worn accelerometer in 8-12- year-old children. *Pediatric Obesity*, *11*(2), 120–127. doi:10.1111/ijpo.12033

Clark, J. E., & Metcalfe, J. S. (2002). The mountain of motor development: A metaphor. *Motor Development: Research and Reviews*, *2*, 163–190.

Committee, Physical Activity Guidelines Advisory. (2018). *Physical activity guidelines advisory committee scientific report* (F2–33). Washington, DC: US Department of Health and Human Services.

Croix, M. D. S., & Korff, T. (2013). *Paediatric biomechanics and motor control: Theory and application*. Oxford, UK: Routledge.

Crouter, S. E., Clowers, K. G., & Bassett, D. R. (2006). A novel method for using accelerometer data to predict energy expenditure. *Journal of Applied Physiology*, *100*(4), 1324–1331. doi:10.1152/japplphysiol.00818.2005

Crouter, S. E., Flynn, J. I., & Bassett, D. R., Jr. (2015). Estimating physical activity in youth using a wrist accelerometer. *Medicine and Science in Sports and Exercise*, *47*(5), 944. doi:10.1249/MSS.0000000000000651

Crouter, S. E., Oody, J., & Bassett, D. R., Jr. (2018). Estimating physical activity in youth using an ankle accelerometer. *Journal of Sports Sciences*, *36*, 2265–2271. doi:10.1080/02640414.2018.1449091

Duffield, R., Dawson, B., Pinnington, H., & Wong, P. (2004). Accuracy and reliability of a Cosmed K4b 2 portable gas analysis system. *Journal of Science and Medicine in Sport*, *7* (1), 11–22. doi:10.1016/S1440-2440(04)80039-2

Duncan, M. J., Roscoe, C., Faghy, M., Tallis, J., & Eyre, E. (2019). Estimating physical activity in children aged 8-11 years using accelerometry: Contributions from fundamen- tal movement skills and different accelerometer placements. *Frontiers in Physiology*, *10*, 242. doi:10.3389/fphys.2019.00242

Escamilla, R. F., & Andrews, J. R. (2009). Shoulder muscle recruitment patterns and related biomechanics during upper extremity sports. *Sports Medicine*, *39*(7), 569–590. doi:10.2165/00007256-200939070-00004

Evenson, K. R., Catellier, D. J., Gill, K., Ondrak, K. S., & McMurray, R. G. (2008). Calibration of two objective mea- sures of physical activity for children. *Journal of Sports Sciences*, *26*(14), 1557–1565. doi:10.1080/02640410802334196

Freedson, P., Melanson, E., & Sirard, J. (1998). Calibration of the Computer Science and Applications, Inc. accelerometer. *Medicine and Science in Sports and Exercise*, *30*(5), 777–781.

Freedson, P., Pober, D., & Janz, K. F. (2005). Calibration of accelerometer output for children. *Medicine & Science in Sports & Exercise*, *37*(11), S523. doi:10.1249/01. mss.0000185658.28284.ba

Gabbard, C. P. (2011). *Lifelong motor development*. New York, NY: Pearson Higher Ed.

Girard, O., Micallef, J.-P., & Millet, G. P. (2005). Lower-limb activity during the power serve in tennis: Effects of per- formance level. *Medicine and Science in Sports and Exercise*, *37*(6), 1021–1029.

Jaakkola, T., Yli-Piipari, S., Huotari, P., Watt, A., & Liukkonen, J. (2016). Fundamental movement skills and physical fitness as predictors of physical activity: A 6-year follow-up study. *Scandinavian Journal of Medicine & Science in Sports*, *26*(1), 74–81. doi:10.1111/sms.12407

Katzmarzyk, P. T., Denstel, K. D., Beals, K., Bolling, C., Wright, C., Crouter, S. E., … Sisson, S. B. (2016). Results from the United States of America's 2016 report card on physical activity for children and youth. *Journal of Physical Activity and Health*, *13*(11 Suppl 2), S307–S313. doi:10.1123/jpah.2016-0321

Kim, Y., Beets, M. W., & Welk, G. J. (2012). Everything you wanted to know about selecting the " right" Actigraph accelerometer cut-points for youth, but … : A systematic review. *Journal of Science and Medicine in Sport*, *15*(4), 311–321. doi:10.1016/j.jsams.2011.12.001

Kim, Y., Lee, J.-M., Peters, B. P., Gaesser, G. A., & Welk, G. J. (2014). Examination of different accelerometer cut-points for assessing sedentary behaviors in children. *PloS One*, *9* (4), e90630. doi:10.1371/journal.pone.0090630

Kohl, H. W., III, Fulton, J. E., & Caspersen, C. J. (2000). Assessment of physical activity among children and ado- lescents: A review and synthesis. *Preventive Medicine*, *31* (2), S54–S76. doi:10.1006/pmed.1999.0542

Langendorfer, S., Roberton, M. A., & Stodden, D. (2011). Biomechanical aspects of the development of object pro- jection skills. In M. De Ste Croix & T. Korff (Eds.), *Pediatric biomechanics and motor control: Theory and application* (pp. 180–206). Oxford, UK: Routledge.

Laukkanen, A., Pesola, A., Havu, M., Sääkslahti, A., & Finni, T. (2014). Relationship between habitual physical activity and gross motor skills is multifaceted in 5-to 8- year-old children. *Scandinavian Journal of Medicine & Science in Sports*, *24*(2), e102–e110. doi:10.1111/sms.12116

Lima, R. A., Pfeiffer, K., Larsen, L. R., Bugge, A., Moller, N. C., Anderson, L. B., & Stodden, D. F. (2017). Physical activity and motor competence present a positive reciprocal longitudinal relationship across childhood and early adolescence. *Journal of Physical Activity and Health*, *14*(6), 440–447. doi:10.1123/jpah.2016-0473

Lyden, K., Kozey, S. L., Staudenmeyer, J. W., & Freedson, P. S. (2011). A comprehensive evaluation of commonly used accelerometer energy expenditure and MET prediction equations. *European Journal of Applied Physiology*, *111*(2), 187–201. doi:10.1007/s00421-010-1639-8

Machado-Rodrigues, A. M., Coelho-E-Silva, M. J., Mota, J., Cyrino, E., Cumming, S. P., Riddoch, C., … Malina, R. M. (2011). Agreement in activity energy expenditure assessed by accelerometer and self-report in adolescents: Variation by sex, age, and weight status. *Journal of Sports Sciences*, *29* (14), 1503–1514. doi:10.1080/02640414.2011.593185

MacWilliams, B. A., Choi, T., Perezous, M. K., Chao, E. Y., & McFarland, E. G. (1998). Characteristic ground-reaction forces in baseball pitching. *The American Journal of Sports Medicine*, *26*(1), 66–71. doi:10.1177/03635465980260012801

McKenzie, T. L., Sallis, J. F., Nader, P. R., Patterson, T. L., Elder, J. P., Berry, C. C., … Nelson, J. A. (1991). BEACHES: An observational system for assessing chil- dren's eating and physical activity behaviors and associated events. *Journal of Applied Behavior Analysis*, *24*(1), 141–151. doi:10.1901/jaba.1991.24-141

Melby, C., Scholl, C., Edwards, G., & Bullough, R. (1993). Effect of acute resistance exercise on postexercise energy expenditure and resting metabolic rate. *Journal of Applied Physiology*, *75*(4), 1847–1853. doi:10.1152/ jappl.1993.75.4.1847

Orloff, H., Sumida, B., Chow, J., Habibi, L., Fujino, A., & Kramer, B. (2008). Ground reaction forces and kinematics of plant leg position during instep kicking in male and female collegiate soccer players. *Sports Biomechanics*, *7*(2), 238–247. doi:10.1080/14763140802255804

Pate, R. R., Almeida, M. J., McIver, K. L., Pfeiffer, K. A., & Dowda, M. (2006). Validation and calibration of an accel- erometer in preschool children. *Obesity*, *14*(11), 2000–2006. doi:10.1038/oby.2006.234

Pinnington, H. C., Wong, P., Tay, J., Green, D., & Dawson, B. (2001). The level of accuracy and agreement in measures of FEO2, FECO2 and VE between the Cosmed K4b2 porta- ble, respiratory gas analysis system and a metabolic cart. *Journal of Science and Medicine in Sport*, *4*(3), 324–335. doi:10.1016/S1440-2440(01)80041-4

Ridley, K., Ainsworth, B. E., & Olds, T. S. (2008). Development of a compendium of energy expenditures for youth. *International Journal of Behavioral Nutrition and Physical Activity*, *5*(1), 45. doi:10.1186/1479-5868-5-29

Robinson, L. E., Stodden, D. F., Barnett, L. M., Lopes, V. P.,Logan, S. W., Rodrigues, L. P., & D'Hondt, E. (2015). Motor competence and its effect on positive developmentaltrajectories of health. *Sports Medicine*, *45*(9), 1273–1284. doi:10.1007/s40279-015-0351-6

Rodacki, A. L., Fowler, N. E., & Bennett, S. J. (2002). ertical jump coordination: Fatigue effects. *Medicine & Science in Sports & Exercise*, *37*(1), 105–116. doi:10.1097/00005768-200201000-00017

Sacko, R. S., Brazendale, K., Brian, A., McIver, K., Nesbitt, D., Pfeifer, C., & Stodden, D. F. (2018). Comparison of indir- ect calorimetry- and accelerometry-based energy expendi- ture during object project skill performance. *Measurement in Physical Education and Exercise Science*, 1–11. doi:10.1080/1091367X.2018.1554578

Sacko, R. S., McIver, K., Brian, A., & Stodden, D. F. (2018). New insight for activity intensity relativity, metabolic expenditure during object projection skill performance. *Journal of Sports Sciences*, 2018, *36*(21), 2412–2418. doi:10.1080/02640414.2018.1459152

Sacko, R. S., Nesbitt, D., McIver, K., Brian, A., Bardid, F., & Stodden, D. F. (2019). Children's metabolic expenditure during object projection skill performance: New insight for activity intensity relativity. *Journal of Sport Sciences*, 1–7. doi:10.1080/02640414.2019.1592801

Stodden, D. F., Langendorfer, S. J., Fleisig, G. S., & Andrews, J. R. (2006). Kinematic constraints associated with the acquisition of overarm throwing part I: Step and trunk actions. *Research Quarterly for Exercise and Sport*, *77* (4), 417.

Stodden, D. F., Langendorfer, S. J., Goodway, J. D., Roberton, M. A., Rudisill, M. E., Garcia, C., & Garcia, L. E. (2008). A developmental perspective on the role of motor skill competence in physical activity: An emergent relationship. *Quest*, *60*(2), 290–306. doi:10.1080/00336297.2008.10483582

Stodden, D. F., True, L. K., Langendorfer, S. J., & Gao, Z. (2013). Associations among selected motor skills and health-related fitness: Indirect evidence for Seefeldt's pro- ficiency barrier in young adults? *Research Quarterly for Exercise and Sport*, *84*(3), 397–403. doi:10.1080/02701367.2013.814910

Troiano, R. P. (2006). Translating accelerometer counts into energy expenditure: Advancing the quest. *Journal of Applied Physiology*, *100*(4), 1107–1108. doi:10.1152/ japplphysiol.01577.2005

Trost, S. G., McIver, K. L., & Pate, R. (2005). Conducting accelerometer-based activity assessments in field-based research. *Medicine & Science in Sports & Exercise*, *37*(11), S531. doi:10.1249/01.mss.0000185657.86065.98

van Hees, V. T., Renström, F., Wright, A., Gradmark, A., Catt, M., Chen, K. Y., … Ekelund, U. (2011). Estimation of daily energy expenditure in pregnant and non-pregnant women using a wrist-worn tri-axial accelerometer. *PloS One*, *6*(7), e22922. doi:10.1371/journal.pone.0022922

Wiecha, J. L., Hall, G., & Barnes, M. (2014). Uptake of national after school association physical activity standards among US after-school sites. *Preventive Medicine*, *69*, S61– S65. doi:10.1016/j.ypmed.2014.07.010