International Journal of Obesity Supplements (2015) 5, S53–S58

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REVIEW

Unique contributions of ISCOLE to the advancement of accelerometry in large studies

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Accelerometry has become a mainstay approach for objectively monitoring children's physical activity and sedentary time in epidemiological studies. The magnitude of effort underlying successful data collection, management and treatment is prodigious and its complexity has been associated with increasingly diverse methodological choices that, while defensible relative to specific research questions, conspire to undermine the ability to compare results between studies. Although respecting widespread calls for best practices, it is also important to openly share tools and resources supporting potential improvements to research practice and study design, thus allowing others to replicate, further improve, and/or otherwise build on this foundation. The International Study of Childhood Obesity, Lifestyle and the Environment (ISCOLE) is a large multinational study that included accelerometer-based measures of physical activity, sedentary time and sleep. This review summarizes the unique contributions of ISCOLE to the advancement of accelerometry in large studies of children's behavior, and in particular: (1) open-access publication of the ISCOLE accelerometry Manual of Operations; (2) 24-h waist-worn accelerometry protocol; (3) identification and extraction of nocturnal total sleep episode time (with open access to editable SAS syntax); (4) development of the first interpretive infrastructure for identifying and defining an evolved list of sleep-related variables from 24-h waist-worn accelerometry; (5) provision of a detailed model for reporting accelerometer paradata (administrative data related to accelerometry); and (6) cataloging the most detailed and defensible list of accelerometry-derived physical activity and sedentary time variables to date. The novel tools and resources associated with these innovations are shared openly in an effort to support methodological harmonization and overall advancement of accelerometry in large epidemiological studies.

International Journal of Obesity Supplements (2015) 5, S53–S58; doi:10.1038/ijosup.2015.20

INTRODUCTION

Physical activity epidemiology is the study of the prevalence, distribution and potential determinants of physical activity (and sedentary behavior) and its role in the prevention and treatment of chronic disease, including obesity.[1] As such, physical activity epidemiology is dependent on the accurate measurement of this human behavior. The traditional reliance on self-report methods has given way in recent decades to objective monitoring using body worn accelerometry-based sensors. Accelerometry is particularly important to the study of children's physical activity where self-reported behaviors are known to be particularly inaccurate and unreliable.[2,3] However, even in small studies of children's physical activity, accelerometry is a complex procedure, requiring careful and rationalized planning, attentive execution, diligent management and dedicated processing.[4] The magnitude of effort underlying successful objective monitoring of children's physical activity by accelerometry in large epidemiological studies is prodigious.

The complexity of procedure and magnitude of effort means that there is potential for increasingly diverse methodological choices that may be justifiable for the original study's purpose, but may also ultimately undermine the comparability across studies and the opportunity to build and leverage a broad based foundation of knowledge. In 2013, Cain *et al.*[5] reviewed 183 studies representing ActiGraph accelerometer-based assessment of children's physical activity and sedentary behavior and reported a diversity of methods including 2 ActiGraph models, 6 epoch lengths, 6 non-wear definitions, 13 valid day definitions, 8 minimum wearing day thresholds, 12 moderate-intensity physical activity cut points and 11 sedentary cut points. They proposed a methodological research-based agenda to provide the essential evidence needed to support best practices and decision rules. Although respecting the necessity for best practices, it is also important to continue to consider potential improvements to research practice and study design.

The International Study of Childhood Obesity, Lifestyle and the Environment (ISCOLE) is a multinational cross-sectional study of the relationships between childrens' lifestyle, environment and obesity that included objective monitoring of physical activity, sedentary time and nocturnal sleep-related variables by accelerometry.[6] Other multinational studies[7] that have included an objective measure of children's physical activity and sedentary time are cataloged in Table 1. All focused on European countries, used various models (based on availability at the time) of the ActiGraph accelerometer and included participant samples ranging between 2.0 and 17.5 years of age. Monitoring frames ranged from 3 to 7 days, all employed a daytime wearing protocol (removal at bedtime and for water-based activities), and most defined non-wear time as ⩾20 consecutive minutes of 0 activity counts per minute. As cataloged in Table 1, however, minimal wearing requirements to define a valid case included ⩾3 days (no

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Table 1. Comparison of accelerometer protocols in multi-country studies of children/adolescents

Study	*Design*	*Countries*	*Years of data collection*	*Device*	*Participants*	*Summarization epoch*	*Monitoring protocol*	*Non-wear definition*	*Valid case definition*
European Youth Heart Study[7]	Cross-sectional	4 European countries: Odense (Denmark), Island of Madeira (Portugal), Tartu (Estonia), and Oslo (Norway)	Not reported	ActiGraph MTI 7164	2185 children (number of girls not reported); 9 and 15 years of age (number in each age group not reported)	60 s	4 days, including 1 weekend; hip/waist; removal at bedtime and for water activities	⩾10 min of consecutive zeros	⩾3 Days (⩾10 h wear time), including 1 weekend
HELENA study[23]	Cross-sectional	10 cities from 9 European countries: Athens (Greece), Dortmund (Germany), Ghent (Belgium), Heraklion (Greece), Lille (France), Pecs (Hungary), Rome (Italy), Stockholm (Sweden), Vienna (Austria), and Zaragoza (Spain)	2006–2008	ActiGraph GT1M	2200 adolescents (1184 girls); 12.5–17.5 years of age	15 s	7 days; lower back; removal at bedtime and for water activities	⩾20 min of consecutive zeros	⩾3 days (⩾8 h wear time)
ENERGY-project[10]	Cross-sectional	5 European countries: Belgium, Greece, Hungary, Switzerland and the Netherlands	2010	3 ActiGraph models: Actitrainers (triaxial), GT3Xs and GT1Ms	1082 children (552 girls); 10–12 years of age	15 s	6 days including 2 weekends; waist/right side; removal at bedtime and for water activities	⩾20 min of consecutive zeros	⩾3 weekdays (⩾10 h wear time) and ⩾1 weekend (⩾8 h wear time)
IDEFICS[24]	Prospective cohort with embedded intervention	8 European countries: Sweden, Germany, Hungary, Italy, Cyprus, Spain, Belgium and Estonia	Baseline: September 2007 to June 2008 Follow-up: September 2010 to May 2011	ActiGraph GT1M or ActiTrainer activity monitor	7684 children (3842 girls); 2.0–10.9 years of age	15 s (60 s epoch inadvertently used in a portion of the sample). Analysis done with 60 s.	⩾3 days (including 1 weekend); right hip; removal at bedtime	⩾20 min of consecutive zeros	⩾3 days with at least 8 h of wear time
ISCOLE[6,11]	Cross-sectional	15 cities from 12 international countries: Adelaide (Australia), Bangalore (India), Bath and NE Somerset (United Kingdom), Baton Rouge (United States), Bogota (Colombia), Cape Town (South Africa), Helsinki, Espoo and Vantaa (Finland), Nairobi (Kenya), Ottawa (Canada), Porto (Portugal), São Paulo (Brazil) and Tianjin (China)	September 2011 to Dec 2013	ActiGraph GT3X+	7372 children; 9–11 years of age; 6553 with valid accelerometry data[21]	80-Hz data collection, 15 and 60 s with low-frequency extension enable for analysis	7 days removal only for water activities; right hip in line with mid-axillary line	⩾20 min of consecutive zeros	⩾ 4 days (including 1 weekend day); right hip in line with mid-axillary line

consideration for type of day) with ⩾8 h per day of wear time, ⩾3 days including 1 weekend with ⩾10 h per day of wear time and ⩾3 weekdays (⩾10 h per day of wear time) plus ⩾1 weekend (⩾8 h per day of wear time). As discrepancy and disagreement in the selection and application of various accelerometer-based cut points are well known[5] and can also differ between analyses of the same data set,[8] these additional details are not presented in this simple comparative table.

The purpose of this review is to summarize the unique contributions of ISCOLE to the advancement of accelerometry in large studies of children's behavior, in particular: (1) open-access publication of the ISCOLE accelerometry Manual of Operations (MOPs); (2) implementation of a 24-h waist-worn accelerometry protocol; (3) identification and extraction of nocturnal total sleep episode time (with open access to editable SAS syntax); (4) development of the first interpretive infrastructure for identifying and defining an evolved list of sleep-related variables (for example, movement/non-movement indicators of sleep efficiency, waking episodes, chronotypical midpoint and so on) from 24-h waist-worn accelerometry; (5) provision of a detailed model for reporting accelerometer paradata (administrative data related to accelerometry); and (5) cataloging the most detailed and defensible list of accelerometry-derived physical activity and sedentary time variables to date. Our intent is to summarize these unique contributions and openly provide these novel tools and resources in an effort to support methodological harmonization.

OPEN-ACCESS PUBLICATION OF THE ISCOLE ACCELEROMETRY MOP

Description of accelerometry data collection, management and treatment has been traditionally limited to an abbreviated summary published within a study's methods section. Although researchers acknowledged the importance of a more detailed and developed MOP to guide internal logistics,[9] it was not possible to share these openly or easily. More recently, open-access journals have provided a venue to publish study protocols,[10] although the details of accelerometry are frequently subsumed by the greater need to describe all study procedures that go well beyond solely accelerometry. Indeed, the overall study methods for ISCOLE were published in this more conventional manner.[6] However, we also chose to provide access to the ISCOLE accelerometry MOP (detailing data collection, management and treatment), publishing it as Supplementary Information to a separate methodological study.[11]

24-H WAIST-WORN ACCELEROMETRY PROTOCOL

Reduced compliance to wear-time regimens is considered an important threat to validity for accelerometer-determined estimates of physical activity and sedentary time.[12] The decision to implement a 24-h accelerometer wear protocol was an ISCOLE *a priori* decision to increase wear-time compliance, whereas maintaining the traditional waist attachment site for monitoring.[11] This latter decision allowed us to use existing infrastructures, variables and algorithms to manage and treat the accelerometer data. The 24-h accelerometer wear protocol also provides an opportunity to study the nocturnal total sleep episode time separate and distinct from physical activity and sedentary time detected during waking hours.[13,14]

We have demonstrated that the 24-h accelerometer wear protocol produced 22.6 out of 24 h of possible wear time in 9–11-year-old US children participating in ISCOLE. Further, ISCOLE averaged 61.8 more minutes per day of waking wear time than a similarly implemented and processed waking wear-time waist-worn accelerometry protocol implemented in similarly aged US children participating in the 2003–2006 National Health Nutrition Examination Survey.[11] In the same analyses, we demonstrated that all other ISCOLE sites internationally showed consistently higher accelerometer wear times than the 2003–2006 National Health Nutrition Examination Survey.

IDENTIFICATION AND EXTRACTION OF NOCTURNAL TOTAL SLEEP EPISODE TIME

The ISCOLE decision to implement a 24-h accelerometer wear protocol required that the nocturnal total sleep episode time needed to be first distinguished from the continuously collected accelerometer data before further analysis of daytime wearing patterns and physical activity/sedentary time could begin. The development and refinement of a fully automated algorithm for identifying the nocturnal total sleep episode time was a staged process, beginning first with the development and initial validation against expert visual inspection of the data[13] and subsequently refinement and validation compared with logged sleep behaviors.[14] The original algorithm combines aspects of the Sadeh technique[15] for sleep–wake scoring, makes use of the accelerometer's inclinometer function to make further adjustments, and builds onto the commonly used and publicly available non-wear algorithm developed by the National Cancer Institute (http://riskfactor.cancer.gov/tools/nhanes_pam/) to fully automate identification of sleep onset (that is, 'bedtime') and sleep offset (that is, 'waking') times.[13] The refined algorithm then added additional complexity designed to identify disrupted nocturnal sleep episodes (and exclude episodes of nighttime non-wear/wakefulness) and avoid misclassification of daytime non-wear or sedentary behavior as sleep.[14] Compared with congruently collected sleep logs and traditional sleep log/accelerometer analytical combinations, we achieved acceptable levels of accuracy ($<10\%$ mean absolute percent difference) with this refined fully automated algorithm.[14] Pennington Biomedical Research Center hosts public web-based access to both the original (www.pbrc.edu/SleepPeriodTimeMacro)[13] and refined (http://www.pbrc.edu/pdf/PBRCSleepEpisodeTimeMacroCode.pdf)[14] algorithms to enable future research.

DEVELOPMENT OF INTERPRETIVE INFRASTRUCTURE FOR IDENTIFYING AND DEFINING WAIST-WORN ACCELEROMETER-DETERMINED SLEEP-RELATED VARIABLES

The 24-h waist-worn accelerometry protocol implemented in ISCOLE also provided a unique opportunity to scrutinize all the behaviors, including those contained within the nocturnal total sleep period time, performed within the closed and finite chronological system of the 24-h day. Sleep researchers have traditionally relied on wrist-worn actigraphy to capture the distinct movement and non-movement patterns during the nocturnal sleep period time and make inferences about chronological sleep onset, offset, midpoint (used to chronotype individuals as 'early' or 'late' sleep) and other sleep-related variables.[16] Actigraphy is a preferred term in sleep research, but it is based on the same accelerometer-based technology as used in physical activity and sedentary time research. Although historically applied inconsistently,[17] an interpretive infrastructure exists to help identify these variables from the wrist-worn device's electronic signal.[16] This is not the case with waist-worn accelerometry. With the implementation of a 24-h waist-worn accelerometry protocol, ISCOLE researchers had to tackle the challenge of systematically developing, testing and refining definitions and algorithms, first with the US based sample, and subsequently as applied to all the international accelerometer data collected in ISCOLE.[18] The ultimate list of 24-h waist-worn accelerometer-derived nocturnal sleep-related variables, their definitions, and initial benchmark values based on ISCOLE descriptive data are cataloged in a separate manuscript in this supplement.[19]

PROVISION OF A DETAILED MODEL OF PARADATA REPORTING

Paradata represent the process-oriented data associated with survey administration and are used to standardize communication, facilitate representativeness and comparability, navigate study management, and anticipate and control costs. Accelerometer paradata have been typically limited to the number of days and average wear time recorded, and even these have been inconsistently reported.[20] We have provided a detailed model for reporting accelerometer paradata that includes an administrative checklist, a detailed flow chart and an extensive variable listing (including definitions and benchmark values based on ISCOLE data).[21] The flow chart organizes the paradata into the distinct study stages of participant enrollment, data collection and data processing and also cross-tabulates these with additional paradata derived from accelerometers, participants/data files, and reasons for data loss at each stage.[21]

Using this model,[21] we reported that ISCOLE consented 7806 participants worldwide, 7372 were deemed eligible to participate,

Table 2. Accelerometer-determined sleep, physical activity and sedentary time-related variables and definitions in ISCOLE

Variable	*Definitions*
Sleep-related variables	
Sleep period time	Duration of time from nocturnal sleep onset to nocturnal sleep offset, including all minutes scored as sleep or wake[13]
Nocturnal sleep onset	The beginning of a sleep episode (nocturnal sleep onset) was identified as the first 5 consecutive minutes of sleep (1200–1159 hours)[25]
Nocturnal sleep offset	The end of a sleep episode (nocturnal sleep offset) was identified within a noon-to-noon day (1200–1159 hours) as the first 10 or 20 consecutive minutes of wake time, depending on the time of day (10 min: 0500–1158 hours; 20 min: 0700–0459 hours)[25]
Sleep episode	A sleep episode was only identified when at least 160 min had elapsed following nocturnal sleep onset and could contain an unlimited number of non-consecutive wake minutes. Multiple sleep episodes (⩾160 min) were allowed during each 24-h noon-to-noon day, but only sleep episodes that began between 0700 and 0559 hours were considered. If sleep episodes were separated by < 20 min, then they were combined so that the first minute of the first sleep episode through to the final minute of the last sleep episode constituted a single sleep episode. Sleep episodes that were separated by at least 20 min were not combined[25]
Total sleep episode time	Total minutes from all sleep episodes occurring during the sleep period time[25]
Activity count metrics	
Activity counts/day	Sum of daily activity counts[26]
Activity counts/min	Sum of daily activity counts/number of minutes to be worn[26]
Time (minutes per day) at different activity intensities—Treuth cut points[27]	
Sedentary	< 100 activity counts per minute
Light intensity	100–2999 activity counts per minute
Moderate intensity	3000–5200 activity counts per minute
Vigorous intensity	⩾5201 activity counts per minute
Moderate-to-vigorous intensity	⩾3000 activity counts per minute
Time (minutes per day) at different activity intensities—Evenson cut points[28]	
Sedentary	< 26 activity counts per 15 s
Light intensity	26–573 activity counts per 15 s
Moderate intensity	574–1002 activity counts per 15 s
Vigorous intensity	⩾1003 activity counts per 15 s
Moderate-to-vigorous intensity	⩾574 activity counts per 15 s
Step count metrics	
Steps per day	Sum of daily steps[26]
Steps per minute	Sum of daily steps/number of minutes to be worn[29]
Time (minutes per day) and steps accumulated in incremental cadence bands[30]	
Non-movement	0 steps per minute during valid wear time
Incidental movement	1–19 steps per minute
Sporadic movement	20-39 steps per minute
Purposeful steps	40-59 steps per minute
Slow walking	60-79 steps per minute
Medium walking	80-99 steps per minute
Brisk walking	100–119 steps per minute
Faster locomotion	120 steps per minute
Peak cadence indicators (steps per minute)	
Peak 1-min cadence	Steps per minute recorded for the single highest minute in a day[31]
Peak 30-min cadence	Average steps per minute recorded for the 30 highest, but not necessarily consecutive, minute in a day[31]
Peak 60-min cadence	Average steps per minute recorded for the 60 highest, but not necessarily consecutive, minute in a day[32]
Breaks in sedentary time (transitions per day)	
Transitions per day	Total occurrences of when activity counts rose from < 100 activity counts in 1 min to ⩾100 activity counts in the subsequent minute[33]

Adapted from the ISCOLE accelerometry Manual of Operations published online as an additional file to Tudor-Locke *et al.*[11] http://www.ijbnpa.org/content/12/1/11.

7420 accelerometers were distributed (including those distributed for repeated monitoring if initial data were deemed inadequate) and 7391 were retrieved. Reasons for data loss were tracked and 414 accelerometer data files were deemed inadequate (primarily due to insufficient wear time). Ultimately, the ISCOLE locked data set comprised 6553 participant files (90.0% relative to the number of participants completing monitoring) with valid waking wear time, averaging 6.5 valid days and 888.4 min per day (14.8 h).

CATALOGING THE MOST DETAILED AND DEFENSIBLE LIST OF ACCELEROMETRY-DERIVED VARIABLES TO DATE

Accelerometer-based studies of children's physical activity have typically focused on one or just a few specific variables, most commonly time in moderate-to-vigorous physical activity, steps per day or total activity counts per day, and/or sedentary time. The list is short and it does not take full advantage of the available robust accelerometer output. In the original MOP,[11] ISCOLE cataloged a much longer list of the various sleep-related variables, activity count metrics, time-based intensity (using two different preferred cut points) and sedentary time variables, step count metrics, time and steps accumulated in incremental cadence bands, peak cadence indicators and a count of transitions between sedentary and non-sedentary time. An adapted version is also presented here in Table 2, including source references for each defined variable. Researchers remain interested in using the raw accelerometry signal to study physical activity and sedentary time;[22] however, at this time, there is no infrastructure or guidance on how this is to be analyzed to interpret children's behavior. ISCOLE has archived all of the raw accelerometry signals collected worldwide in anticipation of a future resolution of this issue.

CONCLUSION

Data collection, management and treatment with accelerometry are a complex undertaking, and the effort is exponentially magnified in the administration of large epidemiological studies of children's physical activity and sedentary time. Methodological harmonization is supported by openly sharing tools and resources. As summarized herein, ISCOLE has made a number of unique and innovative contributions to accelerometry in large epidemiological studies. ISCOLE also serves as a model for sharing their tools and resources, including: (1) a detailed MOP (published as Supplementary Information[11]) that provides extensive details for the 24-h waist-worn accelerometry protocol, (2) open-access publication of checklist descriptions, flowcharts and benchmark values in support of collecting and reporting accelerometer paradata;[21] (3) publically available SAS syntax (indicated in related publications[13,14] and posted on a hosted website) to identify the nocturnal sleep period time and the TSET; and (4) catalogs (including ISCOLE-based benchmark values) of accelerometer-derived physical activity and sedentary time[11] and nocturnal sleep-related variables.[19] Researchers have the option of using these tools and resources to replicate ISCOLE protocols, interpret their own collected data and/or edit and build upon them further in a continual effort to advance and harmonize the field of accelerometry.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ACKNOWLEDGEMENTS

We thank the ISCOLE External Advisory Board and the ISCOLE participants and their families who made this study possible. A membership list of the ISCOLE Research Group and External Advisory Board is included in Katzmarzyk *et al*. (this issue). ISCOLE was funded by The Coca-Cola Company.

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