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Use of Global Positioning Systems to Study Physical Activity and the Environment:

A Systematic Review

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Abstract

Context—The Global Positioning System (GPS) represents an innovative way to objectively assess the spatial locations of physical activity behavior.

Purpose—The aim of this systematic review was to determine the capability of GPS to collect high quality data on the location of activities in research on the relationship between physical activity and the environment.

Evidence acquisition—Published and unpublished articles identified from seven electronic databases, reference lists, bibliographies and websites up to March 2010 were systematically searched for, appraised and analysed in summer 2010. Included studies used GPS to measure the spatial locations of physical activity and some form of environmental analysis related to the GPS data. The capability of GPS was expressed in terms of data quality which in turn was defined as the proportion of GPS data lost in each study.

Evidence synthesis—24 studies met the inclusion criteria. Data loss was positively correlated with the measurement period for which participants were asked to wear the GPS device ($r=0.81$, $p<0.001$). Major reasons for data loss included signal drop outs, loss of device battery power, and poor adherence of participants to measurement protocols. Data loss did not differ significantly between children and adults or by study sample size, year of publication or GPS device manufacturer.

Conclusions—GPS is a promising tool for improving our understanding of the spatial context of physical activity. Our findings suggest that the choice of an appropriate device and efforts to maximise participant adherence are key improving data quality, especially over longer study periods.

Context

Physical inactivity is associated with an increased risk of chronic diseases including cardiovascular disease and type 2 diabetes.[1] Various strategies have been proposed to encourage populations to become more physically active.[2,3] A multilevel approach is increasingly advocated[4-7] as social ecological models of health posit that policies and changes in the natural and built environment which encourage physically active lifestyles may be as important as interventions at the individual or social level.

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Recently, two principal approaches have been used to assess potentially relevant environmental characteristics related to physical activity (PA): the assessment of environmental perceptions using questionnaires such as the Neighbourhood Environment Walkability Scale (NEWS),[8] its short version NEWS-A[9] or the European Project ALPHA questionnaire;[10] and the objective assessment of the environment using either audit instruments or Geographic Information Systems (GIS). Whilst audits have a number of benefits, auditing is time-consuming and expensive for larger areas. In contrast, GIS provide an efficient tool for collating and synthesizing routinely available environmental data for large areas.[11,12]

The Global Positioning System (GPS) is a satellite based global navigation system that provides a precise location at any point on the Earth's surface. GPS was initially developed for the US military, but is now ubiquitous in civilian navigation products and used in many leisure and research applications. As GPS can be used to identify individuals' locations at any point in time, and GIS can be used to describe the characteristics of the surroundings, the combination of GIS and GPS provides an objective means of examining the relationship between the natural and built environment and location-based PA.

Two recent reviews have examined GPS in the context of PA measurement. Maddison and Ni Mhurchu[13] reviewed applications of GPS for monitoring human movement in sports, while walking or running and in free-living PA. In the sports applications, GPS was used to track players' movement, distance and speed. The free-living applications focused on active travel in urban areas and on the value of combining GPS with accelerometry. The second review by Duncan et al.[14] focused on transport-related physical activity (TPA) using GPS in combination with accelerometers and/or GIS to identify activity patterns and to provide information on the spatial context of activity. It included studies of the quantity of active travel in terms of distance, time and speed as well as papers about attributes of the built environment related to TPA.

Better quantification of the environmental determinants of PA depends on accurate assessment of the locations where PA takes place combined with appropriate assessment of the environmental characteristics of those locations. The aim of this review was to identify factors that influence the capability of GPS to support these research objectives by systematically searching for, appraising and synthesising evidence from studies in which GPS was used to examine the relationship between environmental characteristics and PA behaviour.

Evidence Acquisition

Search Strategy

Studies were identified by searching electronic databases, bibliographies, reference lists and websites for published and unpublished articles until March 2010. Search terms for 'GPS', 'physical activity' and 'environment', written in both English and German, were combined and applied in seven electronic databases: BioMed Central, Google Scholar, PubMed, Scopus, SportDiscus, TRIS Online and Web of Science (see online supplementary material).

Inclusion Criteria and Selection Process

Studies were eligible for inclusion if they were undertaken in humans, used GPS to measure the locations where PA occurred, and included analysis of the relationship between the characteristics of the environment and any form of PA behaviour including leisure-time PA, sport or active travel. Characteristics of the environment were derived from a variety of sources including GIS databases, orthorectified aerial photographs and descriptions of destinations in activity diaries. Both observational and intervention studies were included,

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and no restrictions were applied regarding age or gender of participants or language of publication. Studies were excluded if the GPS was only used to map the location of particular features of the environment instead of recording the locations of PA. Titles and abstracts of references were initially assessed against the inclusion criteria by the first author. Ten percent of the excluded articles were crosschecked by another author. Two authors then independently checked the full text of all remaining articles for inclusion. Any discrepancies were resolved by group discussion. Authors of the included studies were invited to contribute additional references, and these were subjected to the same assessment process.

Data Extraction and Study Quality

Data on the study population, PA measurements, GPS devices, measurement periods, environmental analyses, and findings were extracted for each paper, tabulated by the first author, and checked by another author. Two authors then independently appraised each of the included studies against eight quality criteria: representativeness of the sample population; sample size; length of GPS recording period; objectiveness of environmental analysis; reporting of intensity of PA; GPS data quality and positional accuracy; and peer review. Five categories were scored by applying binary (0/1) and three by applying tertiary (0/1/2) metrics, with any between-rater discrepancies being resolved by discussion. The quality of each paper was described by a score summarizing the metrics to provide an overall impression of the quality of the available evidence.

Measures

For this review, the capability of GPS was expressed in terms of data quality which in turn was defined numerically as the proportion of data lost. Data loss may be attributable to problems with the GPS device (e.g. lack of signal, inaccurate positioning or loss of battery power) and/or participants' handling (e.g. forgetting to wear or switch on the device). Some causes are difficult to identify, and from the published studies the following factors potentially influencing data loss were identified: year of the study, sample size (small ≤50, medium: 51-100, large >100), age group (children vs. adults), type of GPS device (data logger, watch etc.), recording period (short ≤2 days, medium 3-4 days, long >4 days), provision of instructions to participants (provided versus not) and use of incentives (provided versus not).

Analytical Methods

Data loss was treated as the dependent variable in analysis. Pearson correlation coefficients were calculated between the continuous independent variables (year of publication, sample size and recording period) and the dependent variable. Mann-Whitney U tests were applied to assess the association between the nominal independent variables (age group, receiver type, provision of information, use of incentive) and data loss. The method of the spatial analysis and the major environmental characteristics were categorized for each study. All analyses were undertaken in summer 2010.

Evidence Synthesis

Study Selection

926 potentially relevant publications were identified from electronic databases and an additional six articles were found by checking the reference lists of included papers (Figure 1). Examination of titles and abstracts resulted in the exclusion of 893 articles. The full text of 39 documents was assessed. 19 were found not to meet the inclusion criteria. The most frequent reason for exclusion was that there was no recording of PA with GPS (26%), i.e. the instruments were tested but not for the purpose of assessing the locations of the PA

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behaviour of the participants. Four additional references were contributed by authors of included studies, bringing the total number of studies finally included in the review to 24.

Quality of the Studies

The total quality score for each study, which could range between zero and eleven, varied from three to ten (Table 1). Seven studies had a total score within the upper third of the scale, 16 studies within the middle third, and only one within the lower third of the scale. Overall, the included studies can therefore be regarded as being of moderate to high quality from the perspective of this review.

General Description of the Studies

Almost two thirds of the studies were published in 2009 or 2010 (Table 2). Studies originated from North America (50%), Europe (29%) and Australasia (21%), with sample sizes ranging from one to 1200 (median 44). Ten studies (42%) were focused on children, ten (42%) on adults and one (4%) on older adults, whilst three (13%) did not provide details about their subjects. Most child studies recruited their participants in schools (80%) whereas others used phone and mail recruitment, fliers, newspapers and websites. Nine studies reported participation rates ranging from 7 to 92 percent. No study reported whether the final sample included in analysis after accounting for data loss differed significantly from that originally recruited.

The ten studies on adults were performed under free-living (daily life) conditions and their objectives included understanding associations between PA and the built environment around home or work[17,25,30], assessing the feasibility of different combinations of GPS, accelerometer and GIS[20,23,28], undertaking trip purpose for transportation research[18], analyses of locations where transport related physical activity took place[20,22,31], and validation of travel diaries using GPS.[18,38]

Eight of the ten studies of children also examined PA behaviour under free-living conditions. Parents were asked to equip their child with the GPS device before leaving home. In two of these studies[38] parents were requested to complete an activity diary to enable GPS and PA measurements to be later linked. Two studies[24,36] took place at school during break times; for these, the researchers were present during the whole measurement period. GPS devices were placed by the research staff and children's movements were recorded for 40 and 50 minutes respectively.

Data Loss

The proportion of data loss varied from 2.5 to 92 percent for the 17 studies (71%) that reported such information. In some studies, data loss included a certain amount of GPS data that were recorded but unusable because of specific analytical requirements, such as a minimum continuous period of recording or a need to match GPS and accelerometer data. Information allowing differentiation between missing and unusable data was rarely given and therefore could not be used in this review.

The major problems that led to loss of data were signal drop outs (10 studies), dead batteries (9), participants not wearing the device (6), loss during the initialisation period (4), and misuse of the device (2). Authors of the included studies identified a variety of responses to the problem of data loss. In Bohte and Dill[18,22] missing trips were completed by participants using the internet. Jones et al.[16] consulted participants' activity diaries for missing trips. Troped et al.[17] assumed that points within a 50 metre buffer around home were indoors, and missing coordinates were imputed by carrying forward the last known coordinate until a new point was obtained. If the drop out of GPS data was outside and lasted for more than 30 seconds, Cooper et al.[19] coded the relevant time points as “outside with GPS dropout” for further analysis.

Factors Influencing Data Loss

Data loss was not related to the year of publication (r=0.28, p=0.29) or sample size (r=0.05, p=0.85). There was no difference in data loss between children or adult samples, regardless of whether or not the two studies with children under controlled school playground conditions[24,36] were included.

Various types of GPS device were used for recording position: data loggers without display (7 studies), handheld GPS (7), GPS watches (3), personal digital assistants (PDA) (1), cell phones (2) and self-manufactured GPS devices with external antennae (4). Nine studies used a handheld device or GPS watch from the manufacturer Garmin. The data loggers used were from 4 different manufacturers. Where external antennae were used, these were fixed onto a special rucksack or vest and connected to the receiver device by cables. The GPS devices were predominantly placed on the wrist (29%) or in a pocket or bag (21%), clipped onto a belt (17%), integrated in a vest (8%) or carried on a lanyard or harness (8%). Four studies did not report device positioning. Authors often mentioned factors considered important in selecting the device to be used. The most important were that the device should be small, portable, lightweight and precise, with a battery life of at least one day and sufficient memory for recording. Data loss was not related to the type of device (manufacturer Garmin vs. others).

The GPS recording period varied from 40 minutes to 12 days, with a mean of four days. In thirteen studies (54%) GPS measurement was recorded on both weekdays and weekend days, while four studies (17%) recorded only on weekdays and one study (4%) recorded only at the weekend. Four studies (17%) did not mention if the measurement was made during the week or at the weekend and a further two studies (8%) did not report any information about recording time. In many studies there were differences between the length of recording time participants were asked to undertake, the length they typically completed, and the length required for inclusion in analysis. Where the intended measurement period was greater than one day, this was never achieved by all participants.

There was a clear relationship between data loss and the intended GPS measurement period (r=0.80, p<0.001); the longer the measurement period, the greater the proportion of data lost (Figure 2). The association was changed little by excluding the two child studies under controlled playground conditions[24,36] (r=0.75, p=0.002). A similar pattern was found within the study by Quigg et al.,[15] in which data loss increased with the length of recording. Data loss was calculated on a daily basis: final data loss after six consecutive days was 52%.

Only six studies (26%) explicitly reported that participants were informed about important aspects of the GPS measurement protocol and the importance of standing still until the first position was fixed. We assumed that some information may have been given to participants in all studies and therefore did not examine associations with data loss. Five studies mentioned an incentive for participants. In Quigg et al.[15] the researchers provided a family pass for a swimming facility, Dill and Ong[22,31] provided gift cards and Moudon and Rodríguez[23,30] provided cash incentives. Studies that used an incentive lasted significantly longer (p<0.05), most likely reflecting the greater participant burden entailed. Nevertheless, there was no relationship between data loss and the use of an incentive.

Environmental Analyses

Most studies (75%) involved objective analysis using GIS software which enabled automated spatial analysis with thematic maps. Visual analysis was undertaken using

Google Earth[20,31,34] or by high resolution orthophotos.[31,32,38] Spatial analysis of the recorded GPS data generally focussed on the immediate neighbourhood of the site under study (e.g. home, work or school) or on a route (e.g. between home and work) in about half of the studies. Environmental attributes examined ranged from the presence of parks or green space[15-17,21,23-26,34] or infrastructure for cycling[22] to street connectivity,[23,26,28] intersection density[17,28] and land use mix[16,17,23,28].

DISCUSSION

Main Findings

There was a strong positive relationship between the number of days for which participants were asked to wear a GPS device and the likelihood of data loss. In contrast, the year of publication, sample size, age group, device manufacturer and the use of incentives for participants did not appear to be related to data quality.

Data Quality

The main limitation for studies using GPS for public health research is the fact that data quality is influenced by the amount of GPS data lost. Signal dropout was the major reported reason for bad data quality. GPS signal acquisition is limited in urban canyons, close to tall buildings and under dense vegetation and older GPS devices often fail to record position under these conditions. Newer devices include high sensitivity receivers that also interpret weak signals for continuous recording. Eight studies reported that dead batteries led to missing data. If participants were asked to wear the device for more than one day, devices often ran out of battery power, either because participants forgot to recharge the battery or because the device consumed more power than expected. These problems can be overcome by selecting a GPS device with an appropriate power supply for the planned measurement period and by shutting down the device while indoors if required. Missing data also occurred during the initialization period, which is the time the GPS device takes to establish the first position from the time it is turned on. This is most rapidly achieved if the user stands still, but only six studies (26%) reported that participants were asked to do this. We note that these limitations are not restricted to research with human participants; studies involving the use of GPS to track the behaviour of animals, for example, report similar issues.[40]

Due to the limitations in reporting, it was impossible to distinguish data loss attributable to device errors, participant non-adherence or other study characteristics. Much of the observed data loss is due to device failure and may therefore be regarded as missing at random. However, data loss attributable to failure to remember to recharge batteries, or to signal dropout in certain environmental conditions, may be associated with particular participant characteristics. In that case, the non-random nature of the missing data may lead to a systematic bias in study results. A further potential bias is nonresponse bias due to high nonresponse rates,[39] but it was not possible to determine the significance of nonresponse bias in the studies included in this review.

Factors Influencing Data Loss

Whilst longer periods of study provide better information on habitual PA behaviour, based on the results in Table 1 it appears that data loss increases substantially after four days. This may partly be because in longer studies participants are more likely to move in different environments where GPS does not work well. Secondly, we believe study length will be associated with participant adherence which may mediate the relationship between length of recording and data loss. The total burden for study participants in free-living studies should not be underestimated, and it is unsurprising that some participants may lose motivation after a few days.

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There was no relationship between the number of study participants and data quality, despite the fact that larger studies might be expected to involve a greater administrative burden. Having said that, most studies in this review involved no more than 40 participants and most study samples (54%) appeared unlikely to have been representative of their target populations (Table 1).

Whilst it would have been useful to know whether instruction given to participants was associated with data loss, studies reported little information on the nature of any training given. In the two studies under controlled conditions[24,36] researchers oversaw the fitting of working devices; these studies reported the least data loss. Cooper and Webber[19,34] mentioned that failure to provide instructions to participants resulted in considerable data loss in their studies. More research is needed to determine which aspects of information provision (e.g. training to use the device, or reminders to recharge batteries) are most important for maximizing data quality. The use of incentives was not correlated with data loss in this review, but that finding may reflect the small number of studies in which incentives were used. It remains possible that incentives may help support participant adherence, especially in longer studies.

The increasing acceptance of GPS usage in applications is in part due to smaller, lighter and more accurate receiver units. 29% of the studies used data loggers as their GPS receiver. The advantage of these devices is the small size and low weight that minimizes participant burden. Moreover, data loggers do not have displays, data can only be downloaded by research staff and the devices have settings which are difficult for participants to adjust either accidentally or intentionally. 17% of the studies used devices with external antennae. These impose a greater burden on participants and may considerably restrict free-living PA. However, external antennae are unlikely to be required in future studies due to the improved sensitivity of modern GPS receivers. Cell phones with integrated GPS are becoming more widespread, and may also offer future potential for collecting positional data.

Recommendations

To better identify and manage factors associated with GPS data quality that may influence the results of physical activity and public health research, we recommend that future studies consider, report, and if possible address the following issues: (1) Sample representativeness, none-response rates and potential participant selection bias, (2) the nature of missing or unusable data and the potential influence of this on results (3) the effect of the manner by which participants are instructed to use the GPS devices and (4) the likely influence of the use of incentives. We also recommend careful selection of the GPS device with respect to size and handling, initialization time, battery life, storage capacity, and receiver sensitivity.

Strengths and Limitations

To our knowledge this is the first systematic review to identify factors that influence the capability of GPS to collect data on the location of PA in connection with research about the relationship between PA and the environment. The strengths of this review include the extensive search methods and the fact that each potentially relevant paper was examined by more than one reviewer. A bespoke systematic method for quality assessment was used which provided an overall summary of the quality of the available evidence and reported important technical aspects of the GPS assessment in detail. One potential limitation is that relevant papers in foreign languages may be missing; although no language restriction was applied in searching, all the studies finally included were in English.

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Conclusions

Based on our findings from 24 published studies, sample size is not associated with data loss, but longer measurement periods are associated with greater data loss and it seems that participant adherence decreases with time. The ideal GPS receiver for physical activity studies should have a long battery life and should be small, portable and lightweight. Although there are still relatively few published studies using GPS in the field of physical activity and public health, the system shows promise as a way of improving our understanding of the relationship between environmental attributes and PA behaviour at the population level.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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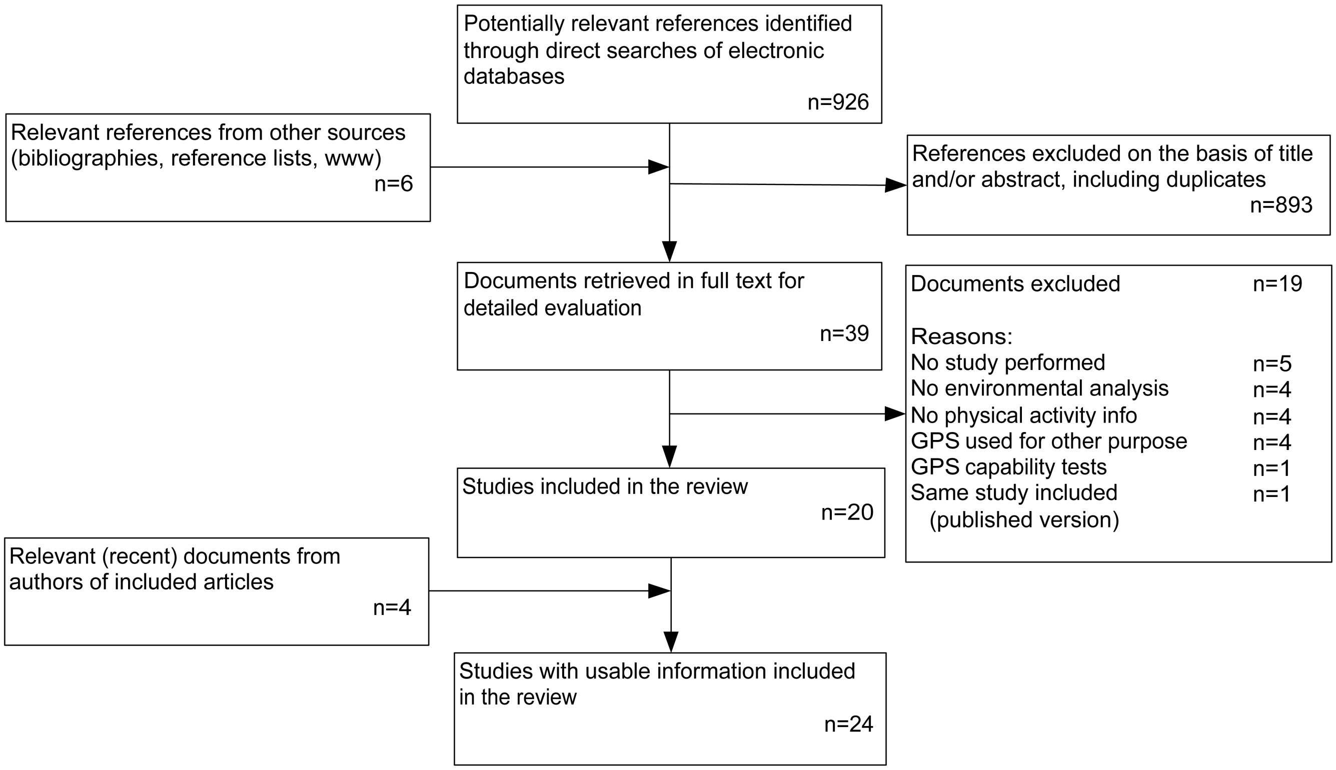

Figure 1.
Study flowchart

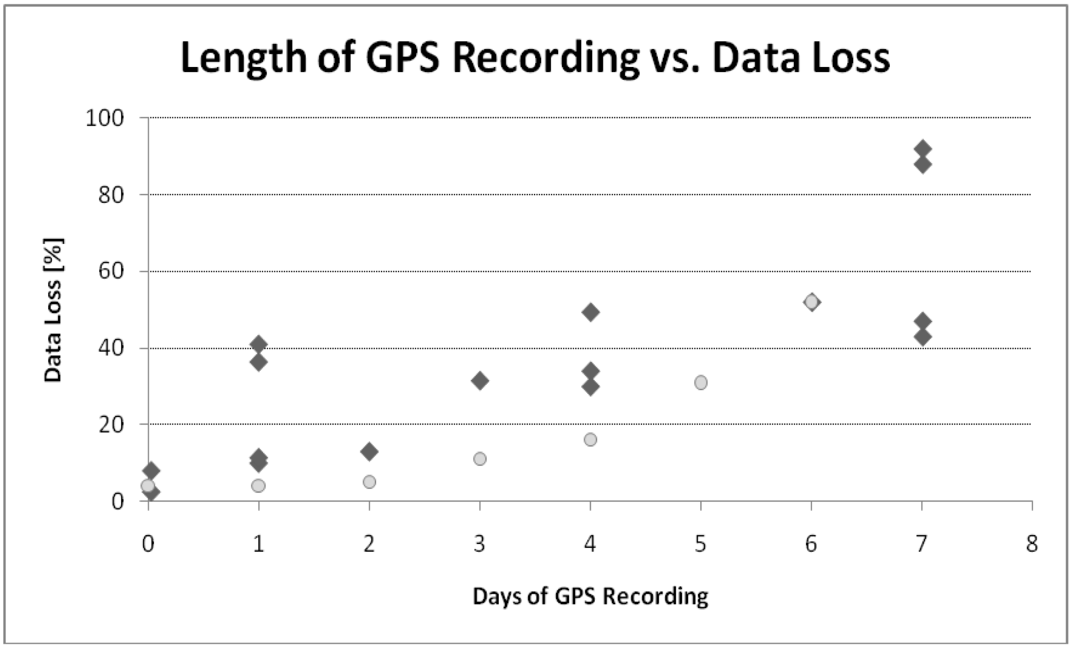

Figure 2.

Relationship between intended GPS measurement time and data loss.

Footnote: Points close to the origin of the scatterplot represent very short studies.

◆Data loss reported after the measurement period of the study[15-17,19-24,26-29,33,34,36]

◍Data loss reported after consecutive days in Quigg et al.[15]

Study	Representativeness[a]	Sample size[b]	Length of recording[c]	Objective environmental Analysis[d]	Intensity of PA[e]	Data quality[f]	Peer reviewed[g]	Positional accuracy reported[h]	Total SCORE
Quigg[15] 2010 New Zealand	1	2	2	1	1	2	1	0	**10**
Jones[16] 2009 UK	1	1	1	1	1	2	1	1	**9**
Troped[17] 2010 USA	1	2	1	1	1	2	1	0	**9**
Bohte[18] 2009 Netherlands	0	2	2	1	0	2	1	0	**8**
Cooper[19] 2010 UK	1	2	0	1	1	2	1	0	**8**
Oliver[20] 2010 New Zealand	0	0	2	1	1	2	1	1	**8**
Mackett[21] 2007 UK	1	2	1	1	1	1	1	0	**8**
Dill[22] 2009 USA	0	2	2	1	0	1	1	0	**7**
Rodríguez[23] 2005 USA	0	0	1	1	1	2	1	1	**7**
Fjortoft[24] 2009 Norway	1	1	0	1	1	1	1	1	**7**
Seeger[25] 2010 USA	0	0	2	1	1	1	1	1	**7**
Duncan[26] 2007 Australia	0	1	1	1	0	1	1	1	**6**
Elgethun[27] 2003 USA	1	0	0	1	0	2	1	1	**6**
Badland[28] 2010 New Zealand	0	0	2	1	0	1	1	0	**5**
MacLellan[29] 2009 UK	0	0	2	0	1	1	1	0	**5**
Moudon[30] 2009 USA	1	-	2	1	1	0	0	0	**5**

Study	Representativeness[a]	Sample size[b]	Length of recording[c]	Objective environmental Analysis[d]	Intensity of PA[e]	Data quality[f]	Peer reviewed[g]	Positional accuracy reported[h]	Total SCORE
Ong[31] 2009 USA	1	1	2	1	0	0	0	0	**5**
Rainham[32] 2008 Canada	-	-	-	0	-	2	1	1	**4**
Michael[33] 2008 USA	-	-	0	0	0	2	1	1	**4**
Webber[34] 2009 Canada	0	0	0	0	1	1	1	1	**4**
Mikkelsen[35] 2009 Denmark	0	0	2	1	0	0	1	0	**4**
Duncan[36] 2009 New Zealand	1	0	0	0	1	1	1	0	**4**
Phillips[37] 2001 USA	1	0	0	0	0	1	1	1	**4**
Elgethun[38] 2007 USA	0	0	0	1	0	1	1	0	**3**

[a]The sample was representative of the selected target group: 0=no, 1=yes

[b]Sample size for the GPS study: 0= ≤50, 1= 51-100, 2= >100

[c]Recording period: 0= ≤2 days, 1= 3-4 days, 2= >4days

[d]Environmental analyisis was done objectively: 0=no, 1=yes

[e]The intensity of physical activity was measured in the study: 0=no, 1=yes

[f]Data quality: 0=not discussed, 1=data quality mentioned, 2=data quality discussed in detail

[g]The study was published in a peer reviewed journal/book: 0=no, 1=yes

[h]Positional accuracy of the device used was reported: 0=no, 1=yes

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Table 2

Description of included studies

Study (Year)	Subjects	Objectives	PA: Domain/ Mode	PA: measure	GPS Device	Time period	Data lost (DL) + problems (P) + solution (S)	Environmental analysis/ attributes
Badland et al. (2010)[28] New Zealand	N=37 Age: n.r. Gender: n.r.	GIS-estimated shortest commute route to estimate the type of environment people travel through	Transport/ all used to and from work	Travel log	Trackstick II Data Logger	7 days	DL: 92% (29/370 usable GPS tracks) P: DL while initialization period S:--	ArcGIS 9.2: buffer (25m, 100m, 250m): residential density, land use mix ,street connectivity, intersection density
Bohte et al. (2009)[18] The Netherlands	N= 1200 Age: 50-65 (35%) Gender: 43% female	Deriving and validating trip purpose and travel mode automatically from GPS and GIS data	Transport/ car, train, bicycle, foot	Only with GPS	Amaryllo Trip Tracker (SirFII chipset)	7 days	DL: n.r. P: misinterpretations of travel mode because of speed (e.g. urban queue), signal problems in train, battery life, trips incorrectly split up, initialization period S: missed trips completed by respondents (user interface)	Work, shop, study, social visit, home, recreation
Cooper et al. (2010)[19] UK	N= 137 Age: 11.3 (±0.3) Gender: 56% female	Level and location of PA in children walking to school	Transport/ walking to school	Report travel mode & ActiGraph LLC acc.	Garmin Foretrex 201	2 days	DL: 13% (61/70 children have data ≥1day) P: signal drop outs (e.g. tall buildings), battery life, user compliance with wearing GPS, estimation of journey time by GPS is influenced by initialization period S: if dropout up to 30sec → recorded as “outside with GPS dropout” (=3,6%)	Polygons: Playground of school and journey to school; Linear distances home-school calculated in ArcGIS
Dill et al. (2009)[22] USA	N= 166 Age:18-80 (Ø=41) Gender: 45% female	Everyday bicycling of adults to meet the recommend-dations of PA and the role of public infrastructure	Transport/ cycling	Self report on PDA	Personal Digital Assistant (PDA)	7 days	DL: 39% not fully recorded and 8% not recorded at all P: dead batteries S: people could correct their data on a secure website	Bike lanes, -pathes & -boulevards
Duncan et al. (2007)[26] Australia	N= 59 (71) Age: 11.09 (±0.79) Gender: n.r.	Travel route to/ from school: shortest route (route planner) vs. actual route (GPS)	Transport/ n.r. (bike or walking)	No	Garmin Etrex (model n.r.)	1 day	DL: 41% not fully recorded (data lost TO school: 17%, FROM school: 24% P: --	(Busy) streets, parks

Study (Year)	Subjects	Objectives	PA: Domain/ Mode	PA: measure	GPS Device	Time period	Data lost (DL) + problems (P) + solution (S)	Environmental analysis/ attributes
							S: trips TO school used for analysis	
Duncan et al. (2009)[36] New Zealand	N= 40 Age: 5-10 Gender: 50% female	Trial combination of GPS and HR monitoring in children	LTPA/, school break activities	HR monitor belt (Polar)	FRWD F500	50min	DL: 2,5% P: indoor no data S: --	Reported differences in the E- W variation
Elgethun et al. (2003)[27] USA	N= 11 Age: 2-8 (Ø=5.5) Gender: 55% female	Suitability of a novel GPS instrument for tracking movement of young children	All/ activity of children	No	Self developed dGPS device	1 day	DL: 3/11 not fully recorded (=27,3%), accidental receiver shut off/ on → 36.4% lost P: no reception if <20m from transformer power substation S: --	5 categories: vehicle, inside house, inside school, inside business, outside
Elgethun et al. (2007)[38] USA	N= 31 Age: 3-5 Gender: 48% female	GPS tracking vs. parent-report diaries	LTPA/ walking	Activity diary (parents)	Self developed dGPS device	1 day	DL: n.r. (11.4% excluded in analysis: 1st logged point <1km from home, more than 6h during 12h period) P: limited remembering of parents to turn unit on, no continuous wearing; mostly inside limitation for GPS device because signal blocked S: --	5 categories: inside home, inside at other, outside in home, outside in other, in transit; Draw polygon around categories using Orthofoto (1m resolution)
Fjortoft et al. (2009)[24] Norway	N= 70 Age: 6 Gender: 56% female	Study of the affordances of PA in two different schoolyards (city vs. rural)	LTPA/ playing, running	Polar HR monitor	Garmin Forerunner 201	40-min	DL: Incorrect data if outside school (10% observations in school A, 6.1% in school B) P: DL near tall buildings especially north position & at dense vegetation; detailed observation on activity at small spots (GPS too inaccurate) S: Incorrect GPS data removed	Asphalt area, forest, swing, hopscotch, sandpit, basketball goal, soccer kicking area
Jones et al. (2009)[16] UK	N= 100 Age: 9-10 Gender: 53% female	Detection of key environments which were supportive of PA in children	All/ MVPA	Activity diary & ActiGraph GTIM acc.	Garmin Forerunner 205	4 days	DL: Missing location data for 34% of activity bouts P: Children did not wear the device all time	Garden, farmland, grassland, woodland, beaches, buildings, other built land use, roads & pavements, parks

Study (Year)	Subjects	Objectives	PA: Domain/ Mode	PA: measure	GPS Device	Time period	Data lost (DL) + problems (P) + solution (S)	Environmental analysis/ attributes
							S: For missing data consult activity diary for reason	
Mackett et al. (2007)[21] UK	N= 162 Age: 8-11 Gender: n.r.	How children behave differently in different local environments (with or without adults)	LTPA/ walking, playing, clubs	Activity diary & RT3 acc.	Garmin Foretrex 201	4 days	DL: 49.4% not usable P: Participants forgot to charge battery, complete diary, wear monitors; too short periods of GPS data (<5min) → eliminate S: --	Building, natural environment, general surface, path, road, track, local park etc.; Analysis of walking pattern: Road vs. open space
MacLellan et al. (2009)[29] UK	N= 1 Age: n.r. Gender: n.r.	Amount of walking and motorized transport and where walking takes place	Transport, LTPA/ walking	Diary & ActivPAL thighworn acc.	Amod AGL 3080	7 days	DL: 43% excluded (GPS gaps when person is inside is normal - not excluded in study) P: -- S: --	Home, work, travel or other destination
Michael et al. (2008)[33] USA	N= 1 Age: n.r. Gender: n.r.	Reliability and validity of GPS enabled cell phones to track outdoor activity.	All/ on foot, by car	No	6 cell phones: Motorola i760 & AGPS	n.r.	DL: 37.2% no position data (acquisition highest in open areas (83,8%) and lowest under cover (37.5%) P: One phone of 6 failed to record data during test; battery life test: 18h 42min S: --	3 standardized loops in scenarios: Urban, Suburban, Hill/ Forest Environment: open area, low-rise, highrise/ sunken
Mikkelsen (2009)[35] Denmark	N= 32 Age: 10-13 Gender: 50% female	Children's (independent) mobility in suburban and rural areas (boys vs. girls)	All activity	Via mobile phone: sms	n.r. (small and portable device)	1 week	DL: -- P: -- (did not always wear device) S: --	Aerial photo: visualize track and duration of stay in 100×100m grid
Moudon (2009)[30] USA	N = 1000 Age: ≥18 46%: 46-65 Gender: n.r.	Total PA of people living near light rail transit (LRT)	All activity	Activity diary & Actigraph GT1M acc.	GlobalSat DG-100	7 days	No analysis yet : 5% recruitment rate in this study So far only describing methods & collection of baseline data	< 1mile from LRT, > 1mile of station (within urban boundary); Perceived environment through abbreviated NEWS scale
Oliver et al. (2010)[20] New Zealand	N=37 Age: >20 Gender: 65% female	Feasibility of combining GPS, GIS, and accelerometers to understand TPA in adults	Transport/ all used to and from work	Travel log sheet & IPAQ long & Actial acc.	Trackstick II Data Logger	7 days	DL regarding participants: 65% DL in terms of total tracks recorded: 88%: signal loss: 10%; battery: 48%; users error: 5%; other: 20%	Visual check (Google Earth), Route analysis in ArcGIS 9.2

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Study (Year)	Subjects	Objectives	PA: Domain/ Mode	PA: measure	GPS Device	Time period	Data lost (DL) + problems (P) + solution (S)	Environmental analysis/ attributes
							P: Battery life, signal drop out, participant noncompliance; Assistant had to replace battery every day; after change: cold start time: 15min S: Exclude non valid GPS tracks → lost of data loss	
Ong et al. (2009)[31] USA	N= 51 Age: 21-65 Gender: n.r.	Measure of travel behavior in lowincome households	Transport/ walking, biking, invehicle	Activity diary	GlobSat DG-100	10-14 days	DL: No info on DL (47/51 adequately recording)	Visual with Orthofoto & Google maps; Major locations: home, public building, service or retail locations, workplace, restaurant, outdoors, traveling, waiting
Phillips et al. (2001)[37] USA	N= 25 (?) Age: 21-55 Gender: n.r.	Diary validation via GPS	All daily activities	Activity diary	March II-E GPS+ external battery+ external antenna	1 day (?)	DL: 70% P: Instrument problems: reduced battery life → operated only 30% of total monitoring time S: Diary validation	Visual analysis with diary data (restaurant, stores) and GPS data by time
Quigg et al. (2010)[15] New Zealand	N = 184 Age: 5-10 (Ø=7.6) Gender: 54% female	Identify the proportion of children's physical activity occurring in public parks with playgrounds	All PA	Actigraph GT1M & monitoring sheet	Globalsat DG-100	6 days	DL: After 6 days: 52% At least five hours with non-zero counts are required for a daily count; 84% matched GPS and acc. data P: If child was not wearing GPS for 2 days → research assistant contacted parent to confirm lost or damage S: A visual scan of mapped data, altitude and speed records identified obvious errors.	Parks and playgrounds; Spatial join procedure(ArcGIS 9.2): match points with exact park cadastral boundaries
Rainham et al. (2008)[32] Canada	n.r. - no info on persons - focus on device	Develope and test GPS devices for health and place research (static and dynamic test)	Transport/ walking, cycling, automobile, transit bus	No	Self developed GPS Logger	n.r.	DL: -- P: In transit bus no recording possible; Positional accuracy under open sky for walking and cycling: 72-99.1% within 5m,	Digitalize true paths in Orthofoto, 3 types of built environment: mixed density, open sky, urban canyon; line buffer around path (2m,3.5m,5m)

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Study (Year)	Subjects	Objectives	PA: Domain/ Mode	PA: measure	GPS Device	Time period	Data lost (DL) + problems (P) + solution (S)	Environmental analysis/ attributes
							mixed density: cycling: 81% within 5m, walking: 74.5% within 5m, urban canyon (walking: 57%, cycling: 53.7%); buildings constructed of impermeable materials limit GPS tracking S: -- **TIPP**: using DOP (dilution of precision) for analysis. Positional accuracy better if distance from potential interference (building) increase	
Rodríguez et al. (2005)[23] USA	N= 35 Age: f:Ø=32.1 m:Ø=31.5 Gender: 60% female	Combination of GPS and accelerometers to determine where PA takes place	All/ MVPA	ActiGraph 7164	Gramin Foretrex 201	3 days	DL: 3 persons no data (unit malfunctioned) → excluded (8.6%) 8 persons: 1 day without data (22.9%) P: No differentiation if device turned off or just inside; Misclassification of location due to GPS errors S: --	Indoor, outdoor within/outside neighborhood; Characteristics: population density, housing density, street density & connectivity, accessibility to commercial or office land uses and parks
Seeger et al. (2008)[25] USA	N=48 Age: > 18 Gender: n.r.	Visualize and identify relationships between landscape characteristics of the built environment and individual's PA levels	All/walking, running	Acc. & paper logbook	Garmin Foretrex 101	4 × 1 week	DL: -- P: Battery life was poor; incorrect points logged; participants error S: Observational and mathematical techniques to identify incorrect points	Which trail used & characteristics of trails, weather conditions; GIS data & self collected data used in ArcGIS
Troped et al. (2010)[17] USA	N=148 Age: 19-78 (Ø=44) Gender: 52% female	Examine associations between built environment variables within home and work buffers and MVPA within the buffers	All/ MVPA	Log sheet & Actigraph 7164 acc.	GeoStats GeoLogger	4 days	DL: 30% Criteria for a valid GPS day: >40min (=mean - 1SD) P: Missed data: no info if device not worn or inside building and no signal S: Points within 50m buffer around home assumed to be indoor. If GPS input	5 parameters within 1km and 50m network buffer around home & work: intersection density, land use mix, population density, housing unit density and vegetation index

Study (Year)	Subjects	Objectives	PA: Domain/ Mode	PA: measure	GPS Device	Time period	Data lost (DL) + problems (P) + solution (S)	Environmental analysis/ attributes
							missing: coordinated by carrying forward last known coordinate	
Webber et al. (2009)[34] Canada	N= 20 Age: 68-88 (Ø=74.4) Gender: n.r.	Explore the feasibility of GPS and accelerometer to monitor walking and other aspects of community mobility in older adults	LTPA, transport/ walking and community mobility	Question-naire & ActiGraph acc.	Garmin Forerunner 205	1 day	DL: 10% P: Indoor no signal; significant delays in satellite lock-in; premature battery failure; misuse of device S: -- **TIPP**: more detailed info to participants (e.g. initializations period: 2-3 min, inside: turn device off)	Google Earth analysis: manual analysis of each track: e.g. golf course (home - away from home)

acc., accelerometer; LTPA, leisure time physical activity; MVPA, moderate to vigorous physical intensity; n.r.: not reported; PA, physical activity; TPA, Transport related physical activity