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Review

# Applying GPS to enhance understanding of transport-related physical activity☆

Mitch J. Duncan[a,*], Hannah M. Badland[b], W. Kerry Mummery[a]

[a] *Centre for Social Science Research, CQUniversity, Australia*

[b] *Centre for Physical Activity and Nutrition, Auckland University of Technology, New Zealand*

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**Abstract**

The purpose of the paper is to review the utility of the global positioning system (GPS) in the study of health-related physical activity. The paper draws from existing literature to outline the current work performed using GPS to examine transport-related physical activity, with a focus on the relative utility of the approach when combined with geographic information system (GIS) and other data sources including accelerometers. The paper argues that GPS, especially when used in combination with GIS and accelerometery, offers great promise in objectively measuring and studying the relationship of numerous environmental attributes to human behaviour in terms of physical activity and transport-related activity. Limitations to the use of GPS for the purpose of monitoring health-related physical activity are presented, and recommendations for future avenues of research are discussed.



*Keywords:* Active transport; Measurement; Physical activity; Geographic information systems; Health

## Contents



☆ The products listed by brand name are done so for identification purposes only and do not constitute endorsement of any product by the authors.

* Corresponding author.

*E-mail address:* m.duncan@cqu.edu.au (M.J. Duncan).

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## 1. Introduction

There has been an increasing focus on examining the relationship between the built environment and health behaviours, with the intent that it can facilitate change across entire population groups. This has led to suggestions that research in this field should focus on how particular environmental characteristics are related to specific health behaviours,[1] such as differentiating between characteristics associated with overall physical activity and specific activities such as transport-related physical activity (TPA) and recreational walking.[2] These considerations are based on evidence that different associations are observed between specific behaviours and particular characteristics of the environment.[3,4]

Studies examining the role of the built environment as an influence of TPA engagement in adults and children have observed associations between TPA and characteristics of the journey origin; where greater diversity of land uses, street network connectivity, pedestrian infrastructure, and reduced traffic volumes have been positively associated with TPA engagement.[5,6] Although less frequently examined, destination characteristics associated with TPA engagement include the presence of pedestrian infrastructure, street connectivity, and land use mixture.[5,7] Whilst origin and destination characteristics appear to be important correlates for travel mode selection, the commute route is increasingly being prescribed a role in influencing travel mode decisions.[7,8] Traffic volumes, street connectivity and presence of pedestrian infrastructure have been associated with TPA using Geographic Information Systems (GIS) estimated travel routes.[9–11] However, GIS estimations of travel route using shortest street network analysis do not necessarily reflect the actual route,[12,13] and therefore may misrepresent those barriers ‘encountered’ enroute. Self-report data can be used to determine travel route, although recall may be difficult when routes are complex,[14] a task particularly difficult for children, thus potentially reducing the accuracy of the estimate. Accurate methods of route identification are therefore required to advance knowledge of how enroute barriers affect TPA and the decision to engage in TPA. Global Positioning Systems (GPS) offer a solution to this problem by offering a passive, low cost, objective and unobtrusive monitoring device to assess the actual movement patterns of travellers through the environment. This approach will better enable travel behaviours to be matched to environmental settings, compared to approaches that match behaviours to GIS estimated routes, thereby clarifying the associations between these variables.[1]

GPS is used widely in other areas of health research and other disciplines, yet its application to assessing physical activity engagement is relatively new.[12,15–19] Earlier applications include the assessment of gait patterns during walking[20,21] and to provide spatial information on locomotion to supplement data on the metabolic cost of different physical activities.[22,23] This paper is not intended to be a comprehensive review of all literature on the application of GPS to monitor human behaviour, nor is it limited to a discussion of this technology to assess children’s and adolescent’s activity. Instead it will outline the potential of GPS to complement existing sources of data to further understand the relationships between TPA, the built environment and health outcomes in child, adolescent and adult populations. In addition it will provide information on methodological issues associated with the use and integration of GPS data with other data sources, and potential limitations of these approaches to examine the interaction of people and their environments on health outcomes.

## 2. Basic operating procedures

GPS is restricted to assessing movement patterns in outdoor areas with a clear line of sight to the sky, as GPS receivers estimate their position on earth by triangulating their position based on signals sent from satellites orbiting the earth. Calculating the difference in time between when a satellite signal was sent to when it was received provides location identification, and a minimum of four satellites is required to estimate position including elevation of the receiver.[21] If the signal is blocked by buildings or mountains, or bounced repeatedly off buildings prior to being received, signal accuracy is degraded or in some instances not received at all.[14] These basic operating requirements have clear limitations in regards to how this technology is used to assess physical activity.

## 3. Initialisation period

When GPS units are first powered on, they need to undergo an initialisation period where the receiver acquires the required number of satellite signals to estimate position. Initialisation periods are specific to GPS units, more specifically the GPS receiver used in the unit, and will differ according to makes and models. GPS units have a warm and cold start signal acquisition period; a warm start refers to when units have been used recently and have not had significant changes in location (such as leaving a building which was entered), whereas a cold start is when the unit has not been used for some time.[14] For example, the Garmin eTrex (Garmin International Inc, KS) requires up to a 5-min initialisation period after turning on the unit for the first time, and requires 15 and 45 s to complete initialisation periods during warm and cold starts, respectively. A device similar to that described by Stopher,[14] the StarvNav BTS 110 (Stars Nav Tech Ltd., Taiwan) claims cold and warm start times of 45 and 35 s respectively, and also a ‘hot’ start time of 1 second. An important consideration is that during an initialisation period the unit may log data that suggests the unit is moving, sometimes large distances, when in fact the unit is stationary. This can have major implications for data cleaning and analysis.

## 4. Accuracy

The accuracy and reliability of any instrument is central to its application in research. GPS is commonly believed to be the 'gold standard' in positional and distance measurement, yet this is not the case.[24] As outlined previously, GPS requires uninterrupted signals from a minimum of four satellites to estimate position, and interference to these signals affects the accuracy of the GPS. Interruptions to the signal can be caused by blockages due to buildings (particularly in urban canyons), heavy foliage, travel on public transport, travel through tunnels and local topography, causing either degradation of the quality and accuracy of the signal or causing a drop out in the signal during monitoring periods.[14] Signal dropout occurs when the receiver temporarily loses satellite reception and creates a gap in the data that can range from several seconds to several minutes. This has obvious implications for monitoring TPA engagement, particularly as short trips could be missed altogether if the unit experiences a large period of signal drop out.[14] A useful summary of studies examining the accuracy of GPS, differential GPS and GPS receivers using Wide Area Augmentation Systems is provided elsewhere[25] as are details of approaches to deal with missing data due to signal drop out.[14]

Studies have shown that GPS provides an accurate measure of position that is useful in assessing human behaviour,[26,27] and this article will build on those findings by highlighting issues related to the accuracy of GPS that may be useful in its application to assessing TPA engagement. Prior to assessing GPS accuracy when moving, it is important to assess its accuracy when stationary. Trials conducted in Queensland, Australia comparing GPS estimated position to a known geodetic point, observed that the Wonde Proud (Wonde Proud Technology Co., Taipei) GPS units in non-differential mode had an average error in positional accuracy of $1.08 \pm 0.34$ m.[25] Importantly, 86.5% and 99.9% of observations were within 1.5 m and 2 m respectively[25], suggesting that whilst stationary the units provided consistent estimations of position. During walking and running trials over a 100 m course the Wonde Proud GPS closely approximated travel distance with an average measured distance of $100.46 \pm 0.49$ m over 40 trials.[25]

Many validation studies are conducted over courses that lack any changes in direction or contain only slightly curved paths, which rarely reflects the actual pattern of movement when walking and cycling in real life.[25] Studies detailing the accuracy of GPS in trials involving many changes in direction are therefore useful to assessing the utility of GPS to monitor TPA engagement. Coutts and Duffield[28] used a field-based sports performance test over a 128.5 m course completed six times during each exercise bout (bout length 771 m) with the course featuring many changes in direction and speed. It was observed that the SPI-10, SPI Elite, and Wi SPI GPS (GPSports, Canberra, Australia) estimated distances of $123.3 \pm 8.3$ m, $126 \pm 5.6$ m, and $129.1 \pm 8.2$ m respectively, with coefficients of variation ranging from 3.6% to 8.4% for individual laps.[28] When examining the longer length exercise bouts the SPI-10, SPI Elite, and WiSPI GPS estimated distances of $739 \pm 35$ m, $756 \pm 29$ m, and $\pm 776 \pm 44$ m, with coefficients of variation ranging from 2.8% to 10.9%.[28] Another study used the SPI-10 (GPSports, Canberra, Australia) to measure travel distances in a series of courses varying in length (range 128–1386 m) and geographic spread to mimic player movements in Australian Football.[24] Significant differences existed between the GPS-measured distance and distance measured via a calibrated trundle wheel.[24] The average error was $4.8 \pm 7.2\%$ with an absolute error of $6.3 \pm 6.0\%$; however, there was no systematic error in the GPS estimated distances as distance increased.[24] It is acknowledged that the shorter distances examined in these studies are less than those typically covered during walking[29] and cycling[30] journeys and likely contain many more rapid changes in direction than most TPA journeys. However, these findings provide some insight into the accuracy of GPS to estimate travel distance during TPA journeys that contain several rapid changes in direction.

In a separate study the Garmin eTrex (Garmin International Inc, KS) was worn in two different sites (waist and neck lanyard) and used to estimate travel distance over a 1489 m course during walking and cycling.[31] The course contained one change in direction after participants completed a section 1289 m in length.[31] The average uncorrected estimated distances during walking and cycling trials, respectively, was $1563.88 \pm 104.62$ m and $1616.00 \pm 237.46$ m for the lanyard worn unit and $1573.22 \pm 83.59$ m and $1573.82 \pm 239.65$ m for the waist worn unit.[31] However, errors in distance estimation in these trials were predominantly associated with erroneous data recorded during the initialisation periods and the accuracy of units improved when these errors were removed.[31] Specifically, the relative Technical Error of Measurement of the lanyard worn unit during walking and cycling trials, respectively, improved from 3.74% and 8.82% to 1.88% and 1.98% and the relative absolute error improved from 5.03% and 8.53% to 1.59% and 1.82%.[31]

This demonstrates the improvements in accuracy that can be achieved when erroneous data logged during initialisation periods are removed from analysis. Erroneous data were simple to identify as the study protocol required participants to remain stationary prior to commencing trials and the logged data suggested participants were moving in movement patterns not consistent with study protocols.[31] This allowed for identification during the trial; however, this approach may be limited in field based studies when the researcher does not have similar control and knowledge of participant's movement patterns prior to commencing the journey proper. An approach based on that outlined by Duncan and colleagues[31] was utilised in subsequent field-based research.[12] However, it relied on strict participant compliance to study protocols requiring participants to power on GPS units whilst still inside of the property boundary of the journey origin. This particular area of GPS research requires further development.

## 5. Factors affecting accuracy

GPS units are capable of providing estimates of distance to within several metres of actual location and can therefore provide rich information about route selection. Despite this, several issues can influence the accuracy of the estimates. Signal interference from buildings and natural structures are obvious impediments to applying GPS to monitoring TPA in dense urban environments. Methods are available to recreate data on speed and travel duration when data are lost in these situations; however, the commute route cannot be simulated as the researcher is unable to accurately determine the network the traveller took.[14] This is particularly an issue when signal drop out occurs in well connected areas where many travel paths are available to the traveler.[14]

Given signal drop out adversely affects data quality, particularly estimations of travel distance and route,[14,31] all attempts should be made to reduce the likelihood of this occurring. If journeys commence prior to the unit completing the initialisation period it may take several minutes for the unit to acquire sufficient satellites to estimate position whilst the unit is moving. Asking participants to remain stationary for 1 min prior to commencing a journey whilst the unit completes the initialisation period (usually <45 s in the case of the Garmin eTrex) has been used previously to improve GPS travel route data.[12] As previously described, erroneous data logged during initialisation periods can adversely affect the accuracy of units[31] and researchers should visually inspect data prior to analysis for potential errors in measurement and not take raw data as final.[14,31] Relatively short stationary times prior to commencing journeys are likely not to greatly inconvenience participants, though excessively long stationary times (>2 min) may compromise participants' willingness to participate and comply.[31] Data quality and potentially data validity may be affected if the delay alters the travel route from that which participants normally select.[31] Therefore, a GPS unit's cold and warm start times should be considered prior to implementation in research.

Increasing technological advances in GPS receiver chip technology will likely contribute to reducing initialisation periods and the likelihood of units to experience signal drop out. Alternate location technology can be used to estimate position when GPS signal is not available, for example inside buildings or in very dense urban areas. This is performed using an inertial measurement unit combining data from multiple gyroscopes and three dimensional accelerometers[32] or radio frequency tracking[33]; however, this technology requires further development prior being widely used in the monitoring of TPA.

## 6. Current applications of GPS in monitoring physical activity

As noted earlier, the application of GPS in monitoring the geographical setting of physical activity is growing; however, GPS has been used in the transportation field for some time to complement travel data collected by self-report.[16,34,35] This section will provide a brief overview of studies using GPS to provide information on the spatial context of physical activity typically integrating GPS with accelerometer and GIS data. Accelerometers measure physical activity by recording changes in acceleration produced by the bodily movement. Resultant data are then used to quantify the relative intensity of the movement. Several reviews are available detailing the application of this technology in the measurement of physical activity and the limitations associated with their use in quantifying physical activity levels.[36,37] GIS is a computer-based software platform that maps and manipulates data to examine relationships and patterns in geographically referenced data.[38] The platform can integrate data from many sources (health, services, transport) with geographical data and is increasingly being used in health-related research. Furthermore, a combination of GPS and accelerometer data have been used to identify the mode of travel (walk, run, bicycle, inline skating, car travel) on trails using information regarding travel speed (GPS), median steps and activity counts per bout (accelerometry) as accelerometer data alone cannot explicitly determine mode of activity.[39] The addition of GPS data enhances the accuracy of predicting travel mode by approximately five percent.[39] However, the authors expressed concern about the increased participant burden when collecting both GPS and accelerometer data due to participants wearing two separate units.[39] In light of these concerns and further validation of this approach, a combined GPS and accelerometer unit may be useful for studies examining mode of travel, and could be easily extended into larger scale studies including travel to other destinations, and in diverse populations.

Wiehe[15] reports on the use of GPS to assess the mobility patterns of adolescents in terms of distance and time spent away from home. This approach is similar to that of UK research combining accelerometers, GPS and travel diaries to assess children's independent mobility and activity patterns.[40] The research suggested that children travel at slower speeds in movement patterns that involved more lateral movements when children travelled without an adult compared to when travelling with adults.[40] Additionally, overall mobility differed by gender with boys permitted greater mobility without adult accompaniment than girls. It was also shown that children walked faster corresponding to greater activity intensity with less lateral movements when travelling along a road compared with walking in a public open space.[40] The authors suggested that this observation is likely related to the opportunities for play in each location. This analysis demonstrates how GPS measures of location can be used to provide insight into fine level movement patterns captured by accelerometers. Studies have also used behavioural mapping techniques to examine relationships between child activity and neighbourhood characteristics.[41,42] However, integrating GPS, GIS and other physiological data on activity patterns in a similar manner to previous studies[40] may provide added insight into how neighbourhood design influences activity patterns in the area being investigated.

An integrative approach of combining GPS, GIS and accelerometer data has been used by Roderiguez et al.[19] to demonstrate that physical activity performed in a person's neighbourhood was of a greater duration and contributed more to the overall accumulation of moderate- to vigorous-intensity physical activity accumulation than activity performed outside of their neighbourhood. Additionally, those people performing the majority of their moderate- to vigorous-intensity physical activity in their neighbourhood resided in settings that had greater levels of street network connectivity and residential density compared to those who were most active outside of their neighbourhood.[19] These studies demonstrate that GPS data can be used to assess a variety of parameters related to travel behaviour of which may be particularly useful in understanding barriers to children's travel given the declining levels of both TPA to school[43,44] and independent mobility in children.[45] There is also a UK based study (http://www.bristol.ac.uk/enhs/peach/) in progress incorporating GPS, GIS and accelerometers to examine the spatial context of children's physical activity. At this time no final data are available; however, over 1100 children have provided accelerometer and GPS data.

## 7. Assessment of barriers to TPA

Apart from distance, which is a major barrier to TPA,[46,47] the application of GPS to understanding other barriers to TPA requires integration with other data sources such as GIS, accelerometry, and self-report. Previously GIS has been used to assess the presence/quantity of variables in the built environment by creating neighbourhood boundaries around origins or destinations.[38] Similar approaches cannot be replicated to assess characteristics of the route if the actual route is unknown. As noted earlier, a feature of GPS is that it provides rich data on the *actual* route taken that can be subsequently integrated with other data sources to assess characteristics of the travel route. Previously GIS shortest route through street networks has been used to estimate travel routes during TPA.[9–11] Although these studies used GIS estimated routes that may not have reflected actual routes[12,14] they were useful in demonstrating the type of analysis that is possible when substituting the simulated route (GIS derived) with a GPS measure of actual route. One potential application is that GPS travel route data can be overlaid on a GIS database to gain insight into frequency of built environment variables or features and then model how the encounters with these hypothesised facilitators/barriers are associated with actual TPA engagement. Such an approach not only offers model specificity between settings and behaviours, but also objective and quantifiable measures of the behaviours and hypothesised correlates at the origin, destination and enroute.

An example of these possibilities has been completed in adult populations using buffers around GIS simulated work commute journeys less than five kilometres to assess the association of travel behaviours and perceptions with GIS-measured land use mix, residential density, and street network connectivity.[10] The findings showed that commute distance was negatively associated with actual and perceived TPA engagement, and those who travelled along the most connected street networks were most likely to commute by TPA modes in comparison with adults who travelled through the least connected street networks (OR = 6.9; 95% CI = 2.2–21.9).[10] Although this study used GIS estimated routes, it clearly demonstrates the scope for applying a GIS-derived buffer to assess route characteristics and travel modes.

Other studies have used non-buffered GIS estimated routes to determine how encounters with hypothesised environmental characteristics are associated with activity behaviour in adults[11,48] and children.[9] In adults, routes containing a footpath network and the absence of a hill were positively associated with TPA engagement.[11] In another study, individuals with a GIS estimated shortest route between home and a bikeway that did not contain a steep hill were more likely to use the bikeway, although the presence of busy street enroute was not associated with bikeway use.[48] In a study of children's school TPA, GIS estimated routes containing a steep hill and a busy street were positively associated with TPA to school.[9] The inverse associations between the presence of hills enroute and TPA in adult and child populations may arise for several reasons, although it may be that adults and children perceive the presence of hills enroute differently in terms of barriers to TPA participation. A more simplistic non-buffered approach was implemented in a recent study comparing travel distance and route characteristics measured by GPS and GIS.[12] The study observed that GIS and GPS travel routes were not different in terms of travel distance but differed in terms of travel path, where GIS estimated routes crossed more, and contained a higher proportion of busy streets compared with GPS routes.[12] This study was limited by a small sample ($n = 59$) with few measures of the travel route and a single day of monitoring, yet illustrated the potential for GPS to assess barriers to TPA engagement.

## 8. Future avenues

TPA has obvious health benefits,[49,50] and understanding the environments that best support this behaviour is critical. Combining GPS, GIS and accelerometry will be useful to complement existing evidence outlining how the built environment influences physical activity that has been obtained primarily using self-report measures of physical activity. Currently research integrating GPS and accelerometer data does so using two separate monitors[19,39,40]; however, products do exist that integrate GPS, accelerometry, heart rate and other movement parameters into a single unit for analysis of player movements in sports settings (GPSports, Canberra, Australia; Catapult Innovations, Scoresby, Australia). The increased technology integrated into these devices increases unit costs accordingly compared to basic data logging units. The increased costs of these units must be balanced with the requirements of the research project, particularly when the project requires moderate to large sample sizes. However, future technological advances will likely see the cost of these *integrated* units decrease. Additionally, if activity outputs from these integrated units can quantify physical activity to accurately determine time spent engaged in sedentary, light, moderate- and vigorous-intensity activities when indoors and outdoors similar to other widely used accelerometer units; it may alleviate concerns of added participant burden associated with wearing multiple units such as GPS' and accelerometers.[39]

A further application of GPS technology is to operate as a comparison with self-report travel information, and Australian researchers have examined the accuracy of completing self-report travel surveys through GPS data.[34] Although start and end times were well matched between the GPS data and the travel survey, households ($n = 45$) under-reported travel by 7.4%, primarily by under-reporting travel distances. Interestingly, those who made many trips or travelled after work were more likely to underestimate their travel time and distance, and trips for social purposes were most likely to be under-reported. As such, when GPS technology is combined with travel surveys, it can be used as a means to correct self-reported travel variables.

Another application of GPS is to understand the potential risks associated with TPA engagement. TPA occurs in close proximity to motor vehicles, and motor vehicle exhaust can increase the risk of several diseases including cardiovascular disease,[51] lung cancer, and all-cause mortality.[52,53] These potential health risks in conjunction with air pollution being identified as a barrier to physical activity,[54] provide scope for GPS measures of travel to be complimented with measures of air pollution to provide spatial information on exposure patterns during travel. The feasibility of this approach has been previously demonstrated[55,56] and could be incorporated into studies examining the health benefits and risks of TPA engagement, particularly to understanding individual exposure patterns during travel.[57] Additionally, the relationships between TPA, urban design and air pollution[58] may be further expanded to examine the spatial patterns of exposure during physical activity in different environments when measures from GPS, GIS, accelerometers and air monitoring equipment are combined.

Such research will be useful given recent acknowledgement of the potential for accumulated negative health effects by engaging in physical activity in areas containing *high* concentrations of air pollution.[52] This information will further add to the evidence to guide policy development on the creation of environments that support and promote physical activity and contribute to creating even healthier built environments. Despite the potential for some negative impact on health due to exposure to pollutants during activity this relationship is not well understood.[57] And until this relationship is better clarified it is likely to be counterproductive to physical activity promotion messages to simultaneously promote activity away from sources of pollution.[57]

## 9. Conclusions and limitations of GPS in health-related physical activity research

Throughout this article methods to integrate GPS technology with other data sources to extend knowledge of how environments may influence TPA and health have been outlined. GPS provides this opportunity by objectively assessing behaviour and when integrated with other data sources offer researchers the potential to assess specific behaviour and setting correlates. The promise of this technology is however not without limitations, that should be balanced with the objectives of the research and the additional participant burden associated with this approach.

GPS provides rich data regarding the movement of individuals through the environment. This richness is met with increased monetary and time costs associated with data collection. GPS units that only log data are relatively inexpensive to purchase outright (∼$90AUD for a StarvNav BTS 110 to approximately $275AUD for a Garmin Forerunner 201), yet the researcher must also consider the costs associated with employing personnel to check the validity and completeness of the data. Some automated processes are available to complete some of these checks; however, there still remains a large manual element[14] that must be performed prior analysis of the data. Also adding GPS units to the data collection process adds an additional layer of complexity for participants who may already be wearing other monitoring devices such as accelerometers or air monitoring devices.[39] Participants may also be required to complete initialisation periods prior to commencing a journey, which if are excessively long may reduce participant compliance.[31]

Many commercially available units have a relatively short battery life compared to other objective measures of physical activity, such as accelerometers. The implication of this is that when monitoring across several days researchers or participants will have to recharge or replace batteries depending on the unit. Units have been recharged by participants during data collection previously[19,59]; however, it is unknown how this affects participant adherence to data collection. Many units currently have relatively low data storage. For example, the Garmin Forerunner and eTrex have memory capacities of 10,000 points, and by using a 1-s recording interval are capable of recording approximately 2.47 h of data. This is less problematic if the GPS unit is only powered on for TPA journeys or using longer sampling frequencies, however, turning the unit on and off may require re-initialisation, which will increase participant burden and/or affect validity. Limited storage capacity may require the researcher to download data during the data collection period if large volumes of data are collected. However, alternate units with greater data storage capacity are available.[14] As previously mentioned, GPS operation in dense urban environments containing tall buildings may also be limited as the units may be unable to readily acquire signals from satellites, although this should not discourage use in other urban environments.

## Practical implications

Notwithstanding the logistical constraints, there are many opportunities to integrate these tools, and it is likely that future work in this field will provide a more complete picture of physical activity accumulation, and a more rigorous understanding of how different environments facilitate different domains of physical activity. Potentially the greatest benefit will exist for understanding TPA engagement, largely because the behaviour lends itself so well to moving through diverse environments that could appropriately be assessed by GPS, GIS, and accelerometry. Although this integrative approach may be particularly useful for understanding relationships between travel route, environments and health in children due to difficulties in recalling travel route; it is not limited to a single population in the age spectrum. Studies conducted to date have demonstrated the promise of this technology to assess movement in outdoor environments; however, much work remains to be done.

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