Facilitators and barriers to real-life mobility in community-dwelling older adults: A narrative review of accelerometry and global positioning system based studies

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Abstract

Real-life mobility, also called “enacted” mobility, characterizes an individual’s activity and participation in the community. Real-life mobility may be facilitated or hindered by a variety of factors such as physical abilities, cognitive function, psychosocial aspects, and external environment characteristics. Advances in technology have allowed for objective quantification of real-life mobility using wearable sensors, specifically, accelerometry and global positioning systems (GPS). In this review article, first, we summarize the common mobility measures extracted from accelerometry and GPS. Second, we summarize studies assessing the associations of facilitators and barriers influencing mobility of community-dwelling older adults with mobility measures from sensor technology. We found the most used accelerometry measures focus on the duration and intensity of activity in daily life. Gait quality measures, e.g. cadence, variability and symmetry, are not usually included. GPS has been used to investigate mobility behavior, such as spatial and temporal measures of path travelled, location nodes traversed, and mode of transportation. Factors of note that facilitate/hinder community mobility were cognition and psychosocial influences. Fewer studies have included the influence of external environments such as sidewalk quality, and socioeconomic status in defining enacted mobility. Increasing our understanding of the facilitators and barriers to enacted mobility can inform wearable technology-enabled interventions targeted at delaying mobility related disability and improving participation of older adults in the community.

Keywords: Physical activity and participation, Spatial movement, Wearable technology

1. Introduction

Mobility is essential for completion of many instrumental activities of daily living and promotes physical function, social engagement, independent living, and quality of life (1). By 2040, the United States is expected to have more than 81 million older adults, and 15.4 million of them will be unable to walk even 2-3 blocks in their neighborhood (2). Active mobility (e.g., walking) is a key source of physical activity in older adults. Mobility limitations such as inability to walk without support and prevalence of sedentary behavior would lead to about $42 billion additional annual healthcare costs (2). Moreover, a sedentary lifestyle can increase the risk of obesity, cardiovascular disease (3), and diabetes (4). Mobility behaviors are risk-factors for cognitive and neuro-degenerative diseases, such as Parkinson's and Alzheimer's (5,6).

Many research studies have focused on measurement of physical functioning in laboratory environments, referred to as "experimental" assessments. These assessments reflect the capacity and capability of a person (7). In the last two decades, focus has increased on assessing real-life mobility and participation, also called "enacted" mobility (8). There are popular self-reported mobility assessment questionnaires such as the Life Space Assessment (see Taylor et al (9), review) to measure enacted mobility. Self-reported measures are quick and easy tools, however, they are prone to recall-bias, individual perception of neighborhood, and present challenges among individuals with cognitive impairment. Self-reported measures are not good at capturing dimensions of activity such as duration and day to day variability.

The use of accelerometry and GPS as objective measures to record temporal activity and spatial movements during community ambulation is growing. We conceptualize enacted mobility in the community as 1) quantity and performance of physical activity and 2) spatial navigation and activity location. Accelerometers can be used to record change in body movements, steps per day, intensity of activity and quality of walking i.e. gait characteristics such as step time variability and symmetry; GPS can record location, mode, path and destinations. Together, these two technologies complement each other in measuring enacted mobility. Existing systematic reviews in the literature are focused on methodological issues such as sensor properties, device placement, and sedentary and physical activity level cut-offs for older adults (10–12). Additionally, studies utilizing GPS to monitor location of activity and participation in older adults (above 50 years) have been reviewed (13). However, no existing reviews have assessed the factors associated with accelerometry and GPS based measures of mobility in natural environments.

An individual's enacted mobility may be facilitated or hindered by a variety of factors such as physical abilities, cognitive function, psychosocial aspects, and external environment characteristics (14,15). In this review article, we summarize the research studies that focus on these facilitators and barriers to enacted mobility in community dwelling older adults, via accelerometry and GPS. Studying these associations will further our understanding of these quantitative mobility measures. We address the following questions in this qualitative review: 1) What metrics extracted from accelerometry and GPS quantify real-world enacted mobility? 2) To what extent are accelerometer and GPS devices being used to assess enacted mobility? 3) What is current knowledge and where are the gaps in assessing associations of facilitators and barriers to enacted mobility?

Search strategy method

PubMed, Web of Science, and IEEE Xplore databases were used to search for research studies with keywords "Mobility" AND "Older Adults" AND ("Accelerometer" OR "GPS" OR "Global Positioning System"). Studies published from January 2000 to March 2021 have been included. A study was included if association of at least one facilitator or barrier to enacted mobility quantified by either GPS or accelerometer or both, was assessed. There was no restriction on study design or country where the research was conducted as long as community dwelling older adults (>60 years) participated. Disabilities such as Parkinson's, dementia and other neuro-motor disorders can limit mobility of older adults, by default. In this review article, we want to include general populations of community-dwelling older adults rather than patient populations with conditions that would severely impair mobility. This will help in understanding facilitators and barriers influencing mobility during the normal aging process. Therefore, studies assessing individuals with existing physical disabilities, severe cognitive impairments, and other neurodegenerative disorders are not included in this review.

2. Results for data extraction and study synthesis

A total of n=459 records were identified using the keyword combination "mobility" AND "older adults" AND ("accelerometer" OR "GPS" OR "global positioning system") in PubMed, Web of Science, and IEEE Xplore, between 01/01/2000 and 03/31/2021 . We removed duplicates (n=126). We next excluded studies based on titles and abstracts (n=151). These consisted of individuals with Parkinson's disease (n=19), Dementia (n=20), Stroke survivors (n=10), Multiple Sclerosis (n=5), wheelchair users (n=3), Osteoarthritis (n=7), Glaucoma and eye diseases (n=5), and other functional/motor disabilities (n=34). Some studies were focused on individuals residing in-care facilities, were hospitalized, or had major surgeries, and fractures (n=36). Further, reviews and protocols were excluded (n=12). The remaining n=182 full-text articles were assessed for eligibility, out of which n=49 articles were included in this final review. The excluded articles (n=133) either did not record daily life/real life mobility using sensors (n=50) or did not assess any facilitator or barrier (n=57), or included individuals with age less than 60 years (n=26). For detailed literature identification and screening process, refer to **Supplementary Table 1** and **Supplementary Figure 1**.

Most studies were cross-sectional in design and used sensors at the lower back position. A total of about n=19,267 older adults (≥ 60 years) were assessed in these studies (Age 76.2 ± 4.7 years, 40% females). These studies analyzed 3-10 days of sensor data. The study sizes typically varied from about 100 to 1000 participants. The studies were from different countries, all notably developed (United States, United Kingdom, Canada, Japan, Finland, Netherlands, Germany). Detailed participant characteristics for studies are tabulated in **Supplementary Table 2**. The sections below provide synthesized takeaways from these studies.

3. Quantification of enacted mobility

Enacted mobility can be captured using Inertial Measurement Units/accelerometers and GPS. These two modalities complement each other with regards to the information provided. A general framework of processing accelerometer and GPS data consists of four steps: 1) determine the protocol, 2) acquire data, 3) data processing, and 4) extract the quantitative measures of enacted mobility. Measures that have been used include activity characteristics (intensity, duration, frequency, walking quality) and spatial navigation behavior **(Figure 1).**

3.1 Accelerometer

Studies have utilized uniaxial as well as triaxial accelerometers to record daily activity, typically for 3-10 days. A considerable number of studies using accelerometry and assessing at least one facilitator or barrier were found. Sedentary behavior includes sitting, reclining or lying position; light physical activities are mostly indoor activities of daily living such as walking inside the home, bathing, or changing one’s clothes whereas moderate-vigorous physical activity (MVPA) includes outdoor activities such as active walking and exercises. Standard accelerometer activity counts range is 1-100 per minute (<1.5 metabolic equivalents) for sedentary, 100-1951 activity counts per minute (1.5-3.0 metabolic equivalents) for light physical activity and >1952 counts per minute (>3 metabolic equivalents) for MVPA (11,16). We adapted the dimensions of physical activity (17), categorizing the accelerometry based measures into volume, activity intensity and gait quality, and have summarized the studies that utilized each measure (**Table 1**). 'Volume' includes counts or quantities of steps, walking bouts, activity and transitions. These likely account for light intensity activity such as casual walking. 'Activity intensity' focuses on time spent in MVPA, energy equivalents and accumulation of MVPA. 'Gait quality' includes cadence, variability and other aspects of walking. Studies utilizing accelerometery have primarily focused on recording physical activity, for which signal in vertical direction provides accurate and sufficient information. Potentially useful signals for gait analysis in the mediolateral and anterior-posterior (18) directions were often not analyzed. Placement of the sensors are usually on the waist, lower back or right hip (**Figure 1**).

3.2 Global positioning system

There were fewer GPS based studies to measure enacted mobility. Most of these studies used both GPS and accelerometer. Spatial (count, extent and shape) and temporal (duration) aspects were the focus, motivated from the detailed GPS measure classification (19,20) (**Table 2**). 'Count' refers to the number of mobility-related events such as number of visited locations and number of trips made (on foot or vehicular). 'Extent' refers to the spatial size of mobility-related behavior, for example, distance travelled, life-space area, etc. 'Shape' is a measure of distribution of activity locations and can be quantified using circularity or compactness of life space. 'Duration' captures temporal aspects such as time out of home and time spent as pedestrian vs in vehicle. In addition to the variables tabulated, GPS devices can record walking speed and driving speed (21).

4. Facilitators and Barriers to enacted mobility

Factors that impact enacted mobility of older adults have been identified using the associations of self-reported mobility, specifically the Life-Space Assessment (22,23) with a) physical capacity and functions (18,24,25), b) cognition (26,27), c) psychosocial factors (28,29), d) the environment (30,31), and e) socio-economic status of the individual and community (32). A canonical framework emphasizing the role of these facilitators and barriers as mobility extends from the home to outdoors, the neighborhood, the surrounding community and beyond has been proposed (15). Gender, cultural and biographical factors also influence one's mobility. The multidimensional nature of mobility and interrelationships among these dimensions is important. We will now explore the relation between physical, cognitive, psychosocial and environmental factors to enacted mobility captured by accelerometry and GPS.

4.1 Individual physical function

Our discussion of physical aspects of mobility is limited to functional measures of gait, balance, walking endurance, posture transfers and fall history. These aspects of function integrate across multiple body systems, so we chose not to include system-specific measures such as muscle strength. The relationships between physical function and enacted mobility are tabulated by modality, accelerometers **(Table 3a)** and GPS **(Table 4a)**.

Faster walking speed measured in the laboratory has been consistently related to higher mobility by accelerometry measures, including volume (33,34), intensity (34–36) and gait quality (37–39) (Table 3). However, not all studies have found positive associations between gait speed and volume (36,40). Gait speed has been associated with the amount of MVPA and gait quality, even after including demographics and step counts as covariates (35–37,39).

Greater walking endurance was consistently related to better mobility by accelerometry measures, regardless of the duration of the walk tests used for assessment (33,35,38,39,41–43) (Table 3). Laboratory measures of balance and transfers were related to better mobility by accelerometry (35,37,42,44,45), though only one study has assessed transfers (43). Like balance, self-reported fall history has been related to multiple aspects of mobility measured by accelerometry (Table 3). However, there is no consensus on if volume, quality or both aspects of mobility are important considerations to reduce fall-risk. Individuals with two or more falls differed from non-fallers on gait quality as measured by step time and entropy rate. In contrast, fall history was not associated with volume-based accelerometry measures such as steps per day (37,46). This contrasts with studies that showed non-recurrent fallers (less than two fall) took significantly more steps per day than recurrent fallers (47,48) and that fall risk was reduced in those walking >5000 steps per day (volume measure) (49). One study found that adjusting for psychosocial factors attenuated the differences in mobility between fallers and non-fallers (48).

Finally, several studies have shown that combined measures of physical function [i.e. Short Physical Performance Battery (33,38,50–53) and Timed Up and Go (34,35,37,42,54,55)] were related to accelerometry measures of mobility, with only a single study finding no association between the Timed Up and Go and volume aspect of mobility (56) (Table 3). Self-reported physical function is also associated with MVPA (43,57).

No study has examined gait speed and fall-history in relation to spatio-temporal GPS measures. Only one study examined endurance in relation to GPS measures and found that individuals with a faster 400m walk time made more walking trips (58); but no association with vehicular trips was found. Interestingly, ability to balance on one leg was a key predictor of mobility in a GPS-accelerometry based study that included physical, cognitive and psychosocial factors (45). GPS measures indicated individuals with better physical functioning were more engaged in walking, had greater spatial extent of travel, and had greater time out of home (21,58,59).

Overall, volume and activity intensity measures from accelerometry are well studied. Quite a few studies assessed gait quality in real-world environment (37–39,44,46), emphasizing a growing interest in quantifying 'how we walk' in real-world settings.

4.2 Domain-specific cognitive function

Performing daily tasks and navigating the environment (e.g., traffic situations, road-crossings and using public transportation) requires adequate cognitive functioning. Studies have explored potential applications of out-of-home mobility behaviors in older adults as indicators of cognitive deficits (60,61). In comparison to the number of studies assessing physical capabilities, fewer studies explored the relationship between cognitive function and enacted mobility measures using accelerometry **(Table 3b)** and GPS **(Table 4b)**.

Only one study assessed associations between executive function and accelerometry measured volume of mobility, finding a positive relation (34). In two studies, better cognitive performance across multiple domains including executive function, planning ability, visuospatial attention, spatial memory and episodic memory were associated with greater amounts of MVPA (34,62) and the associations persisted even after considering covariates such as socio-demographic, sleep quality, perceived stress and comorbidities. Interestingly, Wanigatunga and colleagues suggested that older adults with more preserved cognitive function have the capability to be active for longer periods of time needed for completion of a task-oriented test (62). Studies found no associations between literacy level and mobility measures (45,56) and there were no studies assessing the relationship between cognitive function and free-living gait quality.

Several studies found associations of cognitive domains such as executive function, planning ability, visuospatial attention, spatial memory, working memory and episodic memory with spatial measures of mobility from GPS (34,45,59,63). Episodic memory was a predictor of GPS measures such as time spent out of home, number of locations visited and life-space area, however, no such associations with walking tracks, time and distance in walking were found by the same study (59). Surprisingly, two studies did not find associations of executive functioning with GPS measures (58,61). Visuospatial attention was found to be the strongest predictor of mobility, establishing a close link between attention and enacted mobility (63).

4.3 Psychosocial factors

Studies have explored the relationship between psychosocial factors and enacted mobility measures using accelerometry **(Table 3c)** and GPS **(Table 4c).**

Studies using accelerometry have found that depression, negative affect, and anxiety are associated with less step-count and less amounts of MVPA (34,45,48,64,65). This supports the activity theory of aging (66,67), that people with higher positive affect are more active out of home. A greater confidence in walking and balancing and a reduced fear of falling have shown associations with greater volume and MVPA measures of mobility (34,40,45,47,48,68). Interestingly, fear of falling restricted physical activity in older adults, even when they had relatively high physical functioning (40). Another study found that the association of fear of falling with physical activity was independent of actual fall history (48) indicating that older adults could reduce activity due to fear even without having experienced a fall. Attitude towards walking (i.e. enjoyment of walking) also impacts PA and overall mobility (68,69). This suggests that physical activity intentions are potentially modifiable and may be targeted using cognitive-behavioral interventions. No study evaluated relation between psychosocial factors and free-living gait quality.

In GPS studies, significant negative associations were found for fear of falling and depressive symptoms with number of pedestrian trips, distance walked, trip durations (34,58,59). These associations were inconsistent with vehicular trips (45,58). Two studies did not find associations of negative affect and anxiety with GPS measures (21,45), unlike some accelerometry-based studies that reported such associations. Psychosocial factors in relation to enacted mobility is a growing topic of research.

4.4 External environmental factors

Few studies have explored the relationship between environmental factors and enacted mobility measures using accelerometry **(Table 3d)** and GPS **(Table 4d)** in community-dwelling older adults.

Accelerometry measures of physical activity varied with the weather. As expected, precipitation (69,70) and temperature extremes (70) were associated with reduced volume (step counts), walking minutes and activity (duration and intensity), though the support for this was not consistent across studies. For example, no relation between temperature and enacted mobility was found by Giannouli and colleagues(34).

Neighborhood attributes such as higher street connectivity, greater walkability, proximity to destinations, traffic conditions, presence of parks and overall diversity of land-use are associated with increased mobility, particularly MVPA, among older adults (64,68,71,72). However, one study noted that an individual’s perception of diversity in built-environment and street connectivity influenced their “confidence to walk outside”, suggesting that association of these factors with enacted mobility was not independent of walking confidence (68). Further, two studies showed that the presence of lower-extremity physical limitations affected the strength of some person-environment relationships (51,73). One study found that higher physical functioning scores were associated with higher MVP only in the high-income, highly walkable neighborhoods, whereas no significant association was observed between physical functioning and MVPA in low-income neighborhoods or in high-income, low-walkable neighborhoods, suggesting the additional role of socio-economic status as an additional determinant of mobility (53).

Only two studies have assessed neighborhood characteristics and temperature in relation to spatial measures of mobility from GPS (34,71). One reported individuals in less walkable neighborhoods to have larger activity-spaces (71), while the other found no association of temperature with spatio-temporal measures of mobility (34).

5. Gaps in the literature and future directions

Forty-nine studies were identified that utilized accelerometry and/or GPS measures of community mobility in older adults. Most studies using accelerometry focused on measurement of step count and minutes in MVPA and studies using GPS focused on distance travelled. In contrast, there is a lack of data on quality of walking and spatial metrics of travel. ~~Most studies were cross-sectional in design and use sensors at the lower back position. These studies analyzed 3-10 days of sensor data. The study sizes varied from about 100 to 1000 participants. The studies were from different countries.~~ There is lack of consistency in the data collection methods and quantification of the accelerometry and GPS signals. These inconsistencies make it difficult to compare the studies; however, they do provide insights into the existing gaps in measurement of facilitators and barriers to mobility that future research studies can focus on. In this section we discuss gaps and future directions for accelerometry and GPS sensor-based measurement of enacted mobility. We discuss the facilitators and barriers to enacted mobility that are lacking in literature. Finally, we emphasize the public health implications of sensor technology in mobility assessment of older adults.

5.1 Sensor technology for measurement of enacted mobility

Assessment of community mobility by accelerometry and GPS provides objective methods to quantify mobility. Some of the advantages are overcoming recall bias, and providing a detailed understanding of individual spatio-temporal behavior and valuable insights into person-environmental interactions (74). Valuable insights into environmental facilitators and inhibitors are also being defined. However, using technology to assess enacted mobility comes with technical challenges that must be overcome. Current issues are: 1) limited battery life, 2) relatively low sampling rate for many GPS devices, 3) reliance on the participant to wear and charge the device, and 4) parameterizing the data during processing of accelerometry and GPS signals (Figure 1). Signal drop in GPS satellites leads to missing datapoints which require interpolation. Discontinuous data recording can affect comprehensive analysis. The current technical challenges to using accelerometry and GPS for assessment of enacted mobility have been detailed in recent reviews (12,13,75). Even so, the objective information about variability in mobility that these wearable technologies can provide, have numerous applications. This detailed spatio-temporal assessment potentially outweighs the current challenges in data processing from these modalities that the research community continues to address.

5.1.1 Gaps and future directions of accelerometry based enacted mobility assessment

Most studies used a triaxial accelerometer and the activity measures were based on data from only one axis (usually the vertical axis). Only two studies leveraged the full capabilities of accelerometry (37,46). The temporal and statistical measures extracted from anterior-posterior and medio-lateral signals could provide further information on quality of movement. Studies assessing gait quality in laboratory settings and in real-world settings are not common. Moreover, there is a need to perform analyses beyond the number of steps as it can be a deceiving measure for older adults taking more smaller steps (76). When assessing, it is difficult but necessary to separate the relative influence of volume versus intensity of physical activity. For example, walking at a higher cadence will increase the number of steps per day if distance is maintained (39). Accelerometry may also underestimate physical activity among those walking slowly (77). Most studies in this review utilized single accelerometers placed at lower back or waist. Single accelerometers are limited in that they cannot accurately capture and distinguish between different postures (i.e., standing still, sitting, or lying), which can possibly lead to overestimating or underestimating activity, thereby impacting enacted mobility measures. Some studies have shown that an additional sensor placed on thigh or chest, in combination with sensors on lower back are able to predict postures accurately (78,79). More research is needed to understand role of posture as a component in enacted mobility. Further, accelerometry studies in the review have focused on activity monitoring however, "activity accumulation" through the course of the day is also important and needs more research (52,55,56).

5.1.2 Gaps and future directions of GPS based enacted mobility assessment

GPS has only recently been applied to research studies compared to accelerometry. We only found eight studies that utilized both accelerometer and GPS for older adults (**Supplementary Table 3**). There is little consensus regarding processing of the GPS data. Parameters of the navigated space in relation to physical, cognitive, psychosocial and environmental factors impacting mobility have yet to be explored. The distinction between active and passive modes of transportation is necessary and needs to be considered during analysis. For example, if the participants made little use of passive transportation and instead were mainly physically active, the associations of physical factors to life-space mobility will stand out compared to cognitive and psychosocial measures (34). Destinations and life-space may be associated with objectively measured physical activity

(71,80,81). Therefore, prospective studies should also assess associations between accelerometry based activity and GPS-based space (82). GPS is a popular technology incorporated in most smartphone devices. Validation of spatial measures that can be derived from GPS and their relation to factors influencing enacted mobility have potential to alter intervention strategies to enhance participation of older adults in the community (83).

5.1.3 Bridging semantics and technology output: Mixed-methods approach

Future community outdoor mobility studies could employ both objective and subjective methods to gather in-depth information on individual travel patterns and behaviors. Even the preferred modality of examination (self-reported vs sensor-based) changes with socio-demographic factors. For example, a study examining challenges in using wearable GPS devices in low-income older adults found that older adults with low socio-economic status preferred self-reported Visualization and Evaluation of Route Itineraries, Travel Destinations, and Activity Spaces, (VERITAS) over using GPS (84). And in another study 46% of older adults who had less of a routine refused to wear an accelerometer (85). Self-reported outcomes are important because they consider individual perceptions of mobility and effort. Mixed-method approaches using quantitative (accelerometry or GPS) and qualitative (interviews and diary-based) approaches together can generate different insights and enhance the overall study findings (86,87). Another study via ground visualization approach showed that familiarity influences spatial perceptions of neighborhoods and older adults prioritize destinations that allow them to engage in multiple activities (88).

5.2 Facilitators and barriers to enacted mobility beyond physical capabilities.

Association of accelerometry measured enacted mobility with physical factors has received much attention, however, only a few studies examined the facilitators and barriers categorized as cognitive, psychosocial, or environmental. Specifically, the relation of physical functioning aspects such as walking endurance and strength in lower extremities to activity and space measures seems to be well-established. However, enacted mobility and its associations to fall history needs more investigation as it is unclear whether volume, intensity or quality of walking is providing more insights into fall-risk. Overall, there are inconsistencies regarding the measurement of specific cognition domains and their relationship with mobility behaviors of older adults, thereby requiring further investigation. Interestingly, there is an absence of studies measuring gait quality in the real-world and its association with cognitive, psychosocial and environmental measures.

Moreover, these facilitators are interlinked and the associations among them also should be accounted for in the analysis. For example, recurrent fallers (physical barrier) have increased fear of falling (psychological barrier) reflected in activity specific balance score (37). New research studies can focus on exploring the mediating or independent effects of these factors on mobility. For example, apart from BMI and age as determinants of mobility, variance in mobility couldn't be explained by a wide range of demographic, social, cognitive and physical factors in the regression analysis (56). Similarly, another study showed that of all the barriers and facilitators, physical and psychological factors accounted for a significant but low proportion of variance (between 5 and 30%) in enacted mobility measures (34). Physical, cognitive and psychosocial factors predicted 32 to 43% variance in enacted mobility; ability to balance on single leg was found as one of the prime predictors (45).

No studies included the financial aspect (individual or neighborhood), which is also an important factor determining mobility. For example, not having a car, or not being able to travel in an airplane can restrict life-space. There are some other individual traits for example, pet ownership (64,89), car ownership, and driving capabilities (81,90,91) that can influence one's activity and participation in the community. Additionally, living situation can influence enacted mobility as older couples often influence each other's mobility patterns (92). All studies included in this review were observed to be from developed countries ~~(such as US, Canada, Japan, Finland, Netherlands, Germany)~~. Hence, the findings may not generalize well to developing nations where population density, built environment, and economic disparity are challenges as well. Culture is another important influence, for example, restrictive mobility of women in some countries. Thus, future research studies should be more inclusive and account for access to resources, geography, finance and culture.

While enacted mobility refers to real life environments and actions, laboratory assessments of gait and function still provide unique and relevant insights (18). Laboratory assessments that focus on imitating the complexities of the community may best serve the research focus of enacted mobility. A combination of physical and cognitive tasks such as dual-task walking, changing the surface of the walking path, staircase climbing, obstacle navigation etc., should be a part of assessment. The performance on these tasks may translate more into explaining variability in enacted mobility, recorded by accelerometer and GPS.

5.3 Public health implications

Within each of these facilitators and barriers, some aspects are more modifiable, and some are less modifiable. For example, balance/gait training and lifestyle changes can be provided as an intervention, but the biology of ageing cannot be altered, yet. As another example, consider environmental determinants such as rain, temperature, season and other geographical aspects which are not directly in our control. However, ensuring walkable neighborhoods and maintaining sidewalk accessibility for older adults is a modifiable aspect. Negative sidewalk features have been identified as a barrier to mobility (93). This will reduce the risk of falling accidents (70) and also increase walking confidence. While policies that care about promoting physical activity levels among seniors should keep on improving walkability, those that are focused on car-dependent and low walkable environments could reinforce other forms of physical activity and socialization during cold months, for instance by reinforcing indoor activities at public or community centers. With the rising aging population, in near future, hospital facilities may not be sufficiently available for elderly for intimate examination of well-being. More so, the physical access to medical centers may be limited due to unexpected global situations like a pandemic as we are experiencing since 2020. Home-based remote monitoring of activity-space behavior can help in diagnosis and progression of a mobility related disability and in monitoring rehabilitation after occurrence of stroke (94,95), Parkinson's (96) and Alzheimer's (61,97), and may assist in detection of fall incidence.

5.4 Limitations of the review

Some studies assessed facilitators and barriers in detail but were not included here because they included individuals below our age thresholds (20,74). While this review uncovered a number of studies investigating physical, cognitive, psychosocial and environmental barriers and facilitators, there may be more domains that this review does not include. Domains related to body system functions such as brain networks, cardiovascular, cardiopulmonary, and immune systems are not included. It is important to note that all studies included have assessed the mobility data prior to COVID-19. Since the pandemic, mobility patterns have been drastically affected, especially in the older adult population (98,99). Nevertheless, this review article gives a detailed summary of the understanding of facilitators and barriers to mobility in older adults under normal circumstances.

6. Conclusion

Mobility is a complex concept and leveraging sensor and GPS technology can help in better understanding of associated barriers and facilitators. As the trend in global aging increases, tailoring programs and city planning toward mobility needs of older adults has become important. More research studies in domains outside physical functionalities are needed, since other modifiable factors – cognition, psychosocial elements, external environment, as well as socio-economic considerations play an important role for increased activity and participation of older adults in the community. In conclusion, future enacted mobility research needs to focus on assessing quality of walking in real-world, quantifying spatial movement of individuals, broader and inclusive of geography, culture and individual/neighborhood financial aspects and finally simulating real-life complexities in laboratory to understand the physical and cognition barriers simultaneously.

Statements and Declarations

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Figure 1. A framework for accelerometer and GPS data processing. (A) Experimental protocol (B) Acquisition of data (C) Data processing (D) Extraction of spatio-temporal measures.

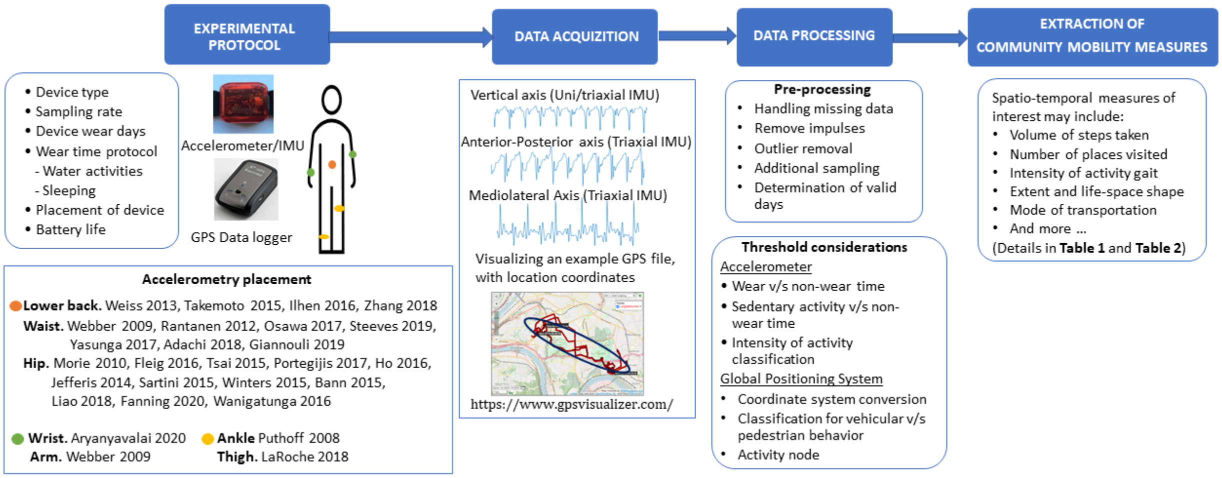

Table 1. Categorization of accelerometer-based measures and associated studies.

Accelerometer-based measures		
Volume	**Moderate-Vigorous Activity**	**Gait Quality**
Step count (34,35,37,39, 42–44,46,47,49,50,57,60–62,65,70,79,80, 87, 99)	Minutes(33,34, 38,42–44,46,48–50, 52,57,65,69,79,80)	Step and stride time (37)
		Smoothness (37)
Walking bouts count (37)	METs[a] (40,53,57,64,85,91)	Complexity (44,46)
Mean daily activity counts (33,43,62)	Accumulation (52,55)	Entropy (37,46)
Transitions from high-low activity (62)		Acceleration range (37,38)
Up-down transitions (41,56)		Cadence (38,39,44)

Notes:

[a]METs: Metabolic equivalents in energy.

Table 2. Classification of GPS acquired spatio-temporal measures of enacted mobility and associated studies.

Spatial measures			**Temporal measures**
Count	**Extent**	**Shape**	**Duration**
Activity nodes (59,74,82)	Total distance (34,45,63,74)	Min. convex polygon (71,74,82)	Time out of home (59)
Pedestrian trips (21,58)	Vehicle distance (58,100)		Walking time (21,59)
Vehicular trips (58)	Pedestrian distance (58,59)	Life-space circularity and compactness (71,82)	Time walking for transport (70)
Total trips (45)	Distance travelled per episode (21)		Time spent driving (21)
Driving episodes (21)	Ellipse standard deviation (71,82)		Vehicle time (58,100)
Walking tracks (59)	Convex hull – life space area (34,63)		Time spent per activity node (74)
	Maximum action range (34,45,59,63)		
	Daily path area (71,82)		

Notes:

Activity nodes: number of places visited (sometimes a threshold on the amount of time spent is considered for the node to qualify as an activity node)

Ellipse standard deviation: measures the directional distribution of a series of GPS points

Convex hull -life space area: Area of convex hull containing all GPS coordinates

Maximum action range: maximum distance travelled from home

Daily path area: Builds buffers (generally 200m) around all of individual’s trips to give geographic extent of travel

Minimum convex polygon: Convex polygon (of minimum edges) around set of points containing all GPS coordinates Life space circularity/compactness: measure of how circular a polygon of activity space is; can be indicative of capacity of neighborhoods to provide opportunities to carry day-to-day activities and role of driving

Table 3. Association of accelerometry quantified enacted mobility with facilitators and barriers - physical function, cognitive function, psychosocial factors and external environment.

Category	**Laboratory Assessment**	**Accelerometry**		
		Volume	**Moderate-Vigorous Intensity**	**Gait Quality**
a. Physical function				
Gait	Walk speed	+ (33),+ (34), o (36), o (40),	+ (35), + (36), + (34), o (40)	+ (37), + (38) + (39)
Walking Endurance	Aerobic capacity (VO2max)	+ (33), o (41)	o (41)	
	400m Walk Test		+ (38)	+ (38), + (39)
	5 Minute Walk Test		+ (35)	
	6 Minute Walk Test		+ (55)	
	10 Minute Walk Test	+ (42)	+ (42)	
	Walking effort	+ (41)	+ (41)	
Balance	One leg standing	+ (42) , + (45)	+ (35)	+ (37)
	Balance and Mobility Scale			+ (44)
Transfers	Five Times Sit to Stand Test		+ (55)	
Fall history	Faller/non-faller	+ (47), + (48), + (49), o (37)	+ (47), + (48)	+ (37), + (46)
Combined function assessments				
Performance-based	Short Physical Performance Battery	+ (33), + (50), + (51)	+ (50), + (52), + (53)	+ (38)^
	Timed Up and Go	+ (54), + (42), + (34), + (45), o (56)	+ (35), + (54), + (55), + (34)	+ (37)
Self-reported	10 item physical function		+ (57)	
	Physical functioning interview		+ (43)	

b. Cognitive function			
Executive function	Trail Making Test	+ (34)	
	Digital Symbol Code		+ (62)
	n-back (1 and 2 back)		+ (62)
	Task switching paradigm		+ (62)
	Erickson Flanker Task		+ (62)
Planning ability	HOTAP.A		+ (34)
Visuospatial attention	Attention Window Test		+ (34)
Spatial memory	Grid Span Test	o (45)	+ (34)
Literacy/IQ	National Adult Reading Test	o (45)	o (56)
Episodic memory	Hopkins Verbal Learning Test		+ (62)
c. Psychosocial factors			
Psychological			
Depression	Geriatric Depression Scale	+ (34)	+ (34), + (64)
Negative affect	Momentary negative affect	+ (65)	
Anxiety	State-trait anxiety inventory	+ (45)	
Confidence and attitudes			
Walking confidence	Gait Efficacy Scale	+ (34)	+ (34), + (68)
Balance confidence	Activities-specific Balance Confidence	+ (34)	+ (34)
Fear of falling	Fall Efficacy Scale	+ (45), + (48)	+ (48), +(40)
Attitude towards walking	Walking-like scale		+ (68)
	Physical activity intentions	+(69)	+(69)
Social network	Luben Scale		+ (64)
	People in network	+ (45)	
Ageism	Ageism survey scale	+ (34)	+ (34)
Personality	Personality test	+ (34)	+ (34)

d. Environmental factors			
Weather	Temperature	o (34)	+ (70), o (34)
	Rain	+ (69)	+ (69), + (70)
Neighborhood	Walkability	+ (51)	+ (53)*
	NEWS-SNQL		+ (68)
	Satisfaction survey		+ (72), + (68)
	PENFOM	o (51)	+ (64)
	Facilities	+ (64)	

Notes: (+) Association in expected direction (o) No association found

^ association found for acceleration range but not cadence

HOTAP: Attention and planning assessment scale

NEWS-SNQL: Neighborhood Quality of Life Survey

PENFOM: Perceived environmental facilitators for outdoor mobility

*mediating effect of high income, high walkable neighborhood in association between physical functioning and activity

Table 4. Association of GPS quantified enacted mobility with facilitators and barriers – physical function, cognitive function, psychosocial factors and external environment

Category	**Laboratory test**	**GPS**			
		Space		**Time**	
		Count	**Extent**	**Shape**	**Duration**
a. Physical function					
Walking endurance	400m Walk Test	+ (58)*	+ (58)*		
Balance	One leg standing	+ (45)	+ (45)		
Combined function assessments					
Performance-based	Short Physical Performance Battery	+ (58)* + (45)	+ (58)* o (45)		+ (58)*
Self-reported	Timed Up and Go	+ (21)	+ (21), + (59)		+ (21), + (59)
	Short form survey -36				
b. Cognitive function					
Executive function	Trail Making Test A and B	o (58)	+ (59), o (55)		o (58)
Planning ability	HOTAP		+ (63), + (34)		
Visuospatial attention	Attention Window Test		+ (63), + (34)		
Spatial memory	Grid Span Test	+ (45)	+ (63), + (34), + (45)		
Working memory	Digit Span Test (forward and backward)		+ (59)		
Episodic memory	Word list learning, word list recall, logical memory-I, logical memory-II	+ (59)	+ (59)		+ (59)
c. Psychosocial factors					
Psychological					
Depression	Geriatric Depression Scale	+ (58)*	+ (58)*		+ (58)*
	Geriatric Depression Scale (Short version)				+ (59)

Negative affect	Positive and negative affect scale	o (21)	o (21)		o (21)
Anxiety	State-trait anxiety inventory	o (45)	o (45)		
Confidence and attitudes					
Fear of falling	Fall Efficacy Scale	+ (58)**, o (45)	+ (58)*, +(34), o (45)		+ (58)*
Ageism	Ageism survey scale		+ (34)		
Quality of life	Life satisfaction 1-10 scale	+ (21)			+ (21)
d. Environmental factors					
Weather	Temperature		o (34)		+ (70)
	Rain				+ (70)
Neighborhood	Walkability			+ (71)^	

Notes: (+) Association in expected direction, (o) No association found

* association only with pedestrian-based measures

** association only with vehicular trips

HOTAP: Attention and planning assessment scale.

^Larger activity space for less walkable neighborhood