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International Journal of Gerontology 8 (2014) 49–55

Contents lists available at ScienceDirect

International Journal of Gerontology

journal homepage: www.ijge-online.com

Review Article

Managing Elders' Wandering Behavior Using Sensors-based Solutions: A Survey☆

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ARTICLE INFO

Article history:
Received 17 May 2013
Received in revised form
1 July 2013
Accepted 29 August 2013
Available online 6 June 2014

Keywords:
people with dementia,
wandering behavior,
wandering detection,
wandering evaluation

SUMMARY

Wandering is one of the most frequent, problematic, and injurious behaviors of elderly people with dementia. It often leads to negative consequences such as falling and getting lost. With increasing proliferation of sensing, communication, and computing techniques, inexpensive technological solutions have been developed to tackle problems associated with wandering. In this article, we review field research and technological solutions on wandering in the context of assisted living for the elderly. Specifically, we present the most cited definition and classification for wandering proposed in wandering behavior research. We further examine existing solutions for managing wandering in terms of our proposed categorization of wandering research, namely event monitoring-based wandering discovery, trajectory tracking-based wandering detection, and location combined with Geofence-based prevention of wandering-related adverse results. Based on the definition, categorization, and the state of the art, we discuss the major research challenges and future directions in detecting wandering locomotion in different settings. To the best of our knowledge, this is the first survey on wandering and technological solutions in this niche area of ambient assisted living.
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1. Introduction

Wandering is among the most problematic, frequent, and dangerous behaviors of people with dementia (PwD)[1], accounting for 15–60% of individuals with a clinical diagnosis of dementia and related impairments[2–6]. It includes a variety of behaviors[7], which are often originated from diverse factors[4,8]. A lot of research has revealed that the frequent wanderers are more likely to experience adverse events such as falling, elopement, getting lost, and emotional distress[9–16]. Furthermore, wandering is also the main reason of early institutionalization[17,18]. Traditional methods to prevent the PwD from wandering include imposing physical restraints and medication. Because of the physical or psychological problems caused by physical restraints[19] and the side effects of neuroleptic drugs[20], traditional methods are not always effective for protecting wanderers, especially for those who are prone to falling or unsafe wandering[21]. Alternatively, nonpharmacological intervention has been recommended to manage rather than prevent wandering, highlighting a shift from prevention toward assisting safe walking[22–24]. The main methods of nonpharmacological intervention include[25] motion tracking, behavioral intervention, cognitive rehabilitation, and design/modification of living environments. With the increasing proliferation of sensing, communication, and computing techniques, localization and monitoring of human movement become not only technically available, but also financially viable in recent years. This makes it possible to develop sensors-based solutions in managing wandering behavior. In the behavioral science area, researchers developed tools to gain an in-depth understanding or to explore new characteristics of wandering based on fine-grained observations from sensors, such as the geographical patterns of wandering movement proposed by Martino-Saltzman et al[26]. In the assisted living area, researchers

☆ Conflicts of interest: The authors have no conflicts of interest to declare.

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http://dx.doi.org/10.1016/j.ijge.2013.08.007
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developed systems that provide assistive services to improve independence and ensure safety of the PwD, by detecting wandering trajectories or preventing them from walking out of predefined safe zones based on real-time sensor readings, such as the commercial off-the-shelf global positioning system (GPS) shoes[27] and the in-home Escort System, Massachusetts Institute of Technology, Boston, USA[28]. Wandering behavior of the PwD has been the topic of several review articles. For instance, Lai and Arthur[29] provide a review on the characteristics and classifications of wandering behavior, the extent of the related problem, the profile of wanderers, and intervention strategies. Halek and Bartholomeyczik[30] provide a number of different definitions, descriptions, and taxonomies for the term wandering. Robinson et al[25] reviewed the effectiveness and cost-effectiveness of nonpharmacological interventions (excluding subjective barriers) in terms of wandering prevention for the PwD. All the existing reviews on wandering either focus on definitions and classifications or on nontechnological interventions to wandering behavior. In this article, we intend to review existing work on technological solutions to managing wandering behavior. Specifically, after an introduction of definition and classification for wandering in field studies, we classify existing work into three different categories according to the applied techniques. For the work in these categories, we present details about the target research objectives, the adopted devices (sensors), and the obtained main results. Next, we discuss research challenges and directions for developing technological solutions to tackling wandering behavior of the PwD. To the best of our knowledge, this is the first survey that simultaneously reviews definition, classification, and technological solutions for managing wandering of the PwD in the assisted living area. The rest of this article is organized as follows: first the method used to search literature is discussed, followed by the definition and the classification of wandering behavior. Existing work is categorized and analyzed, and research challenges and future directions are presented.

2. Literature search method

This review is limited to published work that has undergone scientific peer review and the off-the-shelf devices that have been reported on websites. Our search was restricted to articles written in English in journals, chapters of periodicals, and conferences.

Keyword searches were conducted in PubMed, ISI Web of Science, IEEE Xplore, Springer LINK, Elsevier SDOL, Google Scholar, and Google Search using the search string ("wandering" OR "wandering behavior" OR "elopement" OR "getting lost") AND ("detection" OR "recognition" OR "evaluation") AND ("elderly people" OR "people with dementia" OR "people with cognitive impairment"). A total of 116 distinct articles and 10 different reports on devices have been found. After duplicates were eliminated, 65 articles were read in full length by at least two authors. Furthermore, irrelevant articles and reports were removed after reading in full length. In case of any disagreement about inclusion, the respective article was read by a third author who decided about its inclusion or exclusion. The final 28 systems and methods in 36 articles and eight off-the-shelf devices were included in the analysis. Fig. 1 provides the flowchart of searching literature from different sources.

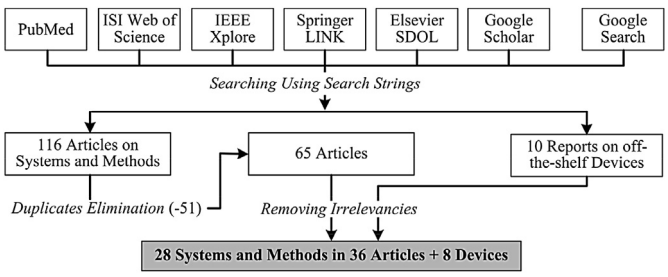

Fig. 1. The flowchart depicting searching of literature from different sources.

3. Wandering behavior: Definition and classification

For completeness, this section provides the most cited definition and classification for wandering behavior. Although several attempts have been made to define wandering behavior[31–34], there is no widely accepted definition thus far because wandering behavior is very complex and occurs for a number of reasons. We present the latest definition, proposed by Algase et al[35], which defines wandering as follows.

A syndrome of dementia-related locomotion behavior having a frequent, repetitive, temporally disordered, and/or spatially disoriented nature that is manifested in lapping, random, and/or pacing patterns, some of which are associated with eloping, eloping attempts, or getting lost unless accompanied.

Different attempts for the classification of wandering behavior exist[36–39]. One of the most cited classification proposed by Martino-Saltzman et al[26] categorizes wandering movement of the PwD into three different spatial categories: (1) *Pacing*: back and forth movement between any two points (i.e., physical locations); (2) *Lapping*: circuitous movement revisiting some points sequentially along a path; and (3) *Random*: haphazard movement without repeating points in a traveling sequence.

Additionally, Algase[40] introduced temporal factor into the aforementioned spatial patters and represented wandering movement as spatiotemporal locomotion. The locomotion refers to the rhythmical movements consisting of two phases: walking and nonwalking. During the walking phase, a PwD would wander following the pacing, lapping, and random pattern. After every walking phase, there will be a nonwalking duration, which may differ from person to person and be closely related to the environmental situations.

4. The state of the technological solutions to wandering

There are two main research objectives pertaining to wandering of the PwD: wandering evaluation and wandering detection. Wandering evaluation targets recognition, evaluation, and testing of wandering movements to find new patterns and characteristics of wandering behavior based on offline analysis of trajectory data collected from sensors deployed in indoor environments. Wandering detection focuses on design, development, and deployment of assistive systems to provide the PwD safety assurance based on online observations of sensors deployed in indoor or outdoor settings. Three types of key techniques were applied in existing work for wandering research: event monitoring, trajectory tracking, and localization combined with Geo-fence technique. Table 1 outlines existing technological solutions on 28 different systems or methods, and Table 2 lists the eight off-the-shelf devices.

Now, we present existing work by separating into three different categories according to the applied techniques.

4.1. Technological solutions

4.1.1. Event monitoring-based wandering discovery

The event monitoring technique collects sequences of events or activities, aiming to discover the rhythmical repetition of events that may correspond to wandering behavior.

Doughtyt et al[41] proposed a system to provide monitoring and support for the PwD living alone in their own homes. A number of

Table 1
Technological solutions on systems and methods for managing wandering of PwD reported in the articles.

Article		Pub year	Country /Region	Physical Location	Objective	Tech.	Used sensors	Exper.[g]
ID	Type							
41	Conf.	1998	UK	Own homes	Design/ Development/	Event Monitoring	Piezosensor, PIR[a]	N
42		2011	Japan	Care facilities	Deployment of Assistive Systems		UWB-IR[b]	Y
43		2002	Japan	Hospitals			Contact sensors	Y
44		2006	Singapore				passive-RFID[c]	N
45	Jour.	2007	USA	Own homes			Air pressure bag	Y
26		1991	USA	Nursing homes	Recognition/ Evaluation/	Trajectory Tracking	Ankle tags	Y
46		2003	USA		Testing of Wandering		Biomechanical	Y
47–51		2008–2012	USA				RFID	Y
28		2011	USA	Own homes	Design/ Development/		Optical sensors	Y
53	Conf.	2011	Singapore		Deployment of Assistive Systems		Detecting algorithm	Y
54		2012	China	Outdoor			GPS[d] sensor	Y
55		2004	USA					Y
57,58	Jour.	2010	Taiwan					Y
59		2006	Singapore				Wi-Fi devices	N
60	Conf.	2007	USA				Camera	N
61	Jour.	2004	Japan	Geriatric homes			Robot	N
62	Conf.	2011	Singapore	Outdoor		Location & Geofence	GPS/802.11/GSM[e]	N
63		2010	USA				GPS, contextual	N
64,65		2010, 2011	Ireland				GPS sensor	N
66,67		2012	Canada				GPS and contexts	N
68	Report	2012	Mexico	Indoor/Outdoor			Wandering model	N
69,70	Conf.	2004, 2011	Japan	Outdoor			GSM, microphone	N
71	Jour.	2005	UK				GPS sensor	N
72	Conf.	2000	Japan				GPS sensor	Y
73	Jour.	2006	Taiwan	Indoor/Outdoor			GPS sensors & button	N
74	Conf.	2009	Spain	Outdoor			GPS sensor, Compass	N
75		2010	UK				GPS sensor	N
79	Jour.	2004	UK	Hospital/Homes			RF[f] electronic tagging	Y

[a] Passive infrared.
[b] Ultrawide-band impulse radio.
[c] Radiofrequency identification.
[d] Global Positioning System.
[e] Global System For Mobile Communication.
[f] Radiofrequency.
[g] Whether the system or method has been tested (Y) or not (N).

noninvasive sensors were used to measure daily activities and habits. Wandering is countered by applying an event-based approach, whereby an event is defined as the opening/closing of doors and drawers, transfers from a chair, toilet, or bed, and movements across/into rooms. Any action that is repeated within a period of 5 minutes will produce a double count. Ota et al[42] investigated ultra-wide band impulse-radio (UWB-IR) sensors to monitor residents' sleeping in bed, sitting up in bed, falling, wandering in the room, and going in/out of the door. Their experimental measurements were conducted in care facilities and the detection performance regarding the defined state was investigated in various scenarios. Experimental results showed a detection rate of more than 95%. Masuda et al[43] developed an unconstrained monitoring system that notifies caregivers when wandering occurs. The system consists of a set of mat-shaped step sensors that detect contact of the feet on the floor; a foot switch is installed next to the patient's bed. When wandering is detected, caregivers will be personally notified by phone. This system has been tested on three patients at Asuke Hospital in Aichi, Japan. A 4-weeks clinical trial at a hospital showed that the system detected 30 cases of wandering for all patients with dementia who frequently wandered in hospital wards. Jit et al[44] proposed a passive radiofrequency identification (RFID)-based system for activity monitoring and patient tracking in the hospital, aiming to reduce the number of falls and the cases of wandering from the ward. To track wandering behavior, a simple sequence matching technique was used to predict the next event, e.g., leaving/entering doors. An action that leads to an event with high probability can predict if the patient is going to wander from the hospital premises. CareWatch, University of Florida, Gainesville, USA[45] is a care system designed for use in homes of the PwD to prevent unattended home exits and to improve caregiver sleep. A bed occupancy sensor consisting of an airbag placed between the box springs and the mattress in the user's bed was developed to report the presence of a person in bed. A consecutive 2-week trial demonstrated that the proposed system obtains no false negatives and less than 10% false positives in comparison with total number of bed occupancy alarms.

4.1.2. Trajectory tracking-based wandering detection

The trajectory tracking technique is used to acquire fine-grained motion trajectories, enabling the detection of spatiotemporal wandering trajectories based on the wandering patterns.

Martino-Saltzman et al[26] investigated travel patterns of the PwD based on data acquired from electronic ankle tags worn by participants. In their experiments, an automatic detection system-activated video recording of travel activity in real time to record the ground truth, and four different patterns of direct, pacing, lapping, and random movement have been found from more than 10,000 recordings of 40 participants. Among these patterns, the direct pattern is normal and the remaining patterns link to wandering behavior. A similar work proposed by Algase el al[46] uses commercial off-the-shelf biomechanical devices to capture movements of residents with dementia in nursing homes. Wandering behavior is determined by either counting the number of steps made by residents (StepWatch, National Institute of Child Health and Human Development, Rockville, USA and StepSensor, TippToes Ltd, Tippeary, Ireland) or measuring locomotion in three-dimensional spaces (Actillume, PHILIPS, Eindhoven, Netherlands

Table 2
Technological solutions on the off-the-shelf devices for preventing wanderers from walking out of defined safe zones reported in technical reports and on websites

Article	Year	Source	Carrier	Technology
76	2009	Technical report	Watch	GPS
77	Accessed April 10–15 2013	Website at http://www.mightygps.com/wherify.htm	Watch	
80		Website at http://www.omnilink.com/	Ankle bracelet	
81		Website at http://www.istsec.fi/eng/Etuotteet.htm	Watch	
27		Website at http://www.gpsshoe.com/	Shoe	
82		Website at http://edition.cnn.com/2009/HEALTH/06/10/gps.shoes/	Shoe	
83		Website at http://www.tunstall.co.uk/solutions/lifeline-vi	Dedicated device	
84		Website at http://www.iloctech.com/	Watch	

and TriTrac-R3D, The Consortium to Lower Obesity in Chicago Children (CLOCC), Chicago, USA). The authors found that StepWatch sensor is particularly effective in assessing the amount of wandering behavior. A series of studies focused on path tortuosity has been performed by Kearns et al[47–51] using RFID devices in common indoor living spaces. Path tortuosity is defined as the number of changes in directions of successive movement paths, and measured by leveraging fractal D (fractal dimension) technique[52]. The value of fractal D ranges from 1, where a path follows a perfectly straight line, to a value of 2, where the path is tortuous (in line with the random pattern[26]). Their experimental results[50] correctly classified all but two residents with dementia, and achieved a sensitivity of 0.857 and a specificity of 0.818.

The Escort system[28] is designed to protect wander-prone residents from experiencing negative events. The mesh-networked badges carried by users can sense location and communicate with a central server. Location data are obtained from a 'talking lights' optical location setup that uses ordinary light fixtures and other light sources as location beacons. Caregivers were responsible for keeping devices charged, attaching them to residents' clothing in the morning, and removing them at night. This iteration of the study ran for 12 weeks from September 1 until November 22, 2008. Vuong et al[53] proposed an algorithm to detect wandering movements based on the geographical patterns[26]. Both temporal and spatial factors were used to detect the lapping and pacing walking, whereas the random walking is inferred as the person moves from point A to B following a nonoptimal route. All other walking behaviors are considering direct movement.

Focusing on outdoor wandering of the PwD, Lin et al[54] investigated real-time detection of pacing and lapping movements from users' GPS traces. Based on the spatial wandering patterns[26], a data-driven method was proposed to examine and count turning points in any ongoing trajectory. The angular sum of the found turning points is chosen as a basis to determine whether a trace is lapping or pacing. Experimental results showed that the proposed method is workable in detecting lapping and pacing wandering locomotion. Opportunity Knock, University Of Washington, Seattle, USA[55] is an assistive tool for people with mild cognitive impairment who are prone to experience path deviations, such as getting on the wrong bus. In this system, a GPS-equipped mobile phone carried by the person is used to acquire and send location information to the remote server. An inference engine running on the server side is responsible for detecting abnormalities based on a transportation mode[56] learned from users' transportation history. If an anomaly is detected by comparing it to an individual's transportation mode, the subsystem on the phone side will play a sound similar to that of a knock on a door to attract the user's attention. Chang[57] investigated to detect deviations from traveling trajectories for cognitively impaired workers. Rather than a model-based approach, in this work, each incoming GPS point is compared in real time with the normal paths to find possible path deviations. Some pilot studies have been conducted among adults with different impairments. Experimental results also showed the feasibility of their proposed method. Nevertheless, the work did not state how to obtain a normal path. Based on this finding, Chang and Wang[58] developed a mobile location-based network system to improve and optimize services for cognitively impaired workers.

Additionally, other work has also been developed to directly or indirectly address wandering behavior, including Lim et al's WiFi localization system[59], Chen et al's camera-based monitoring solution[60], and Tamura et al's motorized toy dog[61].

4.1.3. Location-based prevention of wandering-related adverse events

The localization combined with Geofence technique is used to localize wanderers in outdoor environment, targeting the prevention of elopements or boundary transgressions.

Vuong et al[62] investigated using mobile devices enabled GPS/802.11/cell-tower as personal location sensors to monitor persons who are prone to wandering. Location data obtained from mobile device will be analyzed by the preinstalled inference software to recognize deviations from the normal traces and detects emergencies that may require immediate attention. iWander, Florida State University, Tallahassee, USA[63] is a phone-based mobile application using contextual information (e.g., the time of day, weather conditions, stage of dementia, user feedback, and GPS location data) to estimate the probability that the user is wandering. This system can automatically take actions to help the patient navigate to a safe location, notify caregivers, and provide the current location. Wan et al[64,65] studied the issues of related to managing wandering behavior among patients with early-stage Alzheimer disease. Their OutCare, Institute of Technology Carlow, Carlow, Ireland[64] system uses embedded agent paradigm to analyze behaviors of patients and significant deviations from daily behavior signature based on GPS-based tracking capabilities. Hoey et al[66,67] investigated incorporating background and contextual factors to detect risky wandering behavior and decide the type of required assistance. For wandering detection, a person's location (i.e., latitude and longitude) was converted into a set of discrete locations and was implemented based on a simple model: 'home' means he or she is within sight, 'close-to-home' means he or she can find his or her way back easily, and 'far-from-home' means he or she may have trouble finding his or her way back. An ontological model is proposed by Rodríguez et al[68] to support interventions for wandering. The ontological model extended their Ambient Augmented Memory System (AAMS) to support caregiver to implement interventions based on the external memory aids provided by mobile devices. Ogawa et al[69] investigated the use of mobile phones and Global System for Mobile Communication cellular techniques to locate wandering of PwD. When a PwD is away from the predefined safety zone, the system automatically informs the caregivers according to the phone terminal identification, and sends the person's location to caregivers by email. To sense the user's surroundings, a miniature microphone was added to collect environmental sounds for the purpose of a more accurate localization in their recent work[70]. A similar work done by

Miskelly[71] used GPS techniques to locate the PwD; a mobile phone with GPS acquires the coordinates of the phone, which can pinpoint the mobile phone user's location with an accuracy of 5 m. If a caregiver or relative needs to know a patient's whereabouts, a 24-hour control center can be called. Shimizu et al[72] developed a system that can locate a wandering individual to a physical range of 100-200 m. The system was tested under various conditions such as bad weather and close proximity of tall buildings. Lin et al[73] developed a straying prevention system including indoor residence and outdoor activity monitoring, emergency rescue services, and remote monitoring. The indoor monitor detects movements between some areas within the home environment, and the outdoor activities are monitored in a predefined activity area. In case of an emergency, the PwD can activate an emergency button to send a message to a call center where the situation, location, and geographical information are analyzed and relayed to care providers, search teams, and family members. In addition, there are some systems that can also provide similar monitoring functions, including the social network-based assisting system[74] and the Take Me Home-Service in European Union COGKNOW project[75].

Digital Angel, Digital Angel Corporation, New London, USA[76] is a watch-like wandering monitoring device worn by users. The device comes with a separate clip-on pager unit that uses GPS software. The system will send an e-mail alert to caregivers when a patient has passed the predesignated area. Wherify Wireless, Mightygps.com, Toronto, Canada[77] is a device similar to Digital Angel that was originally developed for children but is now used for PwD to detect elopements. An embedded GPS tracking system developed by GTX Corp and Aetrex Worldwide can pinpoint a person's whereabouts at any given moment in time by embedding a GPS sensor into a person's shoes. Blackburn[78] and Miskelly[79] have verified that boundary alarms or electronic tagging with bracelets and monitoring stations are effective, reliable, and successful to detect wandering. Commercially marketed products such as OmniLink's Solution, OmniLink, Alpharetta, USA[80], Vivago WristCare, Vivago, Helsinki, Finland[81], GPS shoes, GTX Corporation, Scottsdale, USA[27,82], Lifeline Vi, Tunstall Healthcare Group Limited, Yorkshire, UK[83], and iLOC' GPS Locator, TRi LOC, Quebec, Canada[84] can be used to localize the position of the wandering individuals or prevent them from walking outside a safe space.

4.2. Discussion

As can be seen from existing work mentioned previously, different solutions have been proposed to tackle wandering of the PwD. Overall, these existing research efforts are characterized by the following features:

First, in comparison to assistive systems, the technological solutions for evaluating wandering are relatively fewer and simpler. Furthermore, these solutions were obtained in experimental environments or under special conditions. Translating these findings and others acquired via questionnaire [e.g., Algase Wandering Scale (AWS)[37,85]] to support detection of wandering locomotion in real time is still challenging because many of them are multidimensional and not easily acquired when sensors are used in daily life. Second, for indoor assistive applications, both the event monitoring and the trajectory tracking-based methods were applied. Nevertheless, most of these techniques were implemented on sensors deployed in the living setting or carried by PwD themselves. In recognition of the fact that many people with dementia or other impairments always have impaired memory, the effectiveness and usefulness of these techniques may still be problematic for the PwD, especially for those living alone. Third, for tackling outdoor wandering behavior, most existing efforts focused on preventing wandering-related negative events rather than detecting fine-grained wandering trajectory. Even if there are no serious negative consequences, the hyperactivity caused by long-term continuous wandering mobility may lead wanderers to experience strength consumption and falling, bringing indirect impact on the health of the wandering persons. Fourth, most of the reported systems are still in the prototype stage, and system test and evaluation were conducted on small user groups. Large-scale user trials and experimental results are not yet available.

5. Research challenges and future directions

5.1. Large-scale data collection of wandering behavior

Because of the diversity of wandering behavior, large-scale data collection under different conditions with different devices is needed. However, people who wander following some pattern may have different manifestations because of the significant interpersonal difference, and a specific individual wandering in different settings usually causes changed forms of these patterns. Thus, how to collect large-scale data of fine-grained wandering locomotion under different settings using different sensing techniques is the first challenging issue. A possible alternative is to develop a service platform that integrates different heterogeneous facilities and infrastructures, such as cameras or infrared and radio sensors indoors, and GPS devices outdoors.

5.2. Personalized user wandering behavior model and detection algorithms

Despite those available general patterns[26,40], wandering locomotion may have different temporospatial characteristics for different persons in same environmental conditions and a particular person under different environmental conditions. Moreover, in real life, there may be no clear boundary between wandering locomotion and wandering-like but normal walking. Therefore, a personalized user wandering recognition model and reliable wandering detection algorithm with low false positive results is specifically needed. Taking existing spatiotemporal wandering patterns and some established tools[37,85] as the basis, a personalized model can be enabled by combining individuals' health conditions, wandering history and environmental factors.

5.3. Correlation between wandering and its related factors

A quantitative measure of corelation between wandering behavior *per se* and its related factors is very crucial for the in-depth analysis of wandering behavior in field research. As wandering behavior occurs for a variety of reasons and is tightly linked to individuals' health status, wandering history and environmental situations, the measures, criteria, and evaluation of corelation between wandering and the possible related factors become another research challenge. Statistical and data mining methods can be applied to study and extract the hidden corelation and quantitative dependence from large-scale wandering data collected from individuals and group.

5.4. Human computer interaction design for training and guiding the PwD to mitigate possible issues

From the perspective of assistive living, the ultimate goal is to mitigate the possible issues caused by wandering behavior. As such, an appropriate training and guiding mechanism may be beneficial to slow down or defer progression of wandering behavior as far as possible. Human computer interaction-based design will play an important role to effectively intervene wandering behavior with an

easy-to-use and user-friendly manner when the PwD wander in different settings. Nevertheless, a design that integrates training and guiding functions to persistently affect wandering persons in a positive way remains a challenge in real applications.

6. Conclusion

Wandering is one of the most frequent, problematic, and injurious behaviors for PwD, which is closely associated with adverse events such as falling, elopement, and getting lost. In this work, we have conducted a technological review about the research efforts related to wandering detection and evaluation for PwD. Specifically, we introduced the different definitions and proposed a classification structure. We reviewed detection and evaluation techniques for wandering with the special emphasis being placed on the three wandering behavior patterns (e.g. pacing, lapping, and random walking) and three technological solutions, i.e., event monitoring-based wandering discovery, motion trajectory tracking-based wandering detection, and localization combined with Geo-fence based prevention of wandering-related adverse results. We further discuss the research challenges and future directions in this emerging research field.

Acknowledgments

This work was partially supported by the National Natural Science Foundation of China (No. 61332013).

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