Sensor Monitoring to Measure and Support Daily Functioning for Independently Living Older People: A Systematic Review and Road Map for Further Development

Margriet C. Pol, MSc, Soemitro Poerbodipoero, MSc,* Saskia Robben, MSc,† Joost Daams, MA,‡ Margo van Hartingsveldt, MSc,* Rien de Vos, PhD,§ Sophia E. de Rooij, MD, PhD,‖ Ben Kröse, PhD,† and Bianca M. Buurman, RN, PhD‖*

OBJECTIVES: To study sensor monitoring (use of a sensor network placed in the home environment to observe individuals' daily functioning (activities of daily living and instrumental activities of daily living)) as a method to measure and support daily functioning for older people living independently at home.

DESIGN: Systematic review.

SETTING: Participants' homes.

PARTICIPANTS: Community-dwelling individuals aged 65 and older.

MEASUREMENTS: A systematic search in PubMed, Embase, PsycINFO, INSPEC, and The Cochrane Library was performed for articles published between 2000 and October 2012. All study designs, studies that described the use of wireless sensor monitoring to measure or support daily functioning for independently living older people, studies that included community-dwelling individuals aged 65 and older, and studies that focused on daily functioning as a primary outcome measure were included.

RESULTS: Seventeen articles met the inclusion criteria. Nine studies used sensor monitoring solely as a method for measuring daily functioning and detecting changes in daily functioning. These studies focused on the technical investigation of the sensor monitoring method used. The other studies investigated clinical applications in daily practice. The sensor data could enable healthcare professionals to detect alert conditions and periods of decline and could enable earlier intervention, although limited evidence of the effect of interventions was found in these studies because of a lack of high methodological quality.

CONCLUSION: Studies on the effectiveness of sensor monitoring to support people in daily functioning remain scarce. A road map for further development is proposed. **J Am Geriatr Soc 61:2219–2227, 2013.**

Key words: sensor monitoring; community-dwelling older persons; daily functioning; systematic review; functional status

The maintenance of daily functioning is important for allowing older people to live independently at home. Daily functioning can be divided into activities of daily living (ADLs) (e.g., bathing, dressing, grooming, toileting, continence, transferring, walking, eating) and instrumental activities of daily living (IADLs) (e.g., using the telephone, traveling, shopping, preparing meals, doing housework, managing medications, handling money).[1] Many older people have two or more chronic diseases,[2] and they might experience increasing functional limitations that affect their ability to perform ADLs and IADLs.[3,4] The way older people perform ADLs and IADLs provides a measurement of their functional status and ability to live independently at home.[5]

Several methods are used to measure or evaluate ADLs and IADLs. These are often limited to measuring daily functioning using self-report such as with the modified Katz ADL scale[1] or a more-objective measurement method (e.g., the Assessment of Motor and Process Skills).[6] Generally, these assessments are conducted as a small series of measurements at a few time points. More recently, new technologies, such as sensor monitoring, have been developed to measure the daily functioning of older people continuously.

From the *Research Group of Participation and the Environment, Hogeschool van Amsterdam, University of Applied Sciences, †Research Group Digital Life, Hogeschool van Amsterdam, University of Applied Sciences, ‡Medical Library AMC, Academic Medical Center, University of Amsterdam, §Department of Clinical Epidemiology and Biostatistics, Academic Medical Center, University of Amsterdam, and ‖Section of Geriatric Medicine, Department of Internal Medicine, Academic Medical Center, University of Amsterdam, Amsterdam, the Netherlands.

Address correspondence to Margriet C. Pol, Hogeschool van Amsterdam, University of Applied Sciences Amsterdam, Room B1.22, Tafelbergweg 51, PO Box 2557, 1000 CN Amsterdam, the Netherlands.
E-mail: m.c.pol@hva.nl

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Sensor monitoring is based on sensor network technologies and is used to monitor a person's behavior and environmental changes.[7] Sensor monitors can be wearable and wireless. Wearable sensors, attached to a person or his or her clothes, are often used to measure such vital signs as blood pressure and heart rate;[8] to measure human physical movement, such as walking, sitting transitions, and physical exercises; and to monitor rehabilitation progress.[9] Wireless sensor networks, which consist of a combination of simple sensors installed in fixed locations are placed in the home and register in-home movement. The sensor data are processed in a computer that infers the daily functioning that participants perform in their homes.[7]

The use of wireless sensor monitoring enables the measurement of daily functioning and facilitates the early detection of changes in functional status by observing a certain daily activity pattern.[10] A daily activity pattern gives detailed information about which ADLs and IADLs are performed during a regular day and the sequences and variations of these activities.[11] The sensor data are usually analyzed using data mining and machine-learning techniques to build activity models and further enable the measure daily functioning and daily activity patterns.[7] With data mining from wireless sensor data, it is possible to determine most ADLs (e.g., bathing, dressing, toileting, transferring, walking and eating) and some IADLs (e.g., using the telephone, preparing meals, managing medications, doing housework) performed in the home. It is not possible to measure handling money, shopping, and traveling. Specific algorithms are available to detect ADLs and IADLs and to detect uncommon patterns and therefore might enable early intervention.

Although several studies have examined the application and evaluation of sensor monitoring, most have focused on the use of wearable sensors and the technical investigation of sensor monitoring or are conducted in laboratory settings.[12] No systematic review was found in the literature focusing on the application and effectiveness of wireless sensor monitoring for older persons living independently at home.

The aim of this systematic review was therefore to study the application and effectiveness of sensor monitoring to measure and eventually support daily functioning in older people living independently at home.

METHODS

Data Sources and Study Selection

In collaboration with a clinical librarian (JD), a systematic search was conducted in PubMed, Embase, PsycINFO, INSPEC, and The Cochrane Library for articles published in English between 2000 and 2012. The searches were conducted on October 18, 2011, and updated on January 9, 2012, and October 25, 2012. A customized search strategy was conducted for each database (Appendix S1). A manual search of references in the selected articles was also conducted to identify additional studies.

Sensor Monitoring Method

Figure 1 depicts the application process involved in using sensor monitoring to measure and support ADLs.[13] The activity behavior of an ADL or IADL performed by an elderly person (Figure 1A) is monitored using a wireless sensor system installed in the home (Figure 1B). The sensor network consists of simple binary sensors. Such sensors may be passive infrared motion sensors (to detect motion in a specific area), magnetic contact sensors on doors and cabinets (to measure whether doors are opened or closed), and a flush sensor in the toilet (to measure the toilet being flushed).[13] An intelligent machine (Figure 1C), which looks for ADL, IADL, and daily activity patterns in the data (e.g., the sensor system could recognize toileting or bathing but also more-complex IADLs such as preparing breakfast and other kitchen activities), analyzes these sensor data. A sequence of binary sensor data indicates the activity with the help of an ADL recognition algorithm.

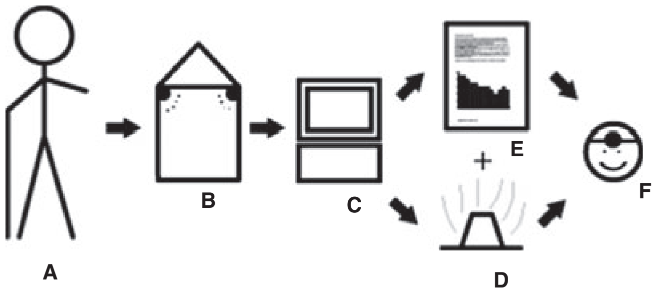

Figure 1. Iconic explanation of the proposed use of sensor monitoring systems to measure and support activities of daily living (ADLs). (A) Elderly person performing ADLs or instrumental ADLs in the home, (B) installed wireless sensor system in home placed at specific points in house and programmed to detect movement, (C) intelligent machine for analyzing sensor data, (D) alarm, (E) report of the sensor data, (F) healthcare professional. For more details, see Methods, Sensor Monitoring Method.

The results of these analyses can automatically trigger an alarm (Figure 1D), for example, when no motion is detected for a long period of time or if an older person is in bed for several days. The automatic generation of a report within a predefined period based on the sensor data is also possible (Figure 1E).

The reports and the alarms can be given to healthcare professionals (Figure 1F), who can use them to make better-informed decisions or to design interventions to support the older person.

Study Selection

Two reviewers (MP and SP) first independently screened titles and abstracts for inclusion and then read the full text of the eligible articles found during this first selection. Differences between the two reviewers were resolved by consulting a third independent reviewer (BB).

Empirical studies that described the use of wireless sensor monitoring to measure daily functioning or to support older people with daily functioning in which study subjects included community-dwelling older persons aged 65 and older and daily functioning was a primary outcome measured in the study were included.

Studies that focused solely on people diagnosed with severe dementia or severe cognitive problems (Mini-Mental State Examination score <16) were excluded.

Data Extraction and Quality Assessment

For each included study, data on study characteristics were extracted. Data were collected on type of sensor monitoring technology, number and type of sensors used, duration of sensor monitoring, and aim of sensor monitoring. Data were collected on participant demographic and clinical (main diagnoses, comorbidities, functional, and cognitive status) characteristics.

The same reviewers also independently assessed the quality of the included studies. Because of the variety of nonrandomized study designs included in this systematic review, the Newcastle-Ottawa Scale[14] was used to evaluate the risk of bias in the case controlled studies, the pre–post design study, and the mixed method study (Appendix S2). Disagreements were discussed; in cases of disagreement, a third reviewer was enlisted.

Data Synthesis and Analysis

Given the heterogeneity of the reporting and designs of the included studies, a descriptive approach was used to summarize study characteristics and outcomes. The included studies were categorized into those that aimed to measure daily functioning and those that aimed to support people in their daily functioning. No statistical pooling was conducted.

RESULTS

Search Result

The literature search identified 6,795 articles (Figure 2, Appendix S1). After the titles and abstracts were screened, 6,717 studies were excluded because they did not pertain to sensor monitoring, were discussion papers or editorials on the topic of sensor monitoring, or did not meet the inclusion criteria. In the next phase, 78 full-text articles were screened, and 61 of those were excluded, 18 for not meeting the inclusion criteria on design (review or theoretical study), 15 for not meeting the criteria for the intervention (only wearable sensors), eight for not meeting the inclusion criteria for participant age, and 16 for not meeting the criteria for the outcome measure (ADL and IADL function was not the primary outcome). Four were duplicates. Seventeen studies were included in this systematic review.

Quality of the Included Studies

Appendix S2 shows the results of the quality assessment of the three case–control studies and the pre–post design and mixed method studies included in this review. Three studies were considered low quality, and two were considered moderate quality. The studies had a small sample size or unclear inclusion and exclusion criteria or lacked follow-up.

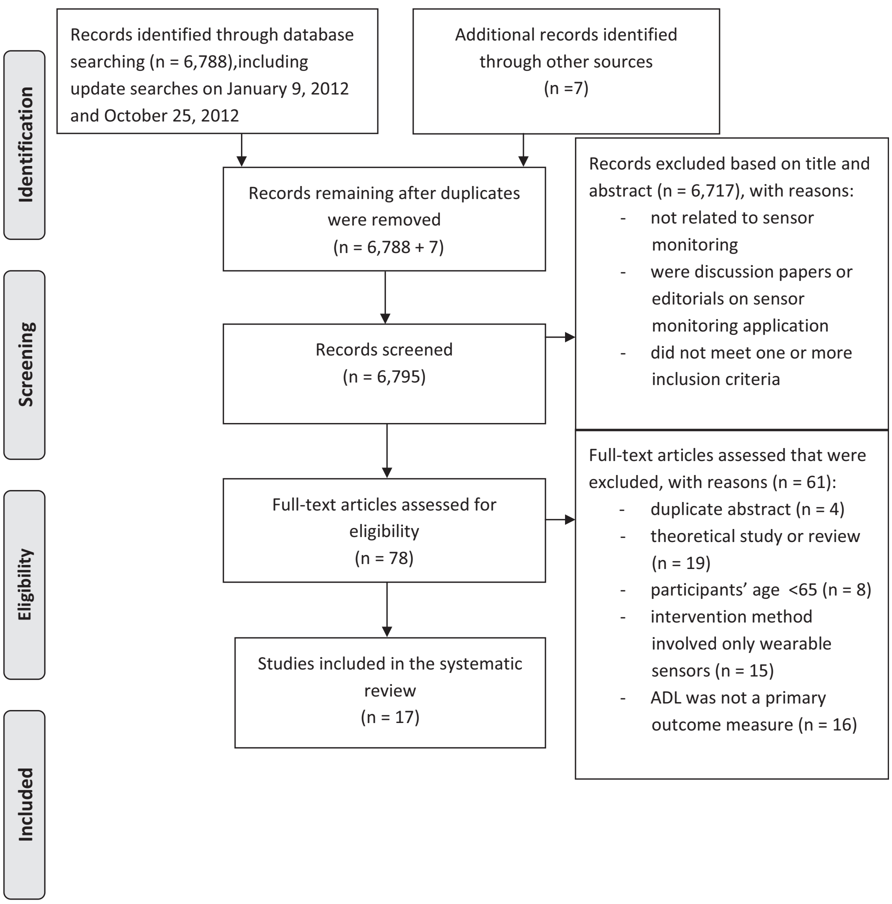

Figure 2. Flow diagram of search strategy and study selection.

Characteristics of the Studies

Table 1 shows the characteristics of the included studies. There were three case–control studies,[15–17] one mixed-methods study,[18] one longitudinal pilot study,[19] one single-group pre–post design study,[20] three multiple-case studies,[8,21,22] seven case studies,[23–29] and one experiment.[30]

The number of people included in the studies varied from one to 52. In seven studies, the mean age of the older participants was not specified. The weighted mean age of the participants in the remaining eight studies was 82.6.

Seven of the studies were conducted in senior houses or assisted living settings,[8,16,17,21,22,24,25] and four studies were conducted in smart home apartments.[23,26,28,30] Six studies were conducted in an independent living setting in the community.[15,18–20,27,29]

Ten studies did not report or specify clinical data of the participants. Four studies included participants without any reported diseases (healthy volunteers). Of the studies that investigated specific subgroups of older persons, most of the included participants had one or more chronic diseases. Only two studies provided a formal description of the functional or cognitive status of the included participants.

All of the studies focused on ADLs and IADLs as an outcome measure. Among the specific focuses were measurement of ADLs and IADLs,[23,28,30] measurement of routines or daily activity patterns,[15,20–22,24,26–28,31] ADL and IADL performance,[8,18,20] presence of the test person,[8,19,28] (in)activity,[8,19,25,31] restlessness,[8,17,22] functional ability,[16,18,20,22,24,26,28] gait speed,[8,15,22] physiological signs,[17] and safety.[8,16,18–20,22,25]

Characteristics of the Sensor Monitoring Method

The summary characteristics of the sensor monitoring method are described in Table 2. Studies were divided according to whether they aimed solely to measure daily functioning[15,21,23–26,28–30] and whether they aimed to support people in performing their ADLs and IADLs.[8,16–20,22,27]

The studies that aimed solely to measure daily functioning focused mainly on technological development or investigating the artificial intelligence analysis method behind the sensor monitoring system. The studies that also focused on supporting people in daily functioning included a more-detailed focus on the clinical relevance of sensor monitoring methods. All studies with a technological viewpoint mentioned some future possibilities for the use of sensor monitoring in daily clinical practice.

Three of the identified studies combined the use of a wireless sensor network with wearable sensors[16,20,30] and video.[8,22,28] The most common wireless sensors used were passive infrared motion sensors, magnetic contact switches, and some other binary sensors, such as pressure, float, and temperature sensors.

Effectiveness of Sensor Monitoring

All of the included studies reported positive results for the use of the sensor monitoring method. These studies investigated the models used to analyze the sensor data or to measure daily functioning or determine ADL patterns for people living alone and to identify changes in their typical ADL patterns. The results are presented in Table 2. Most of the studies reported potential advantages of the use of sensor monitoring to improve healthcare outcomes, although the effects were not studied in randomized clinical trials, and the studies lacked sufficient power to detect changes or effects. Two of the three included case–control studies did report better effects of the sensor monitoring method, such as the early detection of clinically relevant changes, than with the regular care provided to the control group.[15,17] One case–control study reported lower estimated costs of care over a 3-month monitoring period, fewer hospital days, and a positive effect of the method on professional caregiver efficiency,[17] but all of these studies had small sample sizes.

DISCUSSION

This systematic review provides a comprehensive overview of the use of sensor monitoring to measure and support the daily functioning of older people living independently at home.

It found that half of the included studies used sensor monitoring solely as a method to measure ADLs and IADLs and to detect changes in daily functioning for a person living independently. These studies tended to focus on the technical aspects of the sensor monitoring method used. The other half of the studies investigated how the use of sensor monitoring could support people in their daily functioning and allow them to live independently at home, but most of the studies were small in scale, and evidence of the methods' effectiveness was lacking. The included studies demonstrate an important gap between the technological development of sensor monitoring, which is already significant, and its application and effectiveness in daily practice. The included studies illustrated that healthcare professionals could take advantage of sensor monitoring to detect early periods of physical decline more quickly than when traditional means of measuring functional status are used. This might enable professionals to provide early interventions to prevent the decline caused by falls or immobility, thereby influencing clinical outcomes.

A road map is proposed to further develop and improve the use of sensor monitoring to measure and support daily functioning in independently living older people and to collect evidence about the applicability and effectiveness of sensor monitoring for clinical practice. This road map consists of the following steps.

- *Determining the target population that can benefit from sensor monitoring*. Because of the strong focus on the technical considerations of sensor monitoring, a significant number of studies did not specify or report important demographic and clinical data of the participants. Therefore, it was difficult to study which older people might benefit from sensor monitoring to support their daily functioning. Although this review showed that older people with one or more chronic diseases and those with mild cognitive problems could be a potential target group for sensor monitoring, more-specific investigation into the characteristics of the target population

Table 1. General Characteristics of Included Studies

Study	Study Design	Participants, n	Age	Setting	Clinical Data	Sensor Monitoring Method	Outcome Measure
Studies with the aim of measuring daily functioning							
Rashidi (2011)[23]	Experiment [2] case study	n = 2	N/S	Smart home apartment	N/S	Passive sensor network	ADLs and IADLs (ADLs international scale)
Wang (2009)[24]	Case study	n = 1	>65 N/S	Senior housing	N/S	Passive sensor network	Activity level and periodicity of lifestyle Alert conditions ADL pattern
Min (2008)[30]	Experiment	n = 5	N/S	Bathroom (lab)	Healthy volunteers	Static wireless sensors and wearable wireless sensors	ADLs
Poujaud (2008)[25]	Case study	n = 1	>65 N/S	Smart home (senior apartment)	Healthy volunteer	Passive sensor network	ADLs and IADLs Amount of ADLs ADL pattern
Virone (2008)[26]	Case study	n = 1	>65 N/S	Smart home	N/S	Passive sensor network	ADL pattern
Hayes (2008)[15]	Case–control study	n = 14 (9 women)	89.3 ± 3.7	Independent living setting in the community	Control: Healthy cognitive volunteers Intervention: MMSE, clinical dementia rate, years of education, (I)ADL, Tin balance, Tingait	Passive sensor network	Walking speed Amount of ADLs ADLs and IADLs
Virone (2008)[21]	Multiple case studies[4]	n = 22 (15 women) case studies: 4	85 (range 49–93)	Assisted living apartment	N/S 7 participants were memory care unit residents and 15 were non-memory care residents	Passive sensor network	Circadian activity rhythms ADLs and IADLs
Zouba (2010)[28]	Case study	n = 2 (1 woman)	Woman: 64 Man: 85	Smart home	Healthy volunteers	Passive sensor network and video sensors	Presence Postures and events ADLs
Yang [29]	Case study	n = 1	75	Independent living setting in the community	N/S	Passive sensor network	ADLs and IADLs Rhythm of ADLs
Studies with the aim of supporting people in daily functioning							
Rantz (2010)[8]	Retrospective exploratory multiple case study[3]	n = 16 (11 women)	88.4 ± 6.2, range 70–96	Senior housing	Chronic diseases (congestive heart failure, falls, kidney disease, chronic obstructive pulmonary disease)	Passive sensor network and an event-driven video sensor network	ADLs ADL and IADL performance Restlessness in bed Falls Gait speed

(Continued)

Table 1 (Contd.)

Study	Study Design	Participants, n	Age	Setting	Clinical Data	Sensor Monitoring Method	Outcome Measure
Skubic (2009)[22]	Retrospective multiple case study	n = 17	>65 N/S	Senior housing	Chronic diseases N/S	Passive sensor network and an event-driven video sensor network	ADL pattern Functional ability Alert conditions Bed restlessness Falls Gait patterns, gait speed, balance, posture
Brownsell (2008)[16]	Controlled trial	Intervention group, n = 24 (12 women) Control group, n = 28 (17 women)	Intervention: 74 ± 10 Control: 79 ± 7	Sheltered housing of subjects who lived independently	N/S	Passive sensor network and telecare	ADLs and IADLs Fear of falling Health-related quality of life Feeling safe
Alwan (2007)[17]	Case-controlled study	Intervention group, n = 21 (16 women) n = 21 control group	Intervention: 88 ± 6.4, range 73–90 Control: 88 ± 7, range 77–97	Assisted living apartment	N/S	Passive sensor network	ADLs Restlessness in bed Heart and breathing rates Cost of medical care Efficiency and workloads
Suzuki (2006)[27]	Case study	n = 1	72	Independent living setting in the community	N/S	Passive sensor network	ADLs and IADLs Rhythm of ADLs
Ohta (2002)[19]	Longitudinal study	n = 8	81	Independent living setting in the community	N/S	Passive sensor network	In-house movements Duration of stays in rooms Safety, determined by changes in duration of stays in rooms
Reder (2010)[20]	Single-group pre–post design	n = 12 and family member and/or paid caregiver (dyads or triads) (8 women)	>55 N/S	Independent living setting in the community	N/S only in terms of receiving assistance with (I)IADLs	Passive sensor network and wearable sensors	Physical movement Performing ADLs and IADLs Regular use of medication Use and satisfaction with the technology Safety and well-being Communication patterns Family caregiver burden
Mahoney (2009)[18]	Mixed methods: Focus group interview Intervention study	Intervention: n = 10 and their family member, 9 staff members Focus group: n = 13: 4 family members, 9 staff members	83 Focus group >65	Independent living setting in the community	Safety and health concerns, cognitive impairment, N/S	Passive sensor network	Elderly adult, family, and staff understanding of use of wireless sensor monitoring Measures of the elderly adult emotional, physical health, and activity levels

Passive sensor network; subjects did not need to do anything with the sensor network.
N/S = Not Specified; ADLs = Activities of Daily Living; IADLs = Instrumental Activities of Daily Living.

Table 2. Characteristics of Measurement and Support Studies

Study	Technological Development	Clinical Practice	Possibilities for Clinical Practice	Wearable and Passive Sensors	Passive Sensors	Only Passive Infrared Sensors	Diverse Binary Sensors	Other Specific Sensors	Number of Sensors Used	Duration of Monitoring	Recognized ADLs and Instrumental ADLs	Detected Changes in Activity Patterns	Safety	Reduction of Hospital Days and Costs	Efficiency Professionals
Studies with the aim of measuring daily functioning															
Rashidi (2011)[23]	Yes		Yes				Yes		48	3 months	Yes	Yes			
Wang (2009)[24]	Yes		Yes		Yes	Yes			N/S	2–3 years		Yes			
Min (2008)[30]	Yes			Yes			Yes	Yes	N/S	<2 hours	Yes				
Poujaud (2008)[25]	Yes		Yes		Yes		Yes		N/S	1 year	Yes		Yes		
Virone (2008)[32]	Yes		Yes		Yes	Yes			N/S	N/S	Yes	Yes			
Hayes (2008)[15]		Yes			Yes		Yes		N/S	6 months	Yes	Yes			
Virone (2008)[21]	Yes		Yes		Yes		Yes	Yes	N/S	3 months to 1 year	Yes	Yes			
Zouba (2010)[28]	Yes		Yes		Yes		Yes	Yes	25	4 hours	Yes	Yes			
Yang (2012)[29]	Yes		Yes		Yes	Yes		Yes	N/S	6 months	Yes	Yes			
Studies with the aim of supporting people in daily functioning															
Rantz (2010)[8]	Yes	Yes	Yes		Yes		Yes	Yes	N/S	3 years	Yes	Yes	Yes		Yes
Skubic (2009)[22]		Yes			Yes		Yes	Yes	N/S	3 months to 3 year	Yes	Yes	Yes	Yes	
Brownsell (2008)[16]		Yes	Yes	Yes			Yes	Yes	N/S	12 months			Yes		
Alwan (2007)[17]		Yes			Yes		Yes	Yes	N/S	3 months	Yes			Yes	Yes
Suzuki (2006)[27]		Yes			Yes		Yes	Yes	12	6 months	Yes	Yes			
Ohta (2002)[19]		Yes			Yes	Yes			N/S	80 months			Yes		
Reder (2010)[20]		Yes		Yes			Yes	Yes	N/S	3 months	Yes		Yes		
Mahoney (2009)[18]		Yes			Yes		Yes	Yes	N/S	4–18 months			Yes		Yes

ADLs = activities of daily living; N/S = not specified.

is needed to be of value in clinical practice. Future research should include demographic and clinical data.

- *Investigation of the use of sensor monitoring in community-dwelling older persons.* Early observation of a decline in daily functioning enables healthcare professionals to provide early interventions or support clinical decisions. Potential goals for individuals can include living longer independently at home, preventing readmission to the hospital, and minimizing emergency department visits[8,22] It has been suggested that sensor monitoring could also be useful to measure and support the recovery of older people after hospital admission,[8] although evidence pertaining to the effectiveness of these possible applications is still lacking. Further research is needed to investigate and validate these applications and their role in influencing clinical outcomes.
- *Guidelines for healthcare professionals regarding the use of sensor monitoring.* Although all of the included studies illustrated promising possibilities for the use of the sensor data in clinical practice, none of them focused on guidelines for healthcare professionals to use sensor data with their patients. In a few studies, the sensor data were connected over a secure web-based interface for use by healthcare professionals. One study developed a visualization application (density map) for healthcare providers[24] to identify daily activity patterns and changes in patterns. This visualization application was used in two studies by retrospectively viewing and analyzing the data for the periods before and after health events, such as hospitalizations, falls, and emergency department visits.[8,22] The focus for future research should be developing and testing visualizations of sensor data for healthcare professionals for supporting people in daily functioning and guidelines for healthcare professionals regarding the use of the sensor data in caring for their patients and advising caregivers.
- *Involvement of the participants, caregivers, and healthcare professionals in the further development and implementation of sensor monitoring.* Because sensor monitoring is a promising method for supporting older people in their everyday life, research must address the needs and expectations of the endusers and healthcare professionals.[32,31] Study participants indicated that they felt safer having the sensors in their homes and could use the sensor data as feedback, enabling themselves to change their behaviors in an effort to function independently at home for as long as possible.[22] Therefore, future research should involve individuals and healthcare professionals to customize the use of sensors to the participants' specific needs.
- *Conducting large-scale clinical trials.* The success of sensor monitoring depends on evidence of the method's effectiveness in achieving its goals. If studies are established, they should be of a higher methodological quality than existing studies and should express clear inclusion and exclusion criteria, proper research design, and a power calculation to include a sufficient number of people.
- *Study the cost effectiveness of sensor monitoring.* It has been demonstrated that sensor monitoring provides effective care coordination tools that have a positive

effect on professional caregivers' efficiency; reduce caregiver workloads; and result in significantly fewer hospital days, hospital visits, and emergency department visits.[17,24] Possible improved outcomes for healthcare professionals include a positive effect on healthcare professionals' efficiency and workload,[17] although these results were found in just one study with a small sample size, and the results could not be compared with those of other studies. Future research should investigate the cost effectiveness of sensor monitoring.

CONCLUSION

The use of sensor monitoring could provide promising opportunities in clinical practice by measuring and supporting daily functioning in older persons living independently, although clear evidence is still lacking. This systematic review also showed that the research has focused largely on the technical aspects of sensor monitoring and less on its application in everyday life and clinical practice. Future research should focus on facilitating the use of sensor monitoring in everyday life and clinical practice. To encourage this, a roadmap for future research was proposed that includes the participation of the older people themselves.

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Author Contributions: All authors had full access to all of the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis, drafting and critical revision of the manuscript. Pol, Buurman, de Rooij: study concept and design. Pol, Poerbodipoero, Daams: performed search queries. Pol, Poerbodipoero, Buurman: review of articles. Pol, Buurman: drafting of manuscript. Robben, de Rooij, Kröse, van Hartingsveldt, de Vos: critical revision of manuscript for important intellectual content. All authors read and approved the final manuscript.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Search strategies per database.

Appendix S2. Methodological quality of case control studies.