Towards Pervasive Mobility Assessments in Clinical and Domestic Environments

Melvin Isken[1(✉)], Thomas Frenken[1], Melina Frenken[2], and Andreas Hein[3]

[1] OFFIS Insitute for Information Technology, Escherweg 2, 26127 Oldenburg, Germany
{melvin.isken,thomas.frenken}@offis.de
http://www.offis.de

[2] Institute of Technical Assistance Systems, Jade-University of Applied Sciences, Westerstr. 10-12, 26121 Oldenburg, Germany

[3] Devision Automation and Measurement Technology, University of Oldenburg, Ammerlaender Heerstr. 140, 26121 Oldenburg, Germany

Abstract. This paper provides an overview of current research and open problems in sensor-based mobility analysis. It is focused on geriatric assessment tests and the idea to provide easier and more objective results by using sensor technologies. A lot of research has been done in the field of measuring personal movement/mobility by technical approaches but there are few developments to measure a complete geriatric assessment test. Such automated tests can very likely offer more accurate, reliable and objective results than currently used methods. Additionally, those tests may reduce costs in public health systems as well as set standards for comparability of the tests. New sensor technologies and initiatives for data standardization in health processes offer increased possibilities in system development. This paper will highlight some open problems that still exist to bring automated mobility assessment tests into pervasive clinical and domestic use.

Keywords: Assessment · Geriatrics · Clinical · Domestic · Body-worn · Ambient · Sensor · Technology

1 Introduction

1.1 Medical Background

Personal mobility, i.e., the ability to move around and get into and keep up certain body positions, is known to be an important prerequisite for pursuing an independent lifestyle [40]. Mobility normally changes during age. There is no pathological reason for that change at all. Starting at the age of 60 years, elderly peoples' mobility characteristics change [14], i.e., the self-selected gait velocity decreases each decade by 12 %–16 % during self-imposed activities. The decrease is often caused by a reduced step length whereas the step frequency remains stable. This age-related change in gait patterns contributes to a more

A. Holzinger et al. (Eds.): Smart Health, LNCS 8700, pp. 71–98, 2015.
DOI: 10.1007/978-3-319-16226-3_4

stable gait and it is not pathological [52]. If there are pathological reasons for an impairments of mobility the changes of gait parameters are more significant than in age-related changes [52]. Neurological diseases, especially dementia where mobility impairments are an early indicator [111], are one of the most frequent pathological reasons for mobility impairments. In general, severity of gait and balance disorders increases with severity of neurological disorders [100]. Gait and balance disorders have shown being related to a higher risk of falling. Especially slow self-selected gait velocity has found being related to an increased risk for falls and need of care [75]. Due to their often severe gait and balance disorders dementia patients suffer from an increased risk of falling [110].

Costs due to the high need of care of demented people [3] and fall-related costs are two of the major factors influencing the proportionally higher costs to the health care system caused by elderly people. From a clinical perspective long-term monitoring of changes in mobility has a high potential for early diagnosis of various diseases and for assessment to determine the risk to fall [8]. This may help delaying need of care or preventing acute incidents like falls and may thus help saving costs. On a more personal level early detection may help supporting an independent lifestyle by enabling early and purposeful prevention and may therefore increase quality of life for affected people, relatives, and carers.

Therefore, assessment of mobility is an important part of treatments in various medical branches. In the medical domain, mobility is diagnosed in terms of gait and balance respectively in spatio-temporal parameters quantifying these domains. Today, those parameters are either assessed by a medical professional performing a visual analysis or by using highly specialized technical equipment performing either kinetic or kinematic gait or balance analysis. Both alternatives are often not available in less specialized wards and a visual gait analysis is known to be dependent on the subjective capabilities of the analyzing professional. Therefore, some branches of medicine have developed so-called assessment tests in order to enable less specialized physicians to assess a patient's mobility to a certain degree. Geriatrics, the branch of medicine that deals with the illnesses of elderly and multimorbid patients, is such a branch that uses standardized assessment tests in the field of mobility. However, execution of such assessment tests also yields several problems like the required time effort due to manual documentation and the need to deliberately ignore details of a patient's mobility in order to keep the tests easy to use. Additionally, if physicians want to provide prevention and rehabilitation in patients homes most of such assessment tests are not suitable for being executed in domestic environments and cannot be easily executed unsupervised or at least lose their reliability if executed without supervision. Therefore, research was pursued in biomedical engineering of devices for supporting mobility assessment (tests) in clinical and domestic environments.

1.2 Scope of This Paper

The general analysis of personal movement is a wide area (for example sports movement analysis). This paper explicitly focuses on measuring mobility (or single parameters of mobility) in elderly persons using sensor technologies. Since this can be done in various ways, three gold-standard assessment tests are taken as measure for checking the state-of-the-art in technical assessment execution. These three belong to the most common assessment tests used in judging personal mobility: the Timed-up-and-Go test [88], Tinetti test [108] and Berg-Balance-Scale test [10]. A common ground of these tests is to observe people doing several mobility-related tasks like walking, standing or balancing. The tests gain scores which lead to an estimation of the mobility state of a person. More details can be found in the original test descriptions, an extensive selection of those tasks (which are, or can be broken down into, so-called components) is listed in Table 2. This state-of-the-art overview first lists the technologies available and then is matched against the requirements the assessment tests are setting up.

2 Glossary

– Ambient Sensors - Sensors that are attached in the environment of the user, usually installed in homes etc. For example presence detectors, motion detectors or cameras.
– Berg-Balance-Scale (BBS) - Assessment test invented by Katherine Berg et al., detailed description see [10].
– Body-worn Sensors - Sensors that are attached directly to the body or integrated in clothing etc. For example accelerometers, gyroscopes or strain gauges.
– Clinical Document Architecture (CDA) - standardized XML-based markup format for specifying the encoding, structure and semantics of clinical documents for exchange.
– International Classification of Functioning, Disability and Health (ICF) - classification of the health components of functioning and disability coordinated by World Health Organization WHO.
– Kinematic (approaches) - classical mechanics describing the motion of points, and objects without consideration of the causes of motion.
– Kinetic (approaches) - classical mechanics concerned with the relationship between forces and torques.
– Light Detection And Ranging (LIDAR) - sensor measuring distance by calculating times between emitting and receiving light (laser) impulses.
– Mobility - in this context the term mobility relates to personal mobility, i.e., the ability of a person to change its body position. Infrastructural mobility in terms of being able to change places e.g., by using transport systems is not considered here.
– Personal Health Record (PHR), Electronic Health Record (EHR); record where health data and information related to the care of a patient is stored and made accessible to involved third parties.
– Three Dimensional Layer Context Model (3DLC), model which defines the appropriate level of abstraction of data generated by medical applications to be stored inside the PHR, for details see [46].
– Timed Up & Go (TUG) - Assessment test requiring both static and dynamic balance, detailed description see [88].

- Tinetti-Test (TTI) - Assessment test invented by Mary Tinetti et al., detailed description see [108]. Also known as Tinetti Gait and Balance Examination, Tinettis Mobility Test, Tinetti Balance Test or Performance Oriented Mobility Assessment (POMA).
- Ultrasonic sensor (US) - Sensor measuring distance by calculating times between emitting and receiving high-frequency sound waves.

3 State-of-the-Art

3.1 Overview

This state-of-the-art will try to give an overview of current sensor technologies and approaches to measure personal movement parameters. In [33], sensor technologies for measuring single or multiple mobility parameters have been evaluated. Those technologies have been divided into kinetic and kinematic sensors as well as body-worn/ambient usage. An overview is given in Table 1. This section is followed by a comparison of requirements of assessment tests and which requirements are matched by these sensor technologies up to now.

Table 1. Classification of approaches for mobility analysis [33]

	Body worn	**Ambient**
Kinetic	1. **Pressure and force sensors** in shoes [59, 21, 7, 50, 107, 83, 95, 44, 127]	1. **Pressure and force sensors** on the ground [107, 29] / in treadmills [57, 29] / in furniture [16, 76, 123, 58] / in walkers [20, 86, 2, 109]
Kinecmatic	1. **Time of flight** ultrasound [114, 60, 1, 53, 51, 118] 2. **Visual** marker based [6, 79, 106, 29] 3. **Electrical impulse** electromyography [105, 29] 4. **Inertial forces** (accelerometers, gyroskopes) body worn [69, 28, 12, 92, 47, 71, 128, 74, 129, 5, 77, 13, 121, 4, 24, 54, 72, 122, 26] in clothing [65, 92] 5. **Bending forces** electro-goniometer [105, 29, 19]	1. **Time of flight** RADAR [64, 124, 32, 112, 49, 90, 130, 81, 39] LIDAR [82, 93, 37] 2. **Visual** marker less [61, 98, 102, 63, 116, 41] fluoroscopic [6] 3. **Presence sensors** home automation [84, 85, 92, 87, 15, 17, 113, 94, 18] RFID [22]

Commonly used technical approaches to the assessment of mobility like marker-based vision systems, force plates, and electromyographs, are very expensive, time-intensive in use and not mobile. This means that they are only available in specialized wards, can only be used by trained personal, and cannot be executed at point of care which makes their use time-intensive. Therefore, new technical approaches were developed which either use body-worn or ambient, i.e., integrated into the environment, sensor systems. Body-worn sensor, i.e., accelerometers and gyroscopes, are used more widely due to their advantage of being clearly linked to a single person in any environment. Several approaches (e.g., [65,129]) have demonstrated the ability to support the execution of mobility assessment tests and to compute spatio-temporal parameters of gait and balance using body-worn sensors. Some research projects meanwhile made their way into products. However, results of all approaches are very sensitive to sensor placement and even small misplacements can invalidate all assessment results. Over longer time periods assessment results perish due to sensor drift. Additionally, regarding unsupervised use in domestic environments it is questionable whether layman and especially elderly or demented people may be able to handle those sensors on their own or will be willing to wear those sensors in their daily life. Only a single approach to executing mobility assessments in domestic environments unsupervised by use of body-worn sensors, called Directed Routine (DR), has been proposed so far but was not evaluated yet [126]. Ambient sensors are placed in the environment and do thus not require any explicit handling by patients and results are not dependent on correct sensor placement. Sensors used for mobility analysis include home automation sensors [22,84], cameras [61,104], and laser range scanners [34,84] and have been evaluated in domestic environments several times. However, ambient sensor data are not assigned to a certain person and often sophisticated algorithms are required to filter those sensor recordings which represent a person to be monitored. Currently, there is neither a body-worn nor an ambient sensor system available that supports the execution of mobility assessment (tests) in supervised clinical and unsupervised domestic environments. However, some approaches are currently evaluated and will be available in the near future.

3.2 Kinetic Approaches

The following sections give a short overview of sensor technologies that are used in mobility analysis, for references to current research, see Table 1.

Pressure and Force Sensors. Three types of sensors can be distinguished: binary switches, pressure sensors and force reaction systems. Binary switches are the simplest form using binary information e.g., if a step was made or not. Pressure sensors can provide more detailed information, e.g., the weight distribution and sequence of movements. Force reaction systems are usually mounted on ground plates and not only measure weight forces but shear forces as well which is especially interesting in balance analysis. The most common use of body-worn pressure and force sensors is integration of those sensors in shoes. In ambient setups the sensors can be placed in furniture or moving aids so that pressure information is generated. Pressure and force sensors are relatively cheap and easy to use so they are adequate for being used in pervasive systems.

3.3 Kinematic Spproaches

Time-of-Flight Sensors. Time-of-flight sensors use a system of sending and receiving signals and calculating distance information. Classical types are ultrasound (US), light detection and ranging (LIDAR) and radio detection and ranging (RADAR) sensors. US sensors emit an ultrasound impulse and record the reflection of that impulse. Typically the sound beam has a quite broad dispersion so detection of small objects is difficult. Additionally detected objects can not exactly be localized (using one sensor), because the exact direction of the reflected signal is not known. The same holds for RADAR sensors which use an electromagnetic wave impulse. The advantage of RADAR sensors is that they are able to measure through walls for example. LIDAR sensors usually emit a laser beam which is quite narrow and so a relatively detailed environment recognition can be performed.

Since LIDAR and RADAR sensors are usually not suitable to be worn at the body up to now, only ultrasound sensors are available in the body worn category. This normally means that US markers are attached at the body and a fixed base-station is used to provide exact localization [53,60,114]. Ambient approaches attach US sensors e.g., to the ceiling and try to recognize persons and their movements [99]. Multiple sensors have to be used to be able to calculate an exact position of an object. RADAR sensors are rarely used compared to US and LIDAR but some researchers were able to extract gait information from RADAR data [97,117]. LIDAR sensors are quite common in robotics and industry mostly for navigation and safety purposes. Due to the exact data object recognition and tracking is relatively easy. In contrast, most systems are producing only 2D information, 3D-LIDAR sensors are quite expensive at the moment.

Visual Sensors. Visual observation of movement is based on video-frame data where movement is calculated by comparing each frame and checking for moved objects. In general this can be divided into tracking based on markers (body-worn, e.g., [29,106]) or marker-less (ambient, e.g., [38,89,102,103]) approaches. Marker-based systems extract movement by tracking active or passive markers that are attached to the observed body parts. The advantage is the exact and defined recognition of the selected moving objects. The attachment of the markers can be a drawback as well because the position is crucial and should not change during a test. Since human skin is not fixed to the bone structure it may be necessary to attach the markers to the bones directly which is invasive. Marker-less techniques use image recognition algorithms to extract moving objects without the need of invasive marker positioning. On one hand this is easier to set up but on the other hand the recognition precision is usually not as high as marker systems provide. Visual sensors are a common tool for movement observation, the cost heavily depends on the accuracy.

Electrical Impulse. Electromyography detects activity by measuring electrical power/impulses that are used to contract muscles. The measurement can be performed by attaching either non-invasive electrodes or needle electrodes which are able to measure in deeper muscle areas but also cause pain during muscle movement. The attachment of the electrodes though requires good expertise of the investigator. Since there is no general correlation of electrical energy and muscle movement, electromyography is only used in combination with a second modality to observe the actual movement (e.g., camera systems). In general this setup is only suited for laboratory (clinical) environments.

Inertial Forces. Inertial forces are detected by accelerometers and gyroscopes. Since such sensors are small and use few energy, a lot of research has been done on using inertial forces for movement analysis (see Table 1; e.g., [5, 92, 121]). Those developments and products nearly completely belong to the category of body-worn sensors because inertial forces can't be measured from distance (using accelerometers or gyros). Sensors can be directly attached to the body or integrated in clothing. Multiple sensors can be integrated into sensor networks (e.g., body area network). Developed systems mainly differ in number of sensors and area of attachment. The accuracy of measurements depends on correct attachment of the sensors and in general only relative movement can be measured because no absolute position is available. These sensors are also relatively low priced and wide spread.

Bending Forces. Bending forces as used in electro-goniometers are mostly used to measure angles of extremities (arm, leg). Since the sensors are attached to the joints directly, they are filed to body-worn sensors. Electro-goniometers are precise in general but not all joint movements of the body can be measured. Most common use is on elbow and knee joints (e.g., [55]). Since there is only relative information, a second modality is necessary to get absolute position information.

Presence Sensors. Presence sensors are ambient sensors that can be placed in a variety of environments. Common presence sensors are cheap but normally inaccurate as there is the information about a detected movement but no directional information is provided. By adding more sensors positions can be determined more accurately. Single body parts can't be observed so information is reduced to movement of a person through an environment (e.g., gait speed) [18, 43]. Such sensors are often included in smart home setups.

3.4 From Assessment Test to Assessment Components

To be able to track and quantify assessment tests with technical approaches it makes sense to break a single assessment test down into different components. These components are sequences of movements that can be distinguished from other movements within the same test. In case of the TUG test this means that a set of small components are combined to a complete test: Stand up - walk there - turn around - walk back - sit down. Each of those components can be analyzed separately to gain more information than the complete test itself. A usual TUG test only provides the duration of the complete test in seconds. The division into single components enables the measurement system to provide much more detailed information: time duration of single components, movements, movement speeds, balance parameters etc. are a few examples of such information. Each of such movements can be measured by one or more of the sensor technologies mentioned above. Up to now, no approach is able to track all required components with a single sensor setup. Table 2 therefore provides a classification of identified components, technologies that are currently used to measure them and references to research work.

3.5 Assessment Components and Measurement Approaches

Systems to perform a complete mobility assessment test either in a clinical or domestic environment are rare. As shown before, a lot of research has been done in using different kinds of sensors to measure individual movement parameters. Few systems use one single or a combination of sensors to measure a complete assessment test. Table 2 shows the components that are assessed during the tests and recent approaches to observe them. It also includes a list of sensor technologies that are used to measure the according physical movement. The list of commercial systems is used as an example, more systems exist that mostly have at least a slight different focus (like rehabilitation or sports movement analysis). Four main categories of movement have been identified: transfer sit/stand, gait, balance and turning/moving (body motion). It is obvious that the three selected mobility assessment tests focus on different types of movement but are overlapping in most areas. A combination of all three tests covers the whole spectrum of movements. It can be observed as well that there is no system that is capable of measuring all components and consequently there is no system that could perform all three assessments even if they have quite an overlap in necessary components. Additionally, there are some movement components that are currently not explicitly considered by any research the authors know of. Though technically most of them are measurable.

A result of this overview is the obvious fact that some movement parameters are more intensive investigated than others. It seems that instead of concentrating on single movement analysis, an overall effort should be made to coordinate a complete assessment setup. For example gait analysis is quite common in mobility analysis whereas 'reaching with arm forward' is not tracked by any approach. In some cases it may even be necessary to adapt the test descriptions to match the requirements of technical analysis. But since the less examined components are not completely out of reach from a technical point of view it seems possible to develop a system that is capable of analyzing the used group of assessment tests. Regarding sensor types there is a distribution as well (e.g., preferred usage of accelerometers and pressure sensors) this might be an indication of availability (price, usage) of such sensor technologies.

Table 2. Overview of the most relevant components of the selected mobility assessment tests and current approaches to automated measurement (see Sect. 3.5 for more details). TUG = Timed Up and Go Test, TTI = Tinetti-Test, BBS = Berg Balance Scale, aTUG = automated Timed Up and Go [33], BM = Smart/Basic Balance Master (NeuroCom) [62], iTUG = instrumented Timed Up and Go [91], ETGUG = Expanded Timed Get-up-and-Go [115], ISway = instrumented test of postural sway [67], iWalker = instrumented rollator [109], Simi = Simi Motion (Simi Reality Motion Systems GmbH), Gaitrite = GAITRite (CIR Systems Inc.), OT = OrthoTrak (Motion Analysis), Sensfloor (Future Shape GmbH) ACC = accelerometer, PRES = pressure sensor, RAD = radar, LS = laser scanner, US = ultrasound, CAM = visual/camera, SmH = smart home

Type	No.	Component	Test	Tec. Approach	Sensors	Sources
Transfer sit-stand	1	Stand up	TUG, BBS, TTI	aTUG, iTUG	ACC, PRES	[12, 16, 33, 66, 77, 78, 91, 119, 120, 125]
	2	Sit down	TUG, BBS, TTI	aTUG, iTUG	ACC, PRES	[16, 33, 66, 77, 78, 91, 119, 120, 125]
Gait	3	Gait speed	(TUG) ETGUG	aTUG, iTUG, iWalker, Simi, Sensfloor, Gaitrite. OT	ACC, PRES, RAD, LS, US, SmH, RFID, CAM	[4, 5, 7, 20, 26, 33, 42, 49, 51, 59, 70, 74, 78, 82–84, 86, 91, 93, 98, 101, 102, 109, 119, 120, 122, 124, 125, 128, 129]
	4	Step initiation	TTI	aTUG, Simi, Gaitrite, OT	ACC	[4, 5, 7, 21, 33, 42, 63, 70, 78, 91, 119, 120, 125]
	5	Step height	TTI	Simi, OT		
	6	Step length	TTI	aTUG, iTUG	PRES, RAD, LS, US, RFID, CAM	[5, 7, 20, 22, 26, 33, 38, 39, 42, 51, 53, 63, 70, 74, 82, 91, 93, 98, 102, 119, 125]

(*Continued*)

Table 2. (*Contined*)

Type	No.	Component	Test	Tec. Approach	Sensors	Sources
	7	Step continuity	TTI	aTUG, iTUG, Simi, OT	ACC, CAM	[5, 33, 42, 59, 74, 91, 98, 125]
	8	Path deviation	TTI	aTUG	LS	[33]
	9	Trunk stability	TTI	iTUG, iWalker, OT	ACC, PRES, CAM	[20, 70, 91, 98, 109, 116, 125]
	10	Step width	TTI	aTUG, Gaitrite, OT	LS,US	[5, 33, 60]
Balance	11	Balance (5 sec)	TTI	aTUG, BM, ISway, OT	ACC, PRES, LS	[23, 33, 54, 67, 68, 109]
	12	Stand stability	BBS, TTI	ISway	ACC	[23, 25, 66–68, 72, 116]
	13	Balance w/closed eyes	BBS, TTI	BM, ISway	ACC, PRES	[23, 54, 66–68]
	14	Balance sitting	BBS	aTUG	PRES	[33, 66]
	15	Balance feet side by side	BBS	ISway	ACC	[23, 67]
	16	Tandem standing	BBS			
	17	Standing on one foot	BBS	BM	PRES	[25]
	18	Force against trunk	TTI		ACC	[66]
Turning, Moving	19	Turn 360°	BBS, TTI		ACC	[66]
	20	Turn 180°	TUG	aTUG, iTUG	ACC, LS	[33, 42, 78, 91, 120, 125]
	21	Turn around, look backwards	BBS			
	22	Reach arm forward	BBS			
	23	Retrieve object from floor	BBS			
	24	Stool stepping	BBS		ACC	[78, 120]

Fig. 1. aTUG apparatus as approach to offer standardized TUG assessments in clinical environments

3.6 Own Approach and Work Conducted

Our own novel approach, called Automated Timed Up & Go (aTUG, see Fig. 1), to supporting the execution of mobility assessment tests in clinical and domestic environments utilizes exclusively ambient sensor technologies and may be performed in domestic environments without creating a test situation. Compared to approaches using body-worn sensors, aTUG saves more time since no calibration or donning of sensors is required. Patients are not directly aware of being technically measured. Additionally, the technical support provides more details about the patients than a manually executed test by performing a gait and balance analysis, if requested.

Part of the aTUG approach is the aTUG apparatus which was developed from sketch starting in 2008 by demand of physicians from the field of geriatrics in order to make the aTUG approach applicable in daily clinical practice. The general idea of the apparatus is to integrate required sensor technologies with a battery and a display in order to enable physicians to transport all required equipment for performing an assessment and gait analysis at point of care. The basis of the apparatus is a blood withdrawal chair. A laser range scanner is used for performing kinematic gait analysis and is installed under the seat of the apparatus. Four force sensors are integrated into the legs of the chair and enable performing kinetic balance analysis while standing up and sitting down. The apparatus may be accompanied with a set of home automation sensors i.e., light barriers in order to provide even more details and to validate computations. For long-term use at home those sensors can be placed in the environment. After an initial proof of concept, the prototype was used as a basis for a complete redesign with the objective of putting the aTUG chair into circulation as a medical product. After a risk analysis, the construction, and safety tests, a new prototype was technically validated for support of the TUG tests in a residential care facility [36] and its gait analysis results were compared to a commercially available marker-based tracking system. Additionally, the approach was evaluated in a field trial in order to demonstrate the ability to perform TUG unsupervised during daily life [35]. Currently, the aTUG apparatus is in a clinical trial of medical products [56] in which it is clinically validated against manual measurements and the GaitRite system at the Charité in Berlin.

The aTUG device can easily be placed and used in clinical environments. Regarding the integration into domestic environments the aTUG has its drawbacks. First of all, the device is certainly recognized as medical analytic device. Persons using the apparatus are aware of being monitored. As already mentioned, this can lead to biased results since the persons try to perform as good as possible in the case they are observed by someone. Additionally, the aTUG device has a (somewhat) fixed position and recognition area so it has special requirements for being installed (e.g., free path of 3–4 m) so it can't be placed in narrow spaces. As a consequence of these drawbacks the idea of the aTUG apparatus was extended to use the same algorithms on a mobile robot platform (see Fig. 2). The main task of doing gait analysis with aTUG is accomplished by using a LRF sensor. This type of sensor is used in most of current state-of-the-art mobile robot systems for navigation purposes. So this sensor is already available on most robot systems and can easily be used to do the same gait analysis. The major difference to aTUG is the mobility of the platform. The robot is able to follow a person through the home, monitoring gait at various places, under dif-

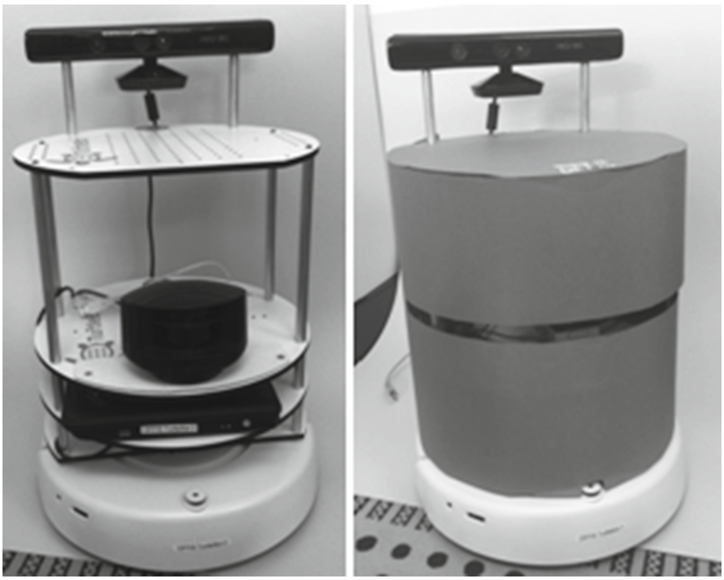

Fig. 2. Mobile robot platform equipped with LRF and Kinect sensor. Approach to bring the aTUG idea to domestic environments.

ferent circumstances and over longer distances even if there is no straight line to perform a classic TUG test. To extend the system even more, 3D sensor information was added to analyze balance parameters and movement characteristics. In this case, the well known Microsoft Kinect sensor was used. The idea is to enable every typical mobile service robot to do such analysis, not to create a new type of robot. So people buy the robot to fulfill any type of service (e.g., cleaning, personal assistance, telepresence) and the mobility monitoring is done in the background (with approval by the user) and after some time the user is not aware of the test situation anymore. So the results of the measured mobility parameters are much more realistic than any test can provide. Using this system, the following major advantages are gained: (1) mobile data acquisition (no need to place many sensors at different locations in the home), (2) gait and full body movement analysis, (3) monitoring over long periods of time, (4) getting mobility data in everyday life, no test situation.

The robot is designed to record the observed movements in a data base so that further analysis can be done by e.g., medical personnel. Open questions are still the communication with medical personnel in terms of data standards and comparability of test results. See Sect. 4 for a more detailed analysis of problems.

4 Open Problems

aTUG and some other body-worn approaches are close to being available as medical products. In daily clinical practice their main advantage will be to provide more detailed and more objective results than manual assessment tests and to save time by digital documentation of results. However, in order to save costs in the future, only more effective procedures in clinical environments are not sufficient. One possibility to save more costs is by early prevention and more sustainable rehabilitation on an individual basis for which domestic assessments may provide the required data. Currently, there are three main open problems in this field: (1) How to implement clinical assessment tests in domestic environments unobtrusively, (2) how to document domestic assessment results in a standardized manner and (3) how to compare these to clinical assessment results.

4.1 Acceptance of Technical Innovations

First of all - if a system shall be used either in clinical or in domestic environments, without acceptance by the users the system will fail. This is even more crucial in the case of domestic environments. It is very hard to predict reactions of users to new technologies brought into their own homes. If there is no real use-case and obvious benefit the system will be rejected usually. In professional environments this is not as serious as in home environments but especially medical personnel is used to work with common tools and new tools are accepted mostly if there is also a benefit for the operator (e.g., faster execution, less stress). So the selection of sensors has to be made in the first place based on acceptance, prices are less important and get even less important due to price decreases through industrial developments.

General Technology Acceptance. Of course all conclusions of acceptance research have to consider the fact that technical developments in recent years also changed the way people react to them [48]. People that will reach the age of the target group of geriatric treatment in 10 or 20 years will have a totally different perspective to new technology than people that are in need of care at present. For example even today's elderly people are used to computer systems etc. since they already worked with them. Ten years ago, this was not the case. The more experience people have, the better they can estimate how this could effect their lives. Perspectively, the group of technically experienced elderly will grow and the other group will scale down [27]. Anyhow, technology is accepted to a greater extend if the benefit of usage is clearly visible [27,73].

In a meta study called *Body-Worn Sensor Design: What Do Patients and Clinicians Want?* Bergmann and McGregor examined the results of multiple studies regarding sensor and technology acceptance of body-worn sensors in medical application areas [11]. They identified 11 studies that provide information about this specific user acceptance. Since the focus of such studies was broad they ware able to draw some overall conclusions like *one of the main recurring factors was the preference for small and embedded sensors, indicating that user are keen to minimize the physical impact of any wearable system*, as well as *the less notable the device is the higher the patient's acceptance will be, which in turn will improve the quality of gathered data, as patient's behavior will then be closer to his/her normal routines.* As already mentioned, this has to be taken into account when designing person monitoring systems. On the other hand, *clinicians were concerned with issues such as restricted recording time due to a limited storage capacity, techniques for attaching the device to the patient and the fact that data should be available in real-time to make instant diagnosis possible.* Which again sets some crucial requirements for hardware and software design.

Robotic Acceptance. An intense study regarding acceptance of robots was conducted in 2011 [9]. It was not focused on elderly but on a broader selection of people. The result of this study was a list of open questions for robot development which also included age dependent acceptance as open problem.

In 2009 there was a survey of the acceptance of service robots comparing different age groups (ages 18–25 and 65–86) [31]. There was no significant difference between these groups as long as the benefit is sufficiently visible. However, elderly persons were more open-minded regarding critical functionality (emergency services) of robots. Another study of the same research group revealed similar results [30].

Smarr et al. gave an overview of robotic assistance systems for elderly people in 2011 [96]. Especially robots assisting at activities of daily living were selected. The study was based on internet and database research which lead to, depending on usage of the system, from 61 to 147 different robot systems. This shows high interest in technological assistance however one conclusion was that there is no comprehensive study that concentrates directly on needs and requests of elderly people.

Concluding this short selection of acceptance research it can be stated that acceptance is crucial for (medical) technical systems but there is still a lack of comprehensive studies which can provide a general guideline for designing such systems. This does not mean that there is no research of acceptance in general, there is a lot, but the diversity of technical solutions is huge and it is hard to create general statements by studying single applications. So every system has to be elaborated carefully for meeting the expectations users have in each case.

4.2 Clinical Assessment Tests in Domestic Environments

Today, several technical approaches to conduct domestic (mobility) assessments have been implemented and are currently evaluated in the field - many will still follow. The most important remaining technical problem is how to implement tests in a way that patients accept these in their daily life. Tests will have to be unobtrusive and should ideally be performed continuously without requiring patients to perform an explicit test. Some researcher i.e., our own work [35] and the work of Stone and Skubic [104] have already shown that assessment tests may be implemented without creating a test situation and thus can be implemented unobtrusively. Some of the lessons learned from the first real world experiences are considered here.

If sensors are used to precisely analyze personal movements those should be broken down into single movement aspects (e.g., the before mentioned components) this will allow better comparability between established test scenarios. The measurement results itself should not remain on a detailed technical level, they should be classified into categories. The ICF already provides a framework for such classification (see next section). Another aspect is data integration. In clinical environments there are established data communication and sharing standards but in home environments there is no such infrastructure. This needs to be considered when systems shall be deployed at home environments but still be useful in the complete medical service environment.

It should not be the goal to try to recreate established tests completely. In fact the original test descriptions have been designed in such a way (being simple) to compensate the lack of technical capabilities. So it is more important to understand the ideas behind the tests and to transfer these to the new circumstances (e.g., home environment). Technical approaches can deliver much more detailed analysis which may provide new insights whereas classical approaches are not able to.

Working within the health sector is often driven by the need of reducing costs. This can be accomplished by introducing automated assessment tests both in preventive as well as actual care scenarios. Though this heavily depends on the costs of the final automated measurement system. Additionally, as mentioned above, in professional medical environments a two-step approach seems to be more realistic. Firstly common techniques should be supported by the new developments which then can be extended to fully replace the former common strategies. Only known and proven technologies are accepted. So adding a completely new technology can face high barriers.

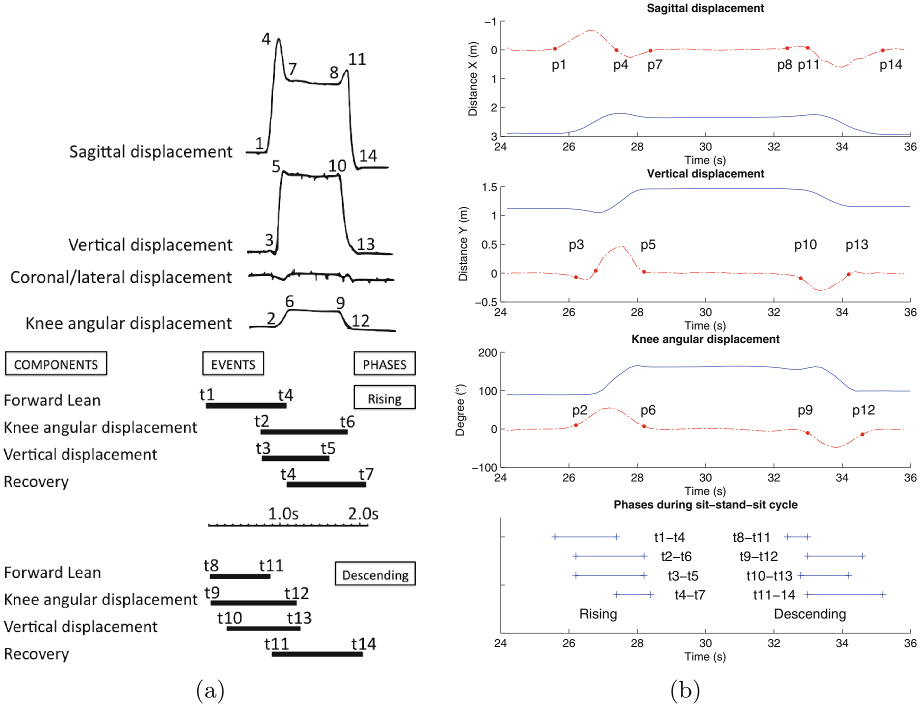

Fig. 3. Sit-stand-sit cycle analyzed by Kerr et al. [55] in laboratory environment (a) and same analysis performed by mobile robot in domestic environment (b, own work). Results seem to be comparable but how to compare such results with clinical practice?

The use of service robots in domestic environments is intensively investigated currently. Using a service robot to perform assessment test analysis is quite new. Since the development of domestic service robots is still at the early stages, questions about acceptance and usability of such a special service is highly speculative. First user tests with robot prototypes have been conducted and results are promising but still far from real world usage (see Fig. 3). This figurative example shows that state-of-the-art systems like robots are able to reproduce results that coincide with former approaches but there is still no way to actually compare both of them. Even more important - there is currently no connection to standard medical procedures that would incorporate these results.

In general an assessment analysis with either robot or other ambient technology can be regarded as feasible. However, the results of different domestic and clinical assessment systems are not comparable to each other today. The main reason for this and another open question is a missing common classification and document format for the results.

4.3 Standardization of Results

Even if technologies for performing mobility assessments in peoples' homes are available, results of such domestic assessments are not directly comparable to clinical assessment tests. Three main problems can be found:

1. Incompleteness of assessment results: Assessments in domestic environments will have to be performed as part of every-day activities without creating a test situation in order to be accepted by patients. Often, not all aspects of clinical assessment tests can be tested during every-day activities.
2. Contextual dependency on assessment results: While clinical assessment results are obtained under standardized conditions during a test, domestic assessment data is gathered in peoples' homes which may contain unclear influence factors even if people have to perform a test at home. Such unknown contextual influences factors may have an unclear influence on the assessment results.
3. Uncertainty of assessment results: Assessments in domestic environments will have to be performed unsupervised by use of sensor technologies in order to be cost-efficient. Such implementation implies that there will always remain a certain amount of uncertainty whether sensor recordings and evaluations do really reflect the abilities of a patient in a certain assessment domain.

Therefore, a common classification for aspects of clinical and domestic assessment results and for expressing contextual influence on these and their uncertainty is currently missing. Additionally, as soon as assessment information has been obtained in peoples' homes it has to be transferred to physicians and caregivers for being considered when making a medical decision. Personal Health Records (PHRs) have the ability to store and exchange this user generated data with Electronic Health Records (EHRs) of the professional domain. Mapping a classification for assessment results to an established semantically annotated document format would enable long-term storage and transfer of fine-grained assessment information on a machine interpretable level. Providing such a common classification and a mapping to standardized document-format would not only enable physicians to use domestic assessment data in their every-day decision making but maybe also enable them to gain new insights into people's daily performance.

In order to make data from clinical and domestic assessments comparable, a common classification for the results is required. Such a classification will have to solve the three described problems of incompleteness, contextual dependency, and uncertainty of assessment results. Additionally, a standardized document-format for transferring and presenting assessment results encoded by a common classification is required. Therefore, we propose three main methods for making clinical and domestic assessment results comparable by machines and medical decision makers:

1. To use component codes from the International Classification of Functioning, Disability and Health (ICF) [80] to decompose clinical and domestic assessment tests into common parts. Therefore, an assessment test will comprised

a sequence of several components from the ICF. Such break down of assessment tests solves the first described problem by enabling the standardized description of even incomplete assessments.

2. To use qualifiers from the ICF's list of activities and participation, i.e., capacity and performance, for expressing contextual influence on assessment results. Encoding assessment results as capacity values expresses low environmental influence; performance values indicate high environmental influence. Usage of aid may be encoded as well.
3. To map assessment results encoded according to our first two methods to the Clinical Document Architecture (CDA) [45] in order to enable a standardized transfer of results between PHRs/EHRs and to provide a machine-interpretable and human-readable representation of results. Additionally, to use CDA in order to annotate uncertainty of assessment results, an extension of CDA must be made.

4.4 Integration and Co-Existence of Clinical and Domestic Assessments

Even if domestic assessment results will be available to physicians in the near future in a common document format, a third open question is how recognized changes over time and differences to clinical assessment results will influence a medical decision. The explanatory power of domestic assessment results and their relationship to clinical results have to be investigated. In order to foster this process, the 3DLC model was developed [46]. 3DLC is a first step towards categorizing available assessment results and to explaining the relationship between clinical and domestic results. Within the proposed model, assessment data is categorized on three axes: relevance to clinical decision, recording frequency, and context dependence of results. Recording frequency refers to the temporal intervals in which the assessment results are obtained. While assessments in professional environments have a low frequency, i.e., once per week or twice per hospital stay, domestic assessments can be performed continuously or at least one per day. The higher frequency should provide a better insight into patients' abilities. However, domestic assessment results are more context-dependent. In a clinical setting a standardized test situation is created which makes results comparable. In a domestic setting, unclear influences, e.g., different floor covers, may results in different assessment results. Since those influences may not be clear, context dependence of results is high. These former two axes influence the third axis - the relevance to the clinical decision. The higher the result frequency and the lower the context dependence the more relevant are assessment results to a clinical decision. New technical systems for implementing both clinical and domestic (mobility) assessment tests should adhere to a common results classification and document-format in order to make their results comparable to other approaches and usable during medical decision making. In order to be accepted by patients in their homes, domestic assessment systems should be implemented unobtrusively. The question how obtained results are used during clinical decision making and how changes over time and differences between clinical and domestic assessment results have to be interpreted remains future work after more usable data was collected.

5 Future Outlook

Summarizing the current open problems and development activities, the following conclusions can be drawn (see Sect. 4 Open Questions for more detailed analysis):

1. A lot of different approaches for mobility analysis already exist. It lacks of a combined effort to bring these single-focused approaches into complete assessment systems.
2. A major factor of providing domestic technology is user acceptance - research has to put emphasis on acceptance by end-users as well as professionals for seamless integration in common work flows so that high user-acceptance is achieved. In the field of automated assessment execution there is no reliable data on user acceptance available.
3. The results of technical analysis have to be transferred into a common language which allows consistent processing. The ICF provides parts of such a tool set. This should be discussed for inclusion.
4. If data is exchanged between home and professional environments, comprehensive standards are necessary. Currently an equivalent to the PHR/EHR systems of the professional domain is missing/not sufficiently integrated in the home environment.
5. The focus should not be to completely copy common procedures but enhance them with the additional information that can be provided by technical analysis systems.
6. One future way of bringing sensors in domestic environments will be service robots. These robots usually will be designed for a different major task but they bring a set of sensors 'for free' that can clearly enhance domestic mobility analysis. Of course, robot technology itself has a lot of open research questions to be solved as well before they can be used as reliable source.

References

1. Abellanas, A., Calderón Estévez, L., Ceres Ruíz, R., Frizera Neto, A., Raya, R.: Ultrasonic time of flight estimation in assistive mobility: improvement of the model-echo fitting. In: Proceedings of Eurosensors XXII, pp. 464–467. VDI/VDE, Elsevier (2008)
2. Alwan, M., Ledoux, A., Wasson, G., Sheth, P., Huang, C.: Basic walker-assisted gait characteristics derived from forces and moments exerted on the walker's handles: results on normal subjects. Med. Eng. Phys. **29**(3), 380–389 (2007)
3. Alzheimer's Disease International. World Alzheimer Report 2009 (2009)
4. Aminian, K., Rezakhanlou, K., De Andres, E., Fritsch, C., Leyvraz, P., Robert, P.: Temporal feature estimation during walking using miniature accelerometers: an analysis of gait improvement after hip arthroplasty. Med. Biol. Eng. Comput. **37**, 686–691 (1999)

5. Auvinet, B., Berrut, G., Touzard, C., Moutel, L., Collet, N., Chaleil, D., Barrey, E.: Reference data for normal subjects obtained with an accelerometric device. Gait Posture **16**(2), 124–134 (2002)
6. Bachmann, C., Gerber, H., Stacoff, A.: Messsysteme, Messmethoden und Beispiele zur instrumentierten Ganganalyse. Schweizerische Zeitschrift für Sportmedizin und Sporttraumatologie **56**(2), 29–34 (2008)
7. Bamberg, S., Benbasat, A.Y., Scarborough, D.M., Krebs, D.E., Paradiso, J.A.: Gait analysis using a shoe-integrated wireless sensor system. IEEE Trans. Inf. Technol. Biomed. **12**(4), 413–423 (2008)
8. Beauchet, O., Allali, G., Berrut, G., Hommet, C., Dubost, V., Assal, F.: Gait analysis in demented subjects: interests and perspectives. Neuropsychiatr. Dis. Treat. **4**(1), 155–160 (2008)
9. Beer, J.M., Prakash, A., Mitzner, T.L., Rogers, W.A.: Understanding robot acceptance. Georgia Institute of Technology (2011)
10. Berg, K.: Measuring balance in the elderly: preliminary development of an instrument. Physiother. Can. **41**(6), 304–311 (1989)
11. Bergmann, J.H.M., McGregor, A.H.: Body-worn sensor design: what do patients and clinicians want? Ann. Biomed. Eng. **39**(9), 2299–2312 (2011)
12. Boonstra, M.C., van der Slikke, R.M.A., Keijsers, N.L.W., van Lummel, R.C., de Waal Malefijt, M.C., Verdonschot, N.: The accuracy of measuring the kinematics of rising from a chair with accelerometers and gyroscopes. J. Biomech. **39**(2), 354–358 (2006)
13. Bussmann, J., Damen, L., Stam, H.: Analysis and decomposition of signals obtained by thigh-fixed uni-axial accelerometry during normal walking. Med. Biol. Eng. Comput. **38**, 632–638 (2000)
14. Butler, A.A., Menant, J.C., Tiedemann, A.C., Lord, S.R.: Age and gender differences in seven tests of functional mobility. J. Neuroeng. Rehabil. **6**, 31 (2009)
15. Cameron, K., Hughes, K., Doughty, K.: Reducing fall incidence in community elders by telecare using predictive systems. In: Proceedings of the 19th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 30 October–2 November 1997, vol. 3, pp. 1036–1039 (1997)
16. Cao, E., Inoue, Y., Liu, T., Shibata, K.: A sit-to-stand trainer system in lower limb rehabilitation. In: Proceedings of the IEEE/ASME International Advanced Intelligent Mechatronics (AIM) Conference, pp. 116–121 (2011)
17. Celler, B.G., Hesketh, T., Earnshaw, W., Ilsar, E.: An instrumentation system for the remote monitoring of changes in functional health status of the elderly at home. In: Proceedings of the 16th Annual International Conference of the IEEE Engineering Advances: New Opportunities for Biomedical Engineers Engineering in Medicine and Biology Society, pp. 908–909 (1994)
18. Chan, M., Hariton, C., Ringeard, P., Campo, E.: Smart house automation system for the elderly and the disabled. In: Proceedings of the IEEE International Conference on Systems, Man and Cybernetics Intelligent Systems for the 21st Century, 22–25 October 1995, vol. 2, pp. 1586–1589 (1995)
19. Chao, E.Y.: Justification of triaxial goniometer for the measurement of joint rotation. J. Biomech. **13**(12), 989–1006 (1980)
20. Chen, C.L., Chen, H.C., Wong, M.K., Tang, F.T., Chen, R.S.: Temporal stride and force analysis of cane-assisted gait in people with hemiplegic stroke. Arch. Phys. Med. Rehabil. **82**(1), 43–48 (2001)
21. Chen, M., Huang, B., Xu, Y.: Intelligent shoes for abnormal gait detection. In: Proceedings of the IEEE International Conference on Robotics and Automation ICRA 2008, 19–23 May 2008, pp. 2019–2024 (2008)

22. Chen, Y.-C., Lin, Y.-W.: Indoor RFID gait monitoring system for fall detection. In: Proceedings of the 2nd International Aware Computing (ISAC) Symposium, pp. 207–212 (2010)
23. Chiari, L., Dozza, M., Cappello, A., Horak, F.B., Macellari, V., Giansanti, D.: Audio-biofeedback for balance improvement: an accelerometry-based system. IEEE Trans. Biomed. Eng. **52**(12), 2108–2111 (2005)
24. Cho, C.Y., Kamen, G.: Detecting balance deficits in frequent fallers using clinical and quantitative evaluation tools. J. Am. Geriatr. Soc. **46**(4), 426–430 (1998)
25. Clark, R.A., Bryant, A.L., Pua, Y., McCrory, P., Bennell, K., Hunt, M.: Validity and reliability of the nintendo wii balance board for assessment of standing balance. Gait Posture **31**(3), 307–310 (2010)
26. Currie, G., Rafferty, D., Duncan, G., Bell, F., Evans, A.: Measurement of gait by accelerometer and walkway: a comparison study. Med. Biol. Eng. Comput. **30**, 669–670 (1992)
27. Czaja, S.J., Charness, N., Fisk, A.D., Hertzog, C., Nair, S.N., Rogers, W.A., Sharit, J.: Factors predicting the use of technology: findings from the center for research and education on aging and technology enhancement (create). Psychol. Aging **21**(2), 333 (2006)
28. de Bruin, E., Najafi, B., Murer, K., Uebelhart, D., Aminian, K.: Quantification of everyday motor function in a geriatric population. J. Rehabil. Res. Dev. **44**, 417–428 (2007)
29. DeLisa, J., Scientific, U.S. Veterans Health Administration, Technical Publications Section: Gait analysis in the science of rehabilitation. Monograph (United States. Veterans Health Administration. Rehabilitation Research and Development Service). Department of Veterans Affairs, Veterans Health Administration, Rehabilitation Research and Development Service. Scientific and Technical Publications Section (1998)
30. Ezer, N., Fisk, A.D., Rogers, W.A.: Attitudinal and intentional acceptance of domestic robots by younger and older adults. In: Stephanidis, C. (ed.) UAHCI 2009, Part II. LNCS, vol. 5615, pp. 39–48. Springer, Heidelberg (2009)
31. Ezer, N., Fisk, A.D., Rogers, W.A.: More than a servant: self-reported willingness of younger and older adults to having a robot perform interactive and critical tasks in the home. In: Proceedings of the Human Factors and Ergonomics Society Annual Meeting, vol. 53, pp. 136–140. SAGE Publications (2009)
32. Fortuny-Guasch, J., Sammartino, P.F., Petit, J.: Radar techniques for human gait automatic recognition. In: Proceedings of the 43rd Annual 2009 International Security Technology Carnahan Conference, pp. 221–226 (2009)
33. Frenken, T.: Technischer Ansatz zur unaufdringlichen Mobilitätsanalyse im Rahmen geriatrischer Assessments. Ph.D. thesis. University of Oldenburg, VDI Verlag, Düsseldorf, January 2013
34. Frenken, T., Gövercin, M., Mersmann, S., Hein, A.: Precise assessment of self-selected gait velocity in domestic environments. In: Pervasive Computing Technologies for Healthcare (PervasiveHealth) (2010)
35. Frenken, T., Lipprandt, M., Brell, M., Wegel, S., Gövercin, M., Steinhagen-Thiessen, E., Hein, A.: Novel approach to unsupervised mobility assessment tests: field trial for aTUG. In: Proceedings of the 6th International Pervasive Computing Technologies for Healthcare (PervasiveHealth) Conference (2012)
36. Frenken, T., Vester, B., Brell, M., Hein, A.: aTUG: fully-automated timed up and go assessment using ambient sensor technologies. In: 2011 5th International Conference on Pervasive Computing Technologies for Healthcare (PervasiveHealth) (2011)

37. Fuerstenberg, K.C., Dietmayer, K.: Object tracking and classification for multiple active safety and comfort applications using a multilayer laser scanner. In: Proceedings of IEEE Intelligent Vehicles Symposium, pp. 802–807 (2004)
38. Gabel, M., Gilad-Bachrach, R., Renshaw, E., Schuster, A.: Full body gait analysis with kinect. In: 2012 Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), pp. 1964–1967. IEEE (2012)
39. Geisheimer, J.L., Marshall, W.S., Greneker, E.: A continuous-wave (CW) radar for gait analysis. In: Proceedings of the Conference on Signals, Systems and Computers Record of the Thirty-Fifth Asilomar Conference, vol. 1, pp. 834–838 (2001)
40. Gill, T.M., Williams, C.S., Tinetti, M.E.: Assessing risk for the onset of functional dependence among older adults: the role of physical performance. J. Am. Geriatr. Soc. **43**(6), 603–609 (1995)
41. Goffredo, M., Carter, J.N., Nixon, M.S.: Front-view gait recognition. In: Proceedings of the 2nd IEEE International Conference on Biometrics: Theory, Applications and Systems BTAS 2008, pp. 1–6 (2008)
42. Greene, B.R., Donovan, A.O., Romero-Ortuno, R., Cogan, L., Ni Scanaill, C., Kenny, R.A.: Quantitative falls risk assessment using the timed up and go test. IEEE Trans. Biomed. Eng. **57**(12), 2918–2926 (2010)
43. Hagler, S., Austin, D., Hayes, T.L., Kaye, J., Pavel, M.: Unobtrusive and ubiquitous in-home monitoring: a methodology for continuous assessment of gait velocity in elders. IEEE Trans. Biomed. Eng. **57**(4), 813–820 (2010)
44. Hausdorff, J.M., Ladin, Z., Wei, J.Y.: Footswitch system for measurement of the temporal parameters of gait. J. Biomech. **28**(3), 347–351 (1995)
45. Health Level Seven International. CDA Release 2. Technical report (2005)
46. Helmer, A., Lipprandt, M., Frenken, T., Eichelberg, M., Hein, A.: 3DLC: a comprehensive model for personal health records supporting new types of medical applications. J. Healthc. Eng. **2**(3), 321–336 (2011)
47. Henriksen, M., Lund, H., Moe-Nilssen, R., Bliddal, H., Danneskiod-Samsøe, B.: Test-retest reliability of trunk accelerometric gait analysis. Gait Posture **19**(3), 288–297 (2004)
48. Holzinger, A., Searle, G., Wernbacher, M.: The effect of previous exposure to technology on acceptance and its importance in usability and accessibility engineering. Univ. Access Inf. Soc. **10**(3), 245–260 (2011)
49. Hornsteiner, C., Detlefsen, J.: Characterisation of human gait using a continuous-wave radar at 24 GHz. Adv. Radio Sci. **6**, 67–70 (2008)
50. Huang, B., Chen, M., Shi, X., Xu, Y.: Gait event detection with intelligent shoes. In: Proceedings of International Conference on Information Acquisition ICIA 2007, 8–11 July 2007, pp. 579–584 (2007)
51. Huitema, R.B., Hof, A.L., Postema, K.: Ultrasonic motion analysis system-measurement of temporal and spatial gait parameters. J. Biomech. **35**(6), 837–842 (2002)
52. Imms, F.J., Edholm, O.G.: Studies of gait and mobility in the elderly. Age Ageing **10**(3), 147–156 (1981)
53. Jang, Y., Shin, S., Lee, J.W., Kim, S.: A preliminary study for portable walking distance measurement system using ultrasonic sensors. In: Proceedings of 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society EMBS 2007, pp. 5290–5293 (2007)
54. Kamen, G., Patten, C., Du, C.D., Sison, S.: An accelerometry-based system for the assessment of balance and postural sway. Gerontology **44**(1), 40–45 (1998)
55. Kerr, K., White, J., Barr, D., Mollan, R.: Standardization and definitions of the sit-stand-sit movement cycle. Gait Posture **2**(3), 182–190 (1994)

56. Kiselev, J., Gövercin, M., Frenken, T., Hein, A., Steinhagen-Thiessen, E., Wegel, S.: A new device for the assessment of gait and mobility with an automated timed up & go (atug): study protocol of an initial validation study. Contemporary Clinical Trials (2012, submitted)
57. Kiss, R.: Comparison between kinematic and ground reaction force techniques for determining gait events during treadmill walking at different walking speeds. Med. Eng. Phys. **32**(6), 662–667 (2010)
58. Knight, H., Lee, J.-K., Ma, H.: Chair Alarm for patient fall prevention based on Gesture Recognition and Interactivity. In: Proceedings of 30th Annual International Conference of the IEEE Engineering in Medicine and Biology Society EMBS 2008, 20–25 August 2008, pp. 3698–3701 (2008)
59. Kong, K., Tomizuka, M.: A gait monitoring system based on air pressure sensors embedded in a shoe. IEEE/ASME Trans. Mechatron. **14**(3), 358–370 (2009)
60. Lai, D.T.H., Wrigley, T.V., Palaniswami, M.: Ultrasound monitoring of inter-knee distances during gait. In: Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society EMBC 2009, pp. 725–728 (2009)
61. Leu, A., Ristic-Durrant, D., Graser, A.: A robust markerless vision-based human gait analysis system. In: Proceedings of 6th IEEE International Symposium on Applied Computational Intelligence and Informatics (SACI), pp. 415–420 (2011)
62. Liao, H.-F., Mao, P.-J., Hwang, A.-W.: Test-retest reliability of balance tests in children with cerebral palsy. Dev. Med. Child Neurol. **43**(3), 180–186 (2001)
63. Liao, T.-Y., Miaou, S.-G., Li, Y.-R.: A vision-based walking posture analysis system without markers. In: Proceedings of the 2nd International Conference on Signal Processing Systems (ICSPS), vol. 3, pp. 254–258 (2010)
64. Lim, D.-W., Kim, D.-H., Shen, L., Kim, H.-M., Kim, S., Yu, H.K.: Stride rate estimation using UWB impulse radar. In: Proceedings of the 3rd Asia-Pacific International Conference on Synthetic Aperture Radar (APSAR), pp. 1–3 (2011)
65. Liu, J., Lockhart, T.E., Jones, M., Martin, T.: Local dynamic stability assessment of motion impaired elderly using electronic textile pants. IEEE Trans. Autom. Sci. Eng. **5**(4), 696–702 (2008)
66. Lombardi, R., Buizza, A., Gandolfi, R., Vignarelli, C., Guaita, A., Panella, L.: Measurement on tinetti test: instrumentation and procedures. Technol. Health Care J. Eur. Soc. Eng. Med. **9**(5), 403–416 (2001)
67. Mancini, M., Salarian, A., Carlson-Kuhta, P., Zampieri, C., King, L., Chiari, L., Horak, F.B., et al.: Isway: a sensitive, valid and reliable measure of postural control. J. Neuroengineering Rehabil. **9**(1), 59 (2012)
68. Mancini, M., Zampieri, C., Carlson-Kuhta, P., Chiari, L., Horak, F.B.: Anticipatory postural adjustments prior to step initiation are hypometric in untreated parkinsons disease: an accelerometer-based approach. Eur. J. Neurol. **16**(9), 1028–1034 (2009)
69. Marschollek, M., Goevercin, M., Wolf, K.-H., Song, B., Gietzelt, M., Haux, R., Steinhagen-Thiessen, E.: A performance comparison of accelerometry-based step detection algorithms on a large, non-laboratory sample of healthy and mobility-impaired persons. In: Proceedings of the 30th Annual International Conference of the IEEE Engineering in Medicine and Biology Society EMBS 2008, pp. 1319–1322 (2008)
70. Marschollek, M., Nemitz, G., Gietzelt, M., Wolf, K., Meyer zu Schwabedissen, H., Haux, R.: Predicting in-patient falls in a geriatric clinic. Zeitschrift fr Gerontologie und Geriatrie **42**, 317–322 (2009)

71. Mathie, M.J., Coster, A.C.F., Lovell, N.H., Celler, B.G.: Accelerometry: providing an integrated, practical method for long-term, ambulatory monitoring of human movement. Physiol. Meas. **25**(2), R1 (2004)
72. Mayagoitia, R.E., Lotters, J.C., Veltink, P.H.: Standing stability evaluation using a triaxial accelerometer. In: Proceedings of 18th Annual International Conference of the IEEE Bridging Disciplines for Biomedicine Engineering in Medicine and Biology Society, October 31–November 3 1996, vol. 2, pp. 573–574 (1996)
73. Melenhorst, A.-S., Rogers, W.A., Bouwhuis, D.G.: Older adults' motivated choice for technological innovation: evidence for benefit-driven selectivity. Psychol. Aging **21**(1), 190 (2006)
74. Menz, H.B., Lord, S.R., Fitzpatrick, R.C.: Age-related differences in walking stability. Age Ageing **32**(2), 137–142 (2003)
75. Montero-Odasso, M., Schapira, M., Soriano, E.R., Varela, M., Kaplan, R., Camera, L.A., Mayorga, L.M.: Gait velocity as a single predictor of adverse events in healthy seniors aged 75 years and older. J. Gerontol. A Biol. Sci. Med. Sci. **60**(10), 1304–1309 (2005)
76. Muras, J.: SMOOTH - a system for mobility training at home for people with Parkinson's disease. Ph.D. thesis, Trinity College Dublin (2010)
77. Najafi, B., Aminian, K., Loew, F., Blanc, Y., Robert, P.A.: Measurement of stand-sit and sit-stand transitions using a miniature gyroscope and its application in fall risk evaluation in the elderly. IEEE Trans. Biomed. Eng. **49**(8), 843–851 (2002)
78. Narayanan, M.R., Redmond, S.J., Scalzi, M.E., Lord, S.R., Celler, B.G., Ast, N.H.L.: Longitudinal falls-risk estimation using triaxial accelerometry. IEEE Trans. Biomed. Eng. **57**(3), 534–541 (2010)
79. Nester, C., Jones, R.K., Liu, A., Howard, D., Lundberg, A., Arndt, A., Lundgren, P., Stacoff, A., Wolf, P.: Foot kinematics during walking measured using bone and surface mounted markers. J. Biomech. **40**(15), 3412–3423 (2007)
80. Organization, W.H., et al.: International classification of functioning disability and health (ICF). resolution WHA 54.21 (2001)
81. Otero, M.: Application of a continuous wave radar for human gait recognition. In: Kadar, I. (ed.) Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, vol. 5809, pp. 538–548, May 2005
82. Pallejà, T., Teixidó, M., Tresanchez, M., Palacín, J.: Measuring gait using a ground laser range sensor. Sensors **9**(11), 9133–9146 (2009)
83. Pappas, I.P.I., Keller, T., Mangold, S., Popovic, M.R., Dietz, V., Morari, M.: A reliable gyroscope-based gait-phase detection sensor embedded in a shoe insole. IEEE Sens. J. **4**(2), 268–274 (2004)
84. Pavel, M., Hayes, T., Tsay, I., Erdogmus, D., Paul, A., Larimer, N., Jimison, H., Nutt, J.: Continuous assessment of gait velocity in Parkinson's disease from unobtrusive measurements. In: Proceedings of the 3rd International IEEE/EMBS Conference on Neural Engineering CNE 2007, 2–5 May 2007, pp. 700–703 (2007)
85. Pavel, M., Hayes, T.L., Adami, A., Jimison, H., Kaye, J.: Unobtrusive assessment of mobility. In: Proceedings of the 28th Annual International Conference of the IEEE Engineering in Medicine and Biology Society EMBS 2006, pp. 6277–6280, August 2006
86. Perez, C., Oates, A., Hughey, L., Fung, J.: Development of a force-sensing cane instrumented within a treadmill-based virtual reality locomotor system. In: Proceedings of the International Conference on Virtual Rehabilitation, pp. 154–159 (2009)

87. Perry, M., Dowdall, A., Lines, L., Hone, K.: Multimodal and ubiquitous computing systems: supporting independent-living older users. IEEE Trans. Inf. Technol. Biomed. **8**(3), 258–270 (2004)
88. Podsiadlo, D., Richardson, S.: The timed "Up & Go": a test of basic functional mobility for frail elderly persons. J. Am. Geriatr. Soc. **39**(2), 142–148 (1991)
89. Poppe, R.: Vision-based human motion analysis: an overview. Comput. Vis. Image Underst. **108**, 4–18 (2007)
90. Ram, S.S., Li, Y., Lin, A., Ling, H.: Doppler-based detection and tracking of humans in indoor environments. J. Franklin Inst. **345**(6), 679–699 (2008)
91. Salarian, A., Horak, F.B., Zampieri, C., Carlson-Kuhta, P., Nutt, J.G., Aminian, K.: iTUG, a sensitive and reliable measure of mobility. IEEE Trans. Neural Syst. Rehabil. Eng. **18**(3), 303–310 (2010)
92. Scanaill, C.N., Carew, S., Barralon, P., Noury, N., Lyons, D., Lyons, G.M.: A review of approaches to mobility telemonitoring of the elderly in their living environment. Ann. Biomed. Eng. **34**(4), 547–563 (2006)
93. Shao, X., Zhao, H., Nakamura, K., Katabira, K., Shibasaki, R., Nakagawa, Y.: Detection and tracking of multiple pedestrians by using laser range scanners. In: IEEE/RSJ International Conference on Intelligent Robots and Systems, 2007, IROS 2007, pp. 2174–2179 (2007)
94. Sixsmith, A.J.: An evaluation of an intelligent home monitoring system. J. Telemedicine Telecare **6**(2), 63–72 (2000)
95. Skelly, M.M., Chizeck, H.J.: Real-time gait event detection for paraplegic FES walking. IEEE Trans. Neural Syst. Rehabil. Eng. **9**(1), 59–68 (2001)
96. Smarr, C.-A., Fausset, C.B., Rogers, W.A.: Understanding the potential for robot assistance for older adults in the home environment. Georgia Institute of Technology (2011)
97. Smith, G.E., Ahmad, F., Amin, M.G.: Micro-Doppler processing for ultra-wideband radar data. In: SPIE Defense, Security, and Sensing, pp. 83610L–83610L. International Society for Optics and Photonics (2012)
98. Spehr, J., Gietzelt, M., Wegel, S., Költzsch, Y., Winkelbach, S., Marschollek, M., Gövercin, M., Wahl, F., Haux, R., Steinhagen-Thiessen, E.: Vermessung von Gangparametern zur Sturzprädikation durch Vision- und Beschleunigungssensorik. In: Demographischer Wandel - Assistenzsysteme aus der Forschung in den Markt (AAL 2011), p. 5 (2011)
99. Steen, E.-E., Eichelberg, M., Nebel, W., Hein, A.: A novel indoor localization approach using dynamic changes in ultrasonic echoes. In: Wichert, R., Eberhardt, B. (eds.) Ambient Assisted Living. Advanced Technologies and Societal Change, pp. 61–76. Springer, Heidelberg (2012)
100. Stolze, H., Klebe, S., Baecker, C., Zechlin, C., Friege, L., Pohle, S., Deuschl, G.: Prevalence of gait disorders in hospitalized neurological patients. Mov. Disord. **20**(1), 89–94 (2005)
101. Stone, E., Skubic, M.: Mapping kinect-based in-home gait speed to tug time: a methodology to facilitate clinical interpretation. In: 2013 7th International Conference on Pervasive Computing Technologies for Healthcare (PervasiveHealth), pp. 57–64 (2013)
102. Stone, E.E., Skubic, M.: Evaluation of an inexpensive depth camera for passive in-home fall risk assessment. In: Proceedings of 5th International Conference on Pervasive Computing Technologies for Healthcare (PervasiveHealth), pp. 71–77 (2011)

103. Stone, E.E., Skubic, M.: Passive in-home measurement of stride-to-stride gait variability comparing vision and kinect sensing. In: 2011 Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBC, pp. 6491–6494. IEEE (2011)
104. Stone, E.-E., Skubic, M.: Passive, in-home gait measurement using an inexpensive depth camera: initial results. In: Proceedings of the 6th International Conference on Pervasive Computing Technologies for Healthcare (PervasiveHealth), pp. 183–186 (2012)
105. Sutherland, D.H.: The evolution of clinical gait analysis part l: kinesiological EMG. Gait Posture **14**(1), 61–70 (2001)
106. Sutherland, D.H.: The evolution of clinical gait analysis: Part II Kinematics. Gait Posture **16**(2), 159–179 (2002)
107. Sutherland, D.H.: The evolution of clinical gait analysis part III - kinetics and energy assessment. Gait Posture **21**(4), 447–461 (2005)
108. Tinetti, M.E.: Performance-oriented assessment of mobility problems in elderly patients. J. Am. Geriatr. Soc. **34**(2), 119–126 (1986)
109. Tung, J., Gage, W., Zabjek, K., Brooks, D., Maki, D., Mihailidis, A., Fernie, G.R., McIlroy, W.E.: iWalker: a 'real-world' mobility assessment tool. In: 30th Canadian Medical and Biological Engineering Society. Canadian Medical & Biological Engineering Society (2007)
110. van Doorn, C., Gruber-Baldini, A.L., Zimmerman, S., Hebel, J.R., Port, C.L., Baumgarten, M., Quinn, C.C., Taler, G., May, C., Magaziner, J., Epidemiology of Dementia in Nursing Homes Research Group: Dementia as a risk factor for falls and fall injuries among nursing home residents. J. Am. Geriatr. Soc. **51**(9), 1213–1218 (2003)
111. Verghese, J., Lipton, R.B., Hall, C.B., Kuslansky, G., Katz, M.J., Buschke, H.: Abnormality of gait as a predictor of non-Alzheimer's dementia. N. Engl. J. Med. **347**(22), 1761–1768 (2002)
112. Vignaud, L., Ghaleb, A., Le Kernec, J., Nicolas, J.-M.: Radar high resolution range & micro-Doppler analysis of human motions. In: Proceedings of the International RADAR Conference-Surveillance for a Safer World, pp. 1–6 (2009)
113. Virone, G., Noury, N., Demongeot, J.: A system for automatic measurement of circadian activity deviations in telemedicine. IEEE Trans. Biomed. Eng. **49**(12), 1463–1469 (2002)
114. Wahab, Y., Bakar, N.A.: Microsystem based portable shoe integrated instrumentation using ultrasonic for gait analysis measurement. In: Proceedings of the 4th International Conference on Mechatronics (ICOM), pp. 1–4 (2011)
115. Wall, J.C., Bell, C., Campbell, S., Davis, J.: The timed Get-up-and-Go test revisited: measurement of the component tasks. J. Rehabil. Res. Dev. **37**(1), 109–113 (2000)
116. Wang, F., Skubic, M., Abbott, C., Keller, J.M.: Body sway measurement for fall risk assessment using inexpensive webcams. In: Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), pp. 2225–2229 (2010)
117. Wang, Y., Fathy, A.E.: Range-time-frequency representation of a pulse Doppler radar imaging system for indoor localization and classification. In: 2013 IEEE Topical Conference on Wireless Sensors and Sensor Networks (WiSNet), pp. 34–36. IEEE (2013)

118. Weir, R.F., Childress, D.S.: Portable devices for the clinical measurement of gait performance and outcomes. In: Proceedings of the 22nd Annual International Conference of the IEEE Engineering in Medicine and Biology Society, vol. 3, pp. 1873–1875 (2000)
119. Weiss, A., Herman, T., Plotnik, M., Brozgol, M., Giladi, N., Hausdorff, J.M.: An instrumented timed up and go: the added value of an accelerometer for identifying fall risk in idiopathic fallers. Physiol. Meas. **32**(12), 2003 (2011)
120. Whitney, J.C., Lord, S.R., Close, J.C.T.: Streamlining assessment and intervention in a falls clinic using the Timed Up and Go Test and Physiological Profile Assessments. Age Ageing **34**(6), 567–571 (2005)
121. Williamson, R., Andrews, B.J.: Gait event detection for FES using accelerometers and supervised machine learning. IEEE Trans. Rehabil. Eng. **8**(3), 312–319 (2000)
122. Yack, H.J., Berger, R.C.: Dynamic stability in the elderly: identifying a possible measure. J. Gerontol. **48**(5), M225–M230 (1993)
123. Yamada, M., Kamiya, K., Kudo, M., Nonaka, H., Toyama, J.: Soft authentication and behavior analysis using a chair with sensors attached: hipprint authentication. Pattern Anal. Appl. **12**, 251–260 (2009)
124. Yardibi, T., Cuddihy, P., Genc, S., Bufi, C., Skubic, M., Rantz, M., Liu, L., Phillips, C.: Gait characterization via pulse-Doppler radar. In: Proceedings of the IEEE International Conference on Pervasive Computing and Communications Workshops (PERCOM Workshops), pp. 662–667 (2011)
125. Zampieri, C., Salarian, A., Carlson-Kuhta, P., Aminian, K., Nutt, J.G., Horak, F.B.: The instrumented timed up and go test: potential outcome measure for disease modifying therapies in Parkinson's disease. J. Neurol. Neurosurg. Psychiatry **81**(2), 171–176 (2010)
126. Zampieri, C., Salarian, A., Carlson-Kuhta, P., Nutt, J.G., Horak, F.B.: Assessing mobility at home in people with early Parkinson's disease using an instrumented Timed Up and Go test. Parkinsonism Relat. Disord. **17**(4), 277–280 (2011).http://dx.doi.org/10.1016/j.parkreldis.2010.08.001
127. Zhu, H.S., Wertsch, J.J., Harris, G.F., Loftsgaarden, J.D., Price, M.B.: Foot pressure distribution during walking and shuffling. Arch. Phys. Med. Rehabil. **72**(6), 390–397 (1991)
128. Zijlstra, W.: Assessment of spatio-temporal parameters during unconstrained walking. Eur. J. Appl. Physiol. **92**, 39–44 (2004)
129. Zijlstra, W., Hof, A.L.: Assessment of spatio-temporal gait parameters from trunk accelerations during human walking. Gait Posture **18**(2), 1–10 (2003)
130. Zubeyde Gurbtiz, S., Melvin, W.L., Williams, D.B.: Comparison of radar-based human detection techniques. In: Proceedings of the Conference Record of the Forty-First Asilomar Conference on Signals, Systems and Computers ACSSC 2007, pp. 2199–2203 (2007)

Reading

Instead of providing even more references than already done, we want to provide a short list of further sources that continuously offer new information in this and relevant research areas (sorted alphabetically).

- International Conference on Intelligent Environments, IE, http://www.intenv.org
- International Conference on Pervasive Computing and Communications, IEEE PerCom, http://www.percom.org/
- International Conference on Pervasive Computing Technologies for Healthcare, http://pervasivehealth.org
- International Conference on PErvasive Technologies Related to Assistive Environments, PETRA, http://www.petrae.org
- Journal of Ambient Intelligence and Smart Environments (JAISE), http://www.jaise-journal.org/
- Journal IEEE Pervasive Computing, http://www.computer.org/portal/web/computingnow/pervasivecomputing
- Journal Pervasive and Mobile Computing, Elsevier, http://www.ees.elsevier.com/pmc