A Novel ICT Approach to the Assessment of Mobility in Diverse Health Care Environments

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Abstract—ICT and medical experts have to work together in order to meet the challenges imposed by the demographic change. The Ambient Timed Up & Go (aTUG) approach, whose development and evaluation is presented and discussed in this paper, is an example for such cooperation which aims at making existing medical processes more effective and at enabling seamless provision of care between professional and domestic environments. aTUG is an approach and apparatus that provides technical support for execution of geriatric mobility assessment tests in professional and domestic environments and that yields the advantages of being more objective and more detailed while saving time. Additionally, aTUG enables physicians to include assessment data from domestic environments into their decisions, especially to enable more early prevention and sustainable rehabilitation. However, the explanatory power of assessment results from domestic environments is still unclear and their integration into medical decisions is discussed within this paper.

I. INTRODUCTION

The so called double aging especially in industrial countries due to the demographic change poses many socio-economic challenges to health care systems. If current trends retain a smaller number of health care professionals will have to deal with a larger number of elderly people requiring either medical treatment in in-patient situations, or care at home. In order to deal with these challenges, current health care provision procedures in professional environments have to become more effective and new procedures have to be developed in order to reduce the number of people requiring help in pursuing an independent lifestyle. The latter can only be achieved by enabling earlier prevention and more effective long-term rehabilitation directly in peoples’ homes. A cost-effective way to achieve these requirements is through ICT. One example for such ICT is the aTUG approach and apparatus presented within this paper. aTUG makes the frequent execution of geriatric mobility assessment tests, especially the Timed Up& Go assessment (TUG) [1] test, in professional environments more time-effective and objective while providing even more information and enables the unobtrusive transfer of mobility assessment tests to domestic environments. Within this paper we will describe the development and evaluation process of the aTUG approach and apparatus as one example for ICT that helps to seamlessly provide care between professional and domestic environments. Starting with the prototyping and construction, the description will mainly focus on technical, domestic, and clinical evaluations performed. The conducted research and development is briefly motivated and the relevant state of the art is described.

II. MEDICAL MOTIVATION

In geriatrics the ultimate aim of each treatment is to recover or maintain a self-dependent lifestyle. Therefore, performing a detailed diagnosis is less important than identifying functional deficits in order to provide rehabilitation or functional aid. In order to identify relevant domains, assessment tests have been developed for which established data exist that represent the abilities of healthy elderly people. Results of assessment tests, which are often only single key figures like the duration of a test, do only indicate that the abilities of a patient are worse than established thresholds. However, in order to provide targeted rehabilitation or aid, at least the causes of some deficits have to be identified. Treatment may be different if a patient performs worse in a time-based test due to insufficient muscle power or due to slow reaction times. Therefore, in some assessment domains more detailed tests have to be performed in order to diagnose the causes of deficits found by using assessment tests.

Most assessment test are performed using no or only very limited technical support. This poses many problems like subjective execution, timely limited insights into patients’ abilities, wrong classifications due to patients performing at their best in a test situation, required training of caregivers, required time-effort and others [2]. If more detailed tests are required in the field of mobility, this often means performing a gait analysis. Today, such analysis requires expert knowledge, specialized equipment, and much time. Most of these are not available in a geriatric team. With regard to the demographic change and the expected increasing numbers of patients compared to the decreasing number of available caregivers such problems become even more important.

In summary, there is a clear demand for technical systems that make the execution of geriatric assessment tests more objective and less time-intensive. Additionally, such systems should ideally enable physician to even explain possible functional deficits found by performing more detailed tests. In the field on mobility this means performing gait analysis. A future step will be to bring assessment tests to patients’ homes.
III. STATE OF THE ART

Within this section technical approaches to gait analysis and support of mobility assessment tests, especially the TUG test, are described. While both field have previously been worked on separately, recent approaches have demonstrated the combination of support for assessment tests and gait analysis even at point of care.

A. Technical Approaches to Gait Analysis

Today, gait analysis is mainly executed in specialized wards of professional care facilities with specialized, expensive, and non-transportable equipment. Recent research investigated mobility (tele-) monitoring by use of less expensive and more mobile approaches. The main research objective was to make mobility analysis usable at point of care. Several approaches to gait analysis either by use of body-worn or ambient sensors have been described so far. Since our approach is exclusively based on the use of ambient sensors, we focus on approaches utilizing those sensors.

Gait and balance analysis using ambient sensors can either be performed by analyzing the kinetics i.e. the force generated while walking or the kinematics i.e. the movements of body-parts of a patient. Gait analysis has been shown to work using pressure sensors integrated into floors, mats or walking aids, by use of imaging technologies like (stereo) cameras with markers, e.g. Vicon, and without, e.g. Kinect sensor or fluoroscopy, by electromyography analyzing electric pulses generated by muscles, by tracking presence, e.g. by use of home automation technology, and by tracking distance through measuring signal propagation time, e.g. by use or SONAR / ultrasonic sensors, RADAR, or LIDAR. While nearly all approaches have their advantages and disadvantages, use of LIDAR technology was heavily investigated especially in the field of robotics within the last years due to the high precision of those sensors supplemented by prices scaling down continuously. [4] have presented an approach to basic gait analysis. Distance to patients’ legs is measured continuously while walking across a straight line towards the used laser range scanner. Recognized extracted circles are tracked in consecutive scans and are assigned to swing and stance phases according to the distance difference to previous scans. Within our own work [5] we have demonstrated the use of a laser range scanner for precise assessment of self-selected gait velocity in domestic environments.

B. Technical Support for Mobility Assessment

The Timed Up & Go (TUG) assessment test, developed by Podsiadlo and Richardson, [1] in one of the most frequently used assessment tests in field of mobility. Within TUG a stopwatch is used to measure the time a patient takes to complete a set of components: rise from a chair, walk 3m, turn around, walk back, and sit down again. According to the time taken by the patient to complete the test, he or she is arranged into a result group which gives a hint to the treating caregiver for required actions. TUG was enhanced several times. For the sake of simplicity the test focuses only on the time used by the patients to complete the whole test. Time taken to perform the single components of the test and other deficits of moving are ignored. Therefore, Wall et al. [6] proposed the so-called Expanded Timed Get-up-and-Go (ETGUG). Measuring the single components’ duration is thought to help discriminate abilities of patients better.

Instrumented TUG has so far most often been implemented using body-worn inertial sensors. TUG-T [7] is an early, technically-supported version of TUG by use of two inertial sensors that measures the duration of six components (standing-up, walking forward, turn 1, walking back, turn 2, sitting down). Recent approaches also compute gait and balance parameters during execution of the test. Greene et al. [8] employed two inertial, Weiss et al. [9] and Marschollek et al. [10] only a single 3D accelerometer to instrument TUG and to evaluate the instrumented tests’ abilities to discriminate fallers from non-fallers compared to manually executed TUG tests. The approach from Marschollek et al. was recently extended with a monocular camera system [11]. Salarin and Zampieri developed iTUG an instrumented version of TUG utilizing seven inertial sensors [12] that measures duration of four components (sit-to-stand, steady-state gait, turning, turn-to-sit) and a set of balance and gait parameters. Meanwhile, iTUG is one of the first commercially available systems. iTUG requires physicians to attach either four or six 3D accelerometers to the patients. Within our own research, we have demonstrated the use of exclusively ambient sensor technologies, i.e. a laser range scanner, four force sensors, and optionally home automation sensors, to support the execution of component-based TUG and a parallel gait and balance analysis [13]. In the authors’ opinion ambient sensor have the major advantage of not requiring a handling by either experts or layman, even in unsupervised situations.

Recent research investigated means for execution of TUG in unsupervised situations. Narayanan et al. [14] employ a waist-mounted 3D accelerometer within their so-called Directed Routine (DR) in which patients are meant to execute the TUG test on their own when coming back home. It is questionable whether such procedures are accepted by patients and if they provide realistic results.

C. Limitations

The most sophisticated and precise technical approach to gait analysis are marked-based tracking systems. However, such systems are not transportable and require much time effort to place markers and analyze the recordings. Pressure sensors in mats, like GaitRite, are also viable but can only measure on a spatially limited area. Other approaches have special use cases but are in most cases too limited or too specialized to be used for a general gait analysis. None of these approaches may be easily transported. Approaches using transportable sensors, either body-worn or ambient, provide similar precision but enable physicians to execute gait analysis at point of care and with less effort. Compared to gait analysis, assessment tests have been technically supported for only a short period of time. Again, transportable sensors have been...
used to enable physicians to execute the tests directly in geriatric stations. An enhancement with gait analysis features was reasonable. Recent research approaches, which are currently transferred into products, perform a detailed gait analysis while executing mobility assessment tests. Regarding body-worn approaches, extra time effort is required for donning the sensors to patients which are then aware of performing a test. Usage of ambient sensors yield the advantage of not requiring any extra time effort and may, especially in domestic environments, be used to assess people without making them aware of the assessment.

In summary, regarding ICT for supporting mobility assessment tests, the main limitations are that some approaches provide more details and more objective results but require more time than manually executed assessment tests e.g. since donning of sensors is required. With the objective of providing assessment information from domestic environments, the greatest limitation are that most available approaches are either not suitable for use by layman themselves or try to perform such domestic environment the same way as performed in clinical environments i.e. as a test which may not be accepted by people and which may not provide realistic results.

IV. APPROACH

Our own novel approach, called automated Timed Up & Go (aTUG), to supporting the execution of mobility assessment tests in professional 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 computing the duration of each component of an assessment test and by utilizing the recordings to perform a gait and balance analysis, if requested.

Part of the aTUG approach is the aTUG apparatus which was 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. An early prototype is shown in Figure 1a. 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. The 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, the new prototype (Figure 1b) was technically validated for support of the TUG tests (section V) 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 (section VI). Currently, the aTUG apparatus is in a clinical trial of medical products (section VII) in which it is clinically validated against manual measurements and the GaitRite system at the Charité in Berlin.

Within the following sections we will describe the results of the technical validation, the field trial, and the objectives of the ongoing clinical trial. Afterwards, we will discuss the possible impact of aTUG and similar products and the future direction of the aTUG approach.

V. TECHNICAL VALIDATION

In order to prepare the aTUG apparatus for usage in a clinical trial, the device was technically validated according to its intended functionality which is (a) computing the duration of TUG and its components and (b) performing a gait analysis by computing a set of spatio-temporal parameters of gait. The results of the first validation is described within the following section, the validation of the gait analysis will be presented in a future paper.

The technical validation of the assessment support had two main goals: (1) To compare the precision of video-based measurements, stopwatch measurements, and sensor measurements in traditional TUG and to compare the precision of the different sensors, and (2) to evaluate whether the aTUG apparatus and algorithms can be used to reliably compute the duration of the aTUG components compared to video recordings.

The experiment was conducted with five elderly patients, four female and one male, with ages ranging from 74 to 91 years in a residential care facility in Oldenburg, Germany [13]. All patients were multi-morbid. Figure 2 shows the experimental
setup within an empty flat of the residential care facility. The chair (A) stood at the wall and white markings were placed on the floor (B) every half meter as reference marks for video comparison. A second light barrier (E) was placed three meters ahead of the chair in order to mark the end of the three meter walk path. The white marking (D) at the end of the path is four meters in front of the chair and marks the latest turning point. The patients were told to turn between the second light barrier and the four meter marking. We used a cost effective Hokuyo URG-04LX-UG01 laser range scanner with a nominal range of 5.6 meters and a measurement range of 240° (120° to each side of the chair). The participants were asked to wear white cuffs (C) to achieve better reflection and thus optimal measurements results with the laser range scanner.

The experiment was conducted on a single day from 1:30 p.m. until 6:00 p.m. maintaining appropriate light levels. One patient after another was asked into the room, the general goal of the experiment was explained and an informed consent document was signed. The course of actions during the experiment, but no technical details on the measurements, were explained. Additionally, the moderator of the experiment showed the complete procedure himself. Afterwards, the patients were allowed one try to practice the TUG. After a short break, the patients were asked to do a first pass of the TUG. The experiments started after a clear sign of the moderator, measurements started as soon as the patients broke contact with the chair’s back. Each attempt was documented by the video camera. A second pass was conducted after another short break. After the experiment, all other questions of the patients regarding technical issues and possible impact for health care were discussed. In summary, the results of ten TUG runs have shown for the first objective that aTUG is capable of precisely computing the duration of the components (using the lowest error for each component) was between −0.52 and 0.67, so below one second compared to the video analysis. Standard deviation was between 0.12 and 0.89, so below one second. In summary, aTUG is capable of precisely computing the duration of the components of TUG. Using only force sensors and the laser range scanner the mean error is 0.05 s, mean standard deviation is 0.59 s. Combining the first light barrier and the laser range scanner gives slightly worse results of 0.09 and 0.59 s.

VI. DOMESTIC EVALUATION

In order to evaluate the application in domestic environments, a field trial with five elderly people was performed in Oldenburg, Germany over a period of five weeks from 2011/10/10 to 2011/11/10 [15]. The two main objectives were: (1) to proof the general feasibility of quality criteria defined to examine sensor recordings of a laser range scanner (LRS) for the components walking there/back and turning and (2) to compare gait velocity computations from a supervised TUG test to gait velocity results computed from LRS measurements and consecutive activations of home automation sensors during unsupervised assessments.

A community-dwelling elderly female person aged 76 years living alone and mostly independent participated. Home automation (HA) sensors, five light barriers and five reed contacts, were installed in the flat. Figure 3 shows an abstracted room model of the flat including sensor placement (grey boxes, LB=light barrier, RC=reed contact) and computed walking paths (lines) at the left side. The model is used to compute the length of possible moving paths between those sensors (details in [16]). Additionally, the flat was equipped with a laser range scanner (Hokuyo URG-04LX) which was placed at a central point within the floor (Figure 3 in the middle). The sensor recorded continuously and each activation of a HA sensor was marked within the data stream. Figure 3 shows a visualization of LRS in a Cartesian coordinate system at the right. Black dots indicate measured environment. Circles and squares indicate stand phases for the left and right leg recognized from someone walking along the floor. The bold dashed line indicates the ideal walking path for this measurement to which differences for each stand phase are computed in order to compute the straightness of walking. As a clinically validated reference value the participant completed six Timed Up & Go assessment tests using the aTUG apparatus before and four tests after the field trial in an unobstructed room.

Over a period of five weeks a total amount of 189 GB sensor recordings were collected. These data included overall 105050 activations of HA sensors from which 27595 traversed walking paths could be detected. 8766 walking path transitions could be measured by HA sensors and LRS continuously. Using the data collected during the TUG tests performed before and after the field trial, a mean gait velocity of 1.18m/s (min. 1.01m/s, max. 1.45m/s including standard deviations) for straight walking was computed. This value was regarded as a clinical reference value for capacity in walking speed during the evaluation. Additionally, thresholds for quality criteria
were computed using the collected data. Using the sensor recordings from the flat, the duration for the transitions as measured by the HA sensors and the LRS and the resulting gait velocities were computed. Using only the data recorded by the LRS the real distance traversed and the quality criteria scores for walking there/back and for turning were computed. Regarding the first objective, results show that the presented quality criteria are suitable to select LRS measurements according to their eligibility to assess a certain test component. The larger the computed validity score the closer is the computed mean gait velocity to the reference value of 1.18m/s. Therefore we conclude that the defined quality criteria can be used to filter sensor recordings so that only those recordings are kept that represent valid results. Regarding the second objective, we conclude that our previous results from a laboratory setting are also valid in a domestic environment: Self-selected gait velocity can be computed unsupervised using HA sensors as well as with a LRS. LRS is more precise, HA sensors provide reasonable results while being more cost-effective. In the domestic environment we found a gait velocity of 0.71m/s compared to 1.18m/s under ideal circumstances. For the evaluated participant and setting there was a difference of 0.47m/s between performance and capacity in gait velocity.

VII. CLINICAL EVALUATION

Currently, aTUG is evaluated in its final application environments. Regarding the usage in professional environments, the aTUG chair is validated within a clinical trial which started in April 2012 at the Charité Berlin [17]. Within the study overall 110 patients will complete the TUG test two times each while being measured manually using a stopwatch, by the aTUG chair’s sensors, and by a GaitRite™ system. Additionally, patients will optionally complete a 6 m walking test while being recorded. Thereby, our approach will be validated in computing the total duration of TUG against manual measurement, which is the current gold standard. Additionally, gait parameters will be computed and compared to results from the GaitRite™ system. Computations will be done for the 3 m walking distances in TUG and the 6 m walking test, if available. The predictive power of all outcome variables for assessing risk of falling is evaluated as well.

VIII. DISCUSSION AND FUTURE DIRECTIONS

aTUG and some other approaches are close to being available as medical products. In daily clinical practice their main advantage will be to provide more detailed and objective results than a 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 are not sufficient. One possibility to save more costs is by early prevention and more sustainable rehabilitation for which domestic assessments may provide the required data. For the aTUG approach we have already shown that such assessment tests may be implemented without creating a test situation and thus can be totally unobtrusive. From a technical point of view, a continuous assessment of patients’ abilities from professional to domestic environments and vice versa is possible today. However, even if continuous assessment results will be available to physicians in the near future it remains unclear how recognized differences and changes over time 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, we have developed the 3DLC model [18]. 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 are 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 result 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. However, 3DLC is not capable of defining the meaning of certain domestic assessment results and their difference to results from professional environments during a medical treatment. More research is required. We are now pursuing more field trials in order to gain a deeper insight into domestic assessment results.

IX. SUMMARY

In order to keep up the quality of care within the next years shaped by the demographic change, there is a clear demand for support by ICT especially in the field of geriatrics. Therefore, efforts have been invested into research and construction of technical systems for assessment support. Several of those approaches are close to product stage. The aTUG apparatus is one example for such a new medical product that have the advantages of providing more detailed information about a patient’s abilities than a manually executed test while saving time. Due to the use of ambient sensor technologies and the computation of quality criteria, aTUG may also be used in domestic environments to implement unsupervised assessment tests without creating a test situation. In 2009 the aTUG apparatus was constructed from sketch according to the demand of medical experts and after that was technically validated in clinical and domestic settings. Currently, the aTUG chair is clinically validated in a trial at the Charité in Berlin. Thereby, we have already shown that it is technically possible to significantly enhance current medical assessment procedures by use of ICT and that those procedures may be brought to domestic environments unobtrusively. Although these new information may help to enable prevention and rehabilitation at home in the future, domestic assessment results differ from clinical results. It is up to medical experts to interpret the results respectively their differences. New models for data interpretation are required. In that aTUG is a typical example for AAL approaches in general which are able to bring health care provision to domestic domains but do also show that medical and technical experts have to work together in order to adapt current procedures to those new health care environments.

REFERENCES


