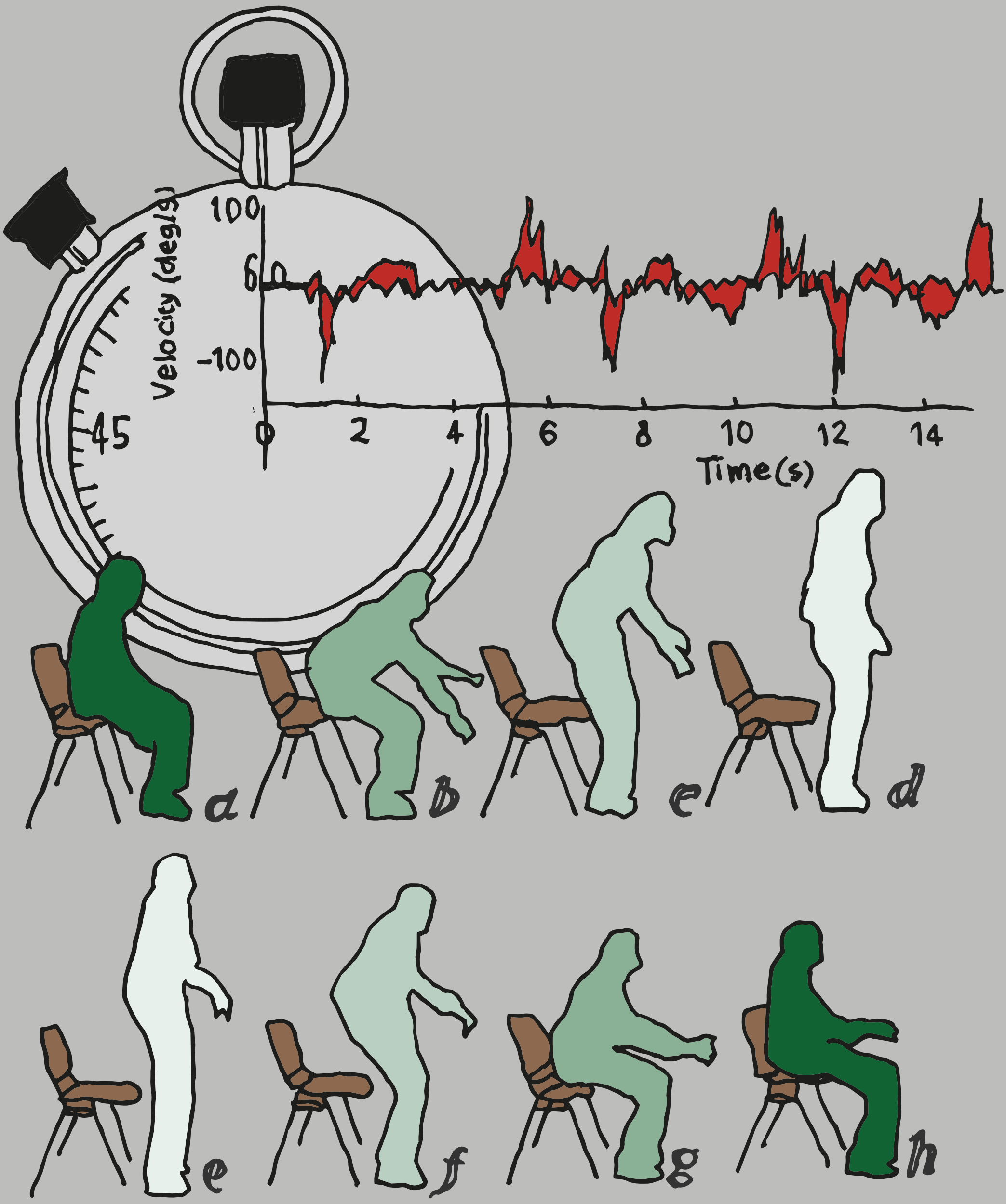

Assessing Sit-to-Stand for Clinical Use

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prof.dr. W. Zijlstra

"If you can't stand up, you can't walk"

CONTENTS

CHAPTER 1

Introduction

INTRODUCTION

WHY STUDYING SIT-TO-STAND?

GROWING NUMBER OF OLDER ADULTS WITH PROBLEMS STANDING UP

In 2015, the Dutch government decided to cut back on long-term care by 3.5 billion euro per year. As a prelude to this decision, the Dutch Central Statistical Office announced in 2014 that the government aims to enable older people to live independently as long as possible, implying that fewer older adults will be admitted to residential care homes. Whether or not this is feasible depends on the health status of those people. It is not so much diseases as such, but rather their ensuing limitations that cause the main obstacles to independent living (https://www.cbs.nl/nl-nl/achtergrond/2015/18/beperkingen-in-dagelijkse-handelingen-bij-ouderen) (25-07-2016). To date, however, no new policy has been announced to enable older patients to stay mobile and live independently for a longer period.

The ability to rise from sitting to standing is critical to an individual's quality of life, as it is a prerequisite for functional independence. One of the few publications on the hierarchy of disability indicates that problems in standing up become manifest much later than limitations in walking [1]. Disability to stand up has long been seen as a problem of the very old and as a consequence the amount of Sit-To-Stand (STS) research has been smaller and of more recent origin than gait research (Figure 1).

There are several reasons why the disability of standing up from sitting increases with age. Above 50 years of age muscle mass reduces at a rate of 1-2% per year while muscle force declines, a process called sarcopenia [2]. It can be expected that a higher life expectancy will result in more people losing motor abilities due to a lack of muscle strength. The Sit-to-Stand (STS) transition is considered one of the most mechanically demanding physical activities in daily life [3], because it requires displacement of body weight against gravity. The loss of muscle mass and muscle force will impact this transfer more than walking. Over the last 100 years the mean life expectancy has increased from 40 to 80 years [4]. By the year 2025, 26 countries are predicted to have a life expectancy at birth of 80 years or older [5]. This implies that more and more people will be confronted with problems standing up.

An increase in longevity will lead to an increasing number of older adults with chronic diseases with a potentially negative impact on the ability to stand up. These chronic diseases include respiratory and cardiovascular diseases, osteoarthritis, Parkinson's disease, stroke, rheumatic disease, vestibular dysfunction, and diabetes. Recent research has shown that limb muscle dysfunction is an essential systemic consequence of Chronic Obstructive Pulmonary Disease, which may have a detrimental effect on the ability to rise from sit to stand [6]. Also patients with Pulmonary Arterial Hypertension present significant peripheral muscle changes [7].

NUMBER OF PUBLICATIONS ABOUT STS

Clinical movement analysis has long been dominated by the analysis of walking, or 'gait analysis'. This dominance is reflected in the number of publications on 'gait analysis' vis-à-vis other motor activities in MEDLINE. The number of publications with the search term 'gait analysis' generated over 9 times more hits than the search term 'sit-to-stand' (Figure 1). ((http://www.ncbi.nlm.nih.gov/pubmed/?term=gait+analysis and term=sit+to+stand)(28-08-2016))

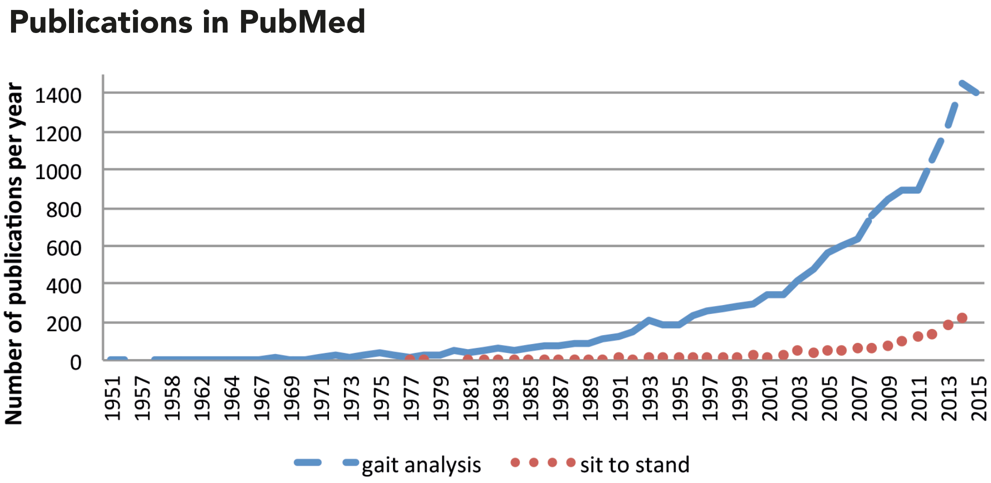

Figure 1. Number of PubMed publications per year using the search terms 'gait analysis' and 'sit-to-stand'. The blue/dashed line represents the number of gait analysis publications and the orange/points line represents the STS publications.

Walking is obviously a very basic motor activity, but the question arises whether these numbers are proportionate to the importance of research in these two mobility domains. Most knowledge about the biomechanics of STS has been generated in motion laboratories with complicated, expensive and time-consuming measurement systems. In this thesis we aim to develop a method to analyze the STS that is easier to use, cheaper and less time consuming.

EFFECTS OF AGEING ON SITTING BEHAVIOR

Losing the ability to stand up may lead to avoidance of moving around, further inactivity and longer sitting. A recent not yet published study involving 884 subjects revealed a significant increase in sitting duration with ageing in the 81-100 age group compared to the 71-80 age group (Figure 2).

Duration of sitting

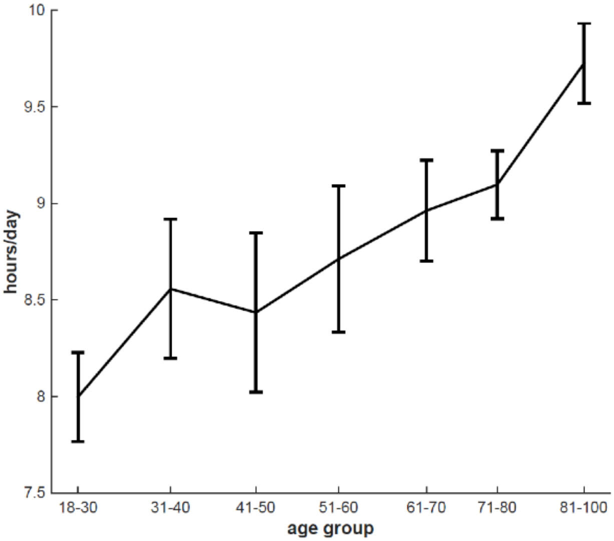

Figure 2. Cross-sectional age differences in sitting duration. Data collected in the Gray Power study of the Vrije Universiteit Amsterdam. https://www.vumc.nl/afdelingen/Amsterdam-Center-on-Aging/nieuws/8362866/

Recent studies have suggested that breaking up prolonged sitting may improve glucose metabolism and could represent an important public health and clinical intervention strategy for reducing cardiovascular risk [8–11] and mortality [12], which underscores the importance of maintaining the ability to stand up from a sitting position.

AGEING AND FALLS

Risk of falling and fear of falling are common causes of becoming inactive at older age. In a study in Bayern, the largest state in Germany, more than 70,000 falls from residents of Bavarian nursing homes were analyzed. Serious falls resulting from walking and standing up, in particular during the morning hours, were compared. Unsuccessful transfers from sitting to standing accounted for 41% of all falls [13]!

Several mechanisms in older adults can lead to instability and thus jeopardize the ability to remain stable while standing up. An important cause of falls during transitions in the morning might find its origin in dizziness. Blood pressure control medication can lead to lower blood pressure in the morning with orthostatic hypotension and dizziness as potential side effects. Furthermore, 35.4% of US adults aged 40 years and older were found to have vestibular dysfunction. Participants with vestibular dysfunction who were clinically symptomatic (reported dizziness) had a 12-fold increase in the odds of falling [14].

Confidence and ability to stand up from sitting in a safe and automatic manner is an important prerequisite for independent living and active and healthy ageing.

PHYSICAL PERFORMANCE TESTS

Since the 1970s several Physical Performance (PP) tests have been introduced, during which the subject is asked to engage in a series of physical activities like walking different distances, standing up and sitting down, turning and balancing. In general, these tests are standardized to allow comparison within and between subjects. In some cases a cognitive task is added, for instance counting down to determine how this additional task affects the motor task. Furthermore, the task can be performed at a self-chosen speed or as fast as possible. In clinical practice a supervisor typically explains the test, monitors whether the performance is correct, records the outcome by counting, timing with a stopwatch or measuring distance, and writes down the results.

A well-known and often used test in the geriatric domain is the Short Physical Performance Battery (SPPB). This test includes three common physical activities: maintaining balance, walking a short distance (4 meter), and performing repeated sit-to-stand transitions. The SPPB was developed for use in the home situation, which resulted in a test protocol tailored to the way older adults engage in physical activity at home.

The SPPB proved highly predictive of impending disability in non-disabled older persons living in the community four years after the baseline measurement [15]. Hence, the physical performance measures obtained with this test may help to identify older persons with a preclinical stage of disability who could benefit from interventions to prevent the development of disability. The choice to include the repeated STS in the SPPB did have significant impact in the interest of the application of the repeated STS in geriatrics.

Another successful test is the Timed Up and Go (TUG) [16]. In this test, the subject starts in a sitting position, stands up, walks around a cone placed at a distance of three meters, turns, walks back, turns and sits down on the same chair from where he or she stood up. The strength of this test is that several basic physical functions have to be accomplished in sequence, allowing for the analysis of transitions from one activity to another. The sequencing of tasks requires cognitive processes, implying that motor functions as well as executive functioning are tested simultaneously in the TUG. Walking back to a chair and sitting down are complex motor behaviors that include estimating distance, turning at the right moment and sitting down after this turning while losing sight of the seat.

Performance measures predict onset of activity of daily living difficulties in community-dwelling older adults [17]. Walking speed has been shown to predict survival [18], while lower extremity disability predicts disability [15,19], hospitalization and mortality [20]. These outcomes seem only partially helpful in clinical work with individual patients.

Well-known and influential researchers in this field have argued in favor of the use of physical performance tests in clinical practice [21,22]. Although these outcomes might be very interesting from an epidemiological viewpoint, or in assigning care, they provide limited insights into the underlying reasons for individual subjects to score low or high on such tests.

Physical performance tests are used extensively in both clinical research and clinical care. Administering the test is easy and fast. The TUG takes only one minute to perform, the repeated STS 2 minutes and the SPPB less than 15 minutes. Most tests only require tape, cones and a stopwatch.

NUMBER OF PUBLICATIONS OF PHYSICAL PERFORMANCE TESTS

Figure 3 shows the growing number of publications per year with regard to six physical performance tests, three of which include standing up from a sitting position: the Sit-to-stand (STS) test, the Timed Up and Go (TUG) and the Short Physical Performance Battery (SPPB). Gait is by far the most frequently studied topic, but interest in the TUG and the Six Minute Walk Test is growing rapidly. The volume of publications on sway, SPPB and the STS is comparable. The outcome of physical performance tests can either be the time to perform a fixed task, the number of tasks during a fixed time or the duration to perform a task with a fixed distance. However, even though these outcomes are informative and predictive of future risk, they do not address the quality of the performance itself and the underlying biomechanics. Adding body-fixed sensors to these tests opens up new opportunities to fill this gap.

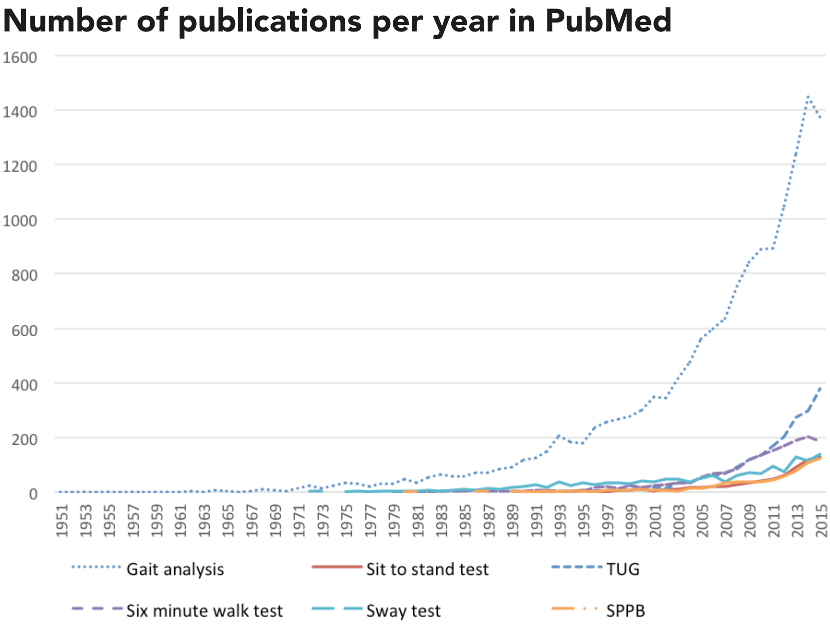

Figure 3. Number of publications per year on six physical performance tests found in PubMed (www.ncbi.nlm.nih.gov/pubmed, August 2016).

ASSOCIATION BETWEEN STRENGTH AND STS

The rates of decline in isokinetic strength in older adults averaged 14% per decade for knee extensors [23]. This decline in muscle strength is much more rapid than the concomitant loss of muscle mass, suggesting a decline in muscle quality [24].

Several authors have used the STS test as a proxy for muscle strength. 'Simple method for measurement of lower extremity muscle strength' was the title of the first study on the sit-to-stand test ever [25]. The time needed to stand up 10 times from a standard chair was recorded in 139 healthy subjects, aged 20 to 85 years. Several authors have focused on the use of the repeated STS test as a proxy for muscle strength [26,27]. Improving muscle strength is a potent means to improve STS capacity. Loss of muscle mass is an established fact of aging and certainly plays a role in losing the ability to rise from a seated position. There are several studies showing that lower extremity muscle force in older adults can be improved by training [28,29]. Resistance exercise training is effective for improving strength among older adults, particularly with higher intensity training. Findings therefore suggest that resistance exercise may be considered a viable strategy to prevent generalized muscular weakness associated with aging [30].

However, strength decline of the lower limbs is not the only modifier of STS performance in older adults, as is evident from the fact that strength parameters only explain half of the variance of the duration of the STS task [31]. STS performance is influenced by multiple physiological and psychological processes, and represents a specific skill, rather than a proxy measure of lower limb strength [32].

ANALYSIS OF SIT-TO-STAND IN THE GAIT LAB

A gait lab is a space specifically instrumented and used to measure human movement under standardized and supervised conditions. A traditional clinical gait lab is equipped with camera systems, force plates and EMG to analyze the biomechanics of movement. Camera systems either use passive retroreflective markers or active markers (LEDs) placed on landmark locations on the subject. Several cameras are calibrated to measure the displacement of these markers in space over time.

In the late 1980s and the early 1990s a body of knowledge about the biomechanics of the Sit-to-Stand transition has been developed in gait labs using camera systems and force plates. In-depth analyses of the STS have led to an improved understanding of the biomechanical and kinematical aspects of the transfer from sitting to standing, including descriptions of the trajectory of the center of gravity, classifications of the different STS phases and the conditions for maintaining stability during the STS. In addition, useful applied research has been conducted, focusing, among other aspects, on the importance of lower limb strength [33], the effect of different seat heights [34] and different STS strategies for patients who were functionally impaired [35].

CHAIR RISE STRATEGIES

Several strategies of standing up have been analyzed using camera systems and force plates [3,34–40]. The two main types are (1) the momentum transfer strategy and (2) the flexion strategy. In the momentum transfer strategy, forward bending of the trunk is limited and seat-off occurs early, while the distance of the center of mass (CoM) at seat-off to the base of support (feet on the ground) is large. At seat-off the lower limbs need to produce a high momentum (integral of force over time) to release the body mass from the seat and to transport it over the new base of support formed by the feet. This is why Schenkmann and Riley [41] called this the momentum transfer strategy. After seat-off the horizontal and the vertical displacement of the trunk have to be well matched. This is necessary because the STS ends in an unstable position with the two feet next to each other. Balance control is crucial in this strategy. For young healthy people standing up is a fully automated maneuver, which does not need much mental attention. But everybody knows how discomfort or pain in ankle, knee, hip or back may break this automatism. For older adults with less muscle strength, or reduced proprioception, a failing vestibular system, impaired vision, pain, restrictions in the joints or a combination of these impairments, the momentum transfer strategy becomes less suitable or even impossible.

With the flexion strategy, the horizontal and the vertical phase of the STS are more separated in time. The horizontal displacement of the CoM is realized by bending the trunk more forward during the flexion phase. As a result, the CoM approaches the base of support. During the extension phase trunk angular velocity is increased to support vertical displacement. 'Because the upper body is much more massive than the thigh, the upper body must contribute more to CoM vertical momentum than the thigh' (p.84) [3].

In healthy elderly, momentum transfer, hip flexion angular velocity (a surrogate measure for momentum) was shown to increase with decreased seat height [34]. Alterations in strategy suggest that functionally impaired elderly attempt to increase their momentum while rising by increasing their hip flexion velocity [35].
It is not evident to what extent this knowledge has helped to improve clinical practice, nor to what extent the studies in question were on the reading list of physiotherapy training. In any case, the measurement methods as used in the lab are not applicable in routine clinical practice.

The set-up, the data collection and the data analysis of most laboratory studies are intricate and time consuming. The instrumentation is expensive and there is a need for engineering expertise. Moreover, the patient has to visit the lab, which is also costly and time consuming. For the clinical application of movement analysis, the method has to be easy to use, efficient and has to yield useful and relevant data.

ADDING BODY FIXED SENSORS TO THE SIT-TO-STAND

In the early 1990s, the first piezo-resistive sensors connected to digital ambulatory monitors became available for movement analysis. After proper calibration these so-called inertial sensors proved to be very accurate and reliable and able to measure the acceleration due to gravity and movement [42]. This allowed one to measure the orientation of the trunk and legs relative to gravity and hence to detect sitting, standing and lying [43]. The raw signals were stored with a high time resolution (100 samples/s) and the raw data were analyzed off-line to maximize computing power and to be able to reanalyze the data, and to increase traceability. Since these inertial sensors were very small and light, they seemed ideal to fix to the human body, thus providing a potential alternative to the complex and expensive equipment commonly used in the gait lab [44]. Gyroscopes that measured angular velocity were the next breakthrough in sensor technology. The combination of three accelerometers and three gyroscopes yielded interesting new opportunities for movement analysis using body fixed sensors [45].

We prefer to use the term body fixed sensors above wearable sensors to ensure that the sensors are worn at a fixed and controlled place in view of the validity and reproducibility of the measurements.

CONCEPTUAL FRAMEWORK

The International Classification of Functioning, Disability and Health, also known as ICF, is a classification of the health components of functioning and disability (Figure 4). The current ICF creates a more integrative understanding of health forming a comprehensive profile of an individual instead of focusing on one's disease, illness, or disability.

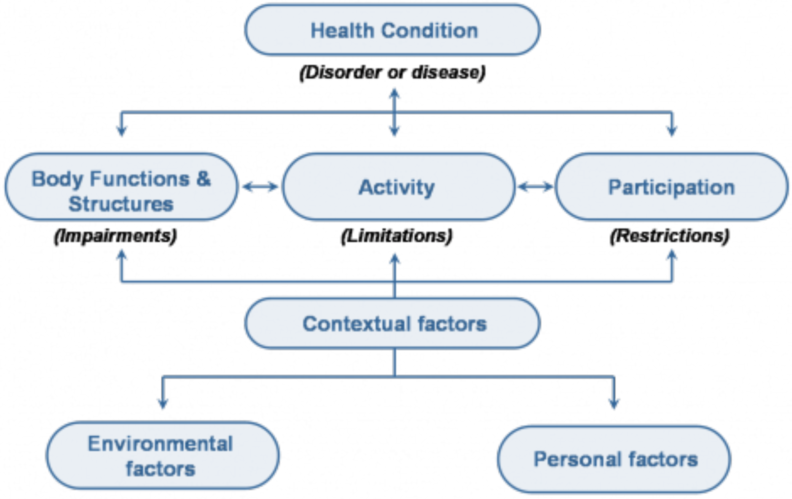

Figure 4.

The use of patient reported outcomes (PROs) in clinical trials has become more widespread in recent years. PROs are defined as a patient's personal report of a health condition and its treatment and are useful instruments in clinical trials and clinical settings. This type of assessment, often in the form of a questionnaire, includes symptoms, functional status, psychological wellbeing, and health-related quality of life (HRQoL). To evaluate products developed to treat chronic, disabling conditions such outcome measures are needed. The United States Food and Drug Administration (FDA) and the European Medicines Agency (EMA) have developed guidance documents concerning the proper development, validation, and use of PROs instruments in clinical trials. In the FDA models, physical performance and disease-related physical limitations are secondary endpoints for PROs. In these models, physical performance can be a PRO or non-PRO assessment. Furthermore, the FDA guidance documents recommend the use of conceptual frameworks [46]. "The conceptual framework explicitly defines the concepts measured by the instrument in a diagram that presents a description of the relationships between items, domain (sub-concepts), and concepts measured and the scores produced by a PRO instrument". We have developed a conceptual framework in which we incorporated the ICF model and met the requirements for clinical trials (Figure 5).

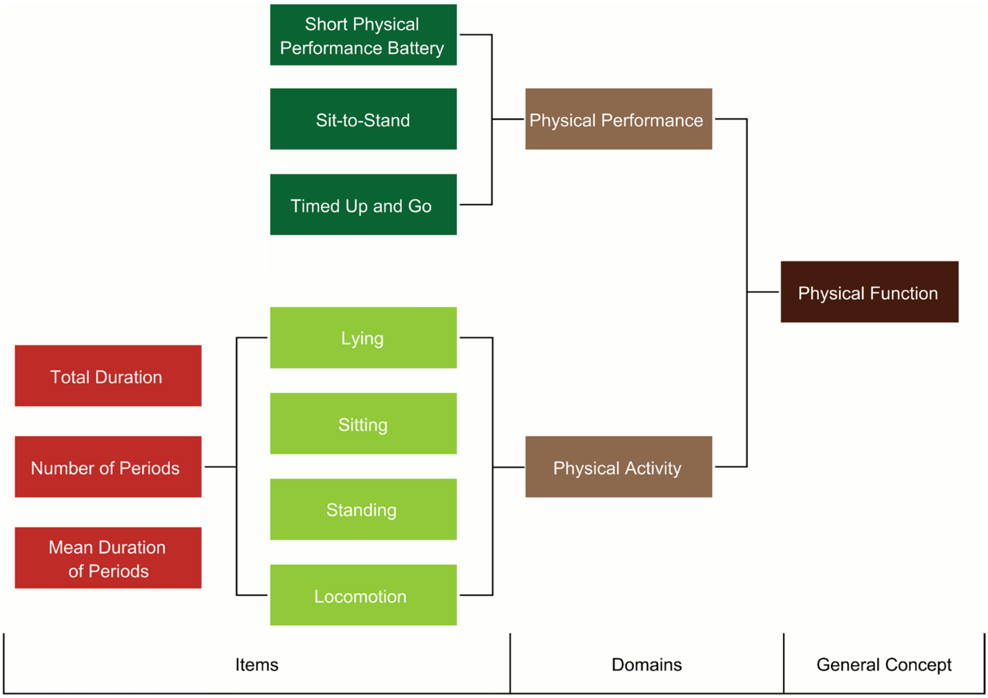

Figure 5. Mobility measures presented in a framework with physical performance and physical activity as domains of physical function. Activity classes are determined and for all types of physical activity total duration, number of periods and mean duration of periods are calculated.

This framework has been developed to study the associations between the ability of physical functioning under standardized conditions and being active under everyday-living conditions. This framework shows the link between physical performance and physical activity and stands for measuring what you can and what you really do (Figure 4). This is an important way of looking at measurement data that are collected in a clinical context for diagnosis as well as for evaluation of effects of interventions.

CONCLUSION

There are several good reasons to investigate the ability and capacity to stand up from a sitting position and its associations with daily life activities. First of all, it is crucial to be able to stand up from sitting in a safe and controlled manner in order to stay independent. If older adults are no longer able to stand up they are also no longer able to walk. This will inevitably lead to a more inactive, sedentary lifestyle with more sitting and prolonged periods of sitting. Life expectancy is increasing and aging is accompanied by a loss of lower extremity muscle strength, as well as an increased prevalence of chronic diseases. A growing number of older adults will face disability in a society that seeks to keep its greying population to stay independent as long as possible, such as in the Netherlands where the government aims to cut down expenses for residential care. These facts and observations were the reasons why the primary focus on the research reported in the present thesis was on STS.

AIM AND OUTLINE OF THIS THESIS

The main aims of this thesis are 1) to develop a new method to measure and analyze sit-to-stand movements using body-fixed sensors, 2) to demonstrate the applicability of this method in a clinical environment, and 3) to analyze associations between sit-to-stand performance and daily-life physical activity. These aims are pursued with the ultimate goal to promote active and healthy ageing of older adults and patients with chronic diseases. The research pertaining to these aims is presented in corresponding sections, which constitute the three main parts of the thesis. To anticipate, the parts in question are organized as follows.

1) Methodological aspects

In this first part of the thesis, various methodological aspects of using body fixed sensors to analyze STS performance are studied. In Chapter 2, the feasibility of using an automated approach for quantifying the STS using a single sensor location is investigated, as well as its discriminative validity by comparing older and younger adults. In Chapter 3, the validity of the adopted approach is examined further in young and older adults, using switches under the chair for reference. Finally, in Chapter 4 the intra-rater, inter-rater and test-retest reliability of the instrumented TUG is determined in patients with Parkinson’s disease (PD).

2) *Clinical value*

In this second part of the thesis, the added clinical value of measuring STS performance with instrumentation is examined. To this end, in Chapter 5, the hypothesis is tested that durations of the different sub phases of the STS, as assessed with the instrumented repeated STS, show stronger associations with health status, functional status and daily physical activity of older adults than manually recorded test durations. In the study reported in Chapter 6, the hypothesis is examined that adults with less handgrip strength tend to apply a STS flexion strategy with more dynamic trunk use. Subsequently, in Chapter 7, a new method for scoring instrumented STS performance is introduced, resulting in scores that are potentially more informative for clinical use than time alone. To anticipate, the scoring system in question involves sub-scores for the instrumented STS based on the durations, kinematics and variability of these measures, which are applicable to individuals as well as groups, making comparison to different reference populations feasible.

3) *The associations between Physical Function and Physical Activity*

The focus of the third and final part of the thesis is on the relation between physical performance and physical activity. The research reported in Chapter 8 addresses the question whether being better able to stand up from sitting automatically leads to shorter and more frequent sitting episodes. and to break up of sitting periods more often. Or, formulated more generally, do physical performance (PP) and physical activity (PA) constitute separate domains of physical function, and is differentiation of PA classes more informative than overall PA in this regard?

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EXCITE

Methodological aspects

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Technical Note

AUTOMATED APPROACH FOR QUANTIFYING THE REPEATED SIT-TO-STAND USING ONE BODY FIXED SENSOR IN YOUNG AND OLDER ADULTS

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ABSTRACT

Much is known about the sit-to-stand (STS) and its biomechanics. Currently, however, there is little opportunity for instrumented quantification of the STS as part of screening or diagnosis in clinical practice. The objectives of the present study were to describe the feasibility of using an automated approach for quantifying the STS using one sensor location and to start testing the discriminative validity of this approach by comparing older and younger adults. 15 older subjects recruited from a residential care home and 16 young adults performed 5 repeated sit-to-stand and stand-to-sit movements. They were instrumented with a small and lightweight measurement system (DynaPort®) containing 1 triaxial seismic accelerometer and 3 uniaxial gyroscopes fixed in a belt around the waist. Durations of the (sub-)phases of the STS were analyzed and maximum angular velocities were determined. All successful STS cycles were automatically detected without any errors. The STS duration in the older adults was significantly longer and more variable in all phases (sit-to-stand, standing, stand-to-sit and sitting) compared to the young adults. Older adults also exhibited lower trunk flexion angular velocity. The results of this first fully automated analysis of instrumented repeated STS movements demonstrate that several STS parameters

can be identified that provide a basis for a more precise, quantitative study of STS performance in clinical practice.

INTRODUCTION

Previous work using camera-based systems and force plates in laboratory settings has quantified sit-to-stand (STS) movements to better understand their biomechanical dynamics [1-2]. Body fixed sensors (BFS) were introduced to movement analysis research in the early 1990s [3] and offer an alternative approach to quantifying the STS. Studies using BFS demonstrated the ability to identify the beginning and end of STS transitions with one gyroscope fixed to the chest [4]. Accelerometers fixed to the sternum and to the upper leg were used to detect the start and end of a STS transition in healthy subjects and stroke subjects [5]. Using accelerometers and gyroscopes, the kinematics of rising from a chair were calculated [6]. Power during STS movements has been recently analyzed by adding magnetic-field sensors [7]. Nonetheless, to date, automated algorithms for quantifying repeated sit-to-stand and stand-to-sit movements using BFS have not been described. This method is expected to be usable for collecting quantitative STS data on a routine basis in clinical practice. Since this is currently not possible, the objective of the present study was to investigate the feasibility of using an automated approach for quantifying the STS using one sensor location and to start testing the discriminative validity of this approach by comparing older and younger adults.

METHODS

Subjects

In this experimental cross-sectional study 15 older adults (OA), living in a residential care home, (11 female, median age 88 (73-99) years; median height 162 (156-192) cm; median weight 66 (44-91) kg) and 16 healthy young adults (YA) were recruited (9 female, median age 20 (18-23) years; median height 167 (162-184) cm; median weight 62 (53-78) kg)). Height and weight were not significantly different in the two groups. All participants provided informed written consent. The protocol was approved by the Ethics committee of the Free University Amsterdam.

Instrumentation and data acquisition

A BFS system (DynaPort® Hybrid, McRoberts; 87x45x1mm, 74g) was inserted in an elastic belt on the lower back positioned at the lumbar vertebra: 3 pre-calibrated accelerometers (STM-LIS3LV02DQ), 3 gyroscopes (EPSON-XV-3500CB), sampling rate 100 Hz. The accelerometer signals have been shown to be highly reproducible [8]. Raw data were stored on a Micro-SD card (SanDisk).

Procedure

Subjects performed 5 STS cycles at a self-selected speed (start and end in a sitting position), while free to swing their arms. A standard chair without arm rests was used. Subjects were video taped from the side to enable post-hoc visual inspection by a single observer of successful and failed attempts. A failed STS attempt was defined as the subject not being able to end in a standing position.

Signal Analysis

Data was corrected for tilt [9]. The acceleration and the angular velocity in the sagittal plane determined the trunk angle (ϕ) [10]. Subsequently, the sine of the trunk angle (sin(ϕ) was calculated. Drift and noise were removed from the sin(ϕ) using the discrete wavelet transform dw_sin(ϕ) [4]. "True vertical acceleration" was estimated by removing the influence of ϕ from the vertical acceleration signal. Finally, vertical velocity was derived by integrating this signal.

The vertical velocity was used to differentiate between successful STS movements and failed STS attempts. The dips in dw_sin(ϕ) were used to detect a change in trunk rotation direction (Figure 1).

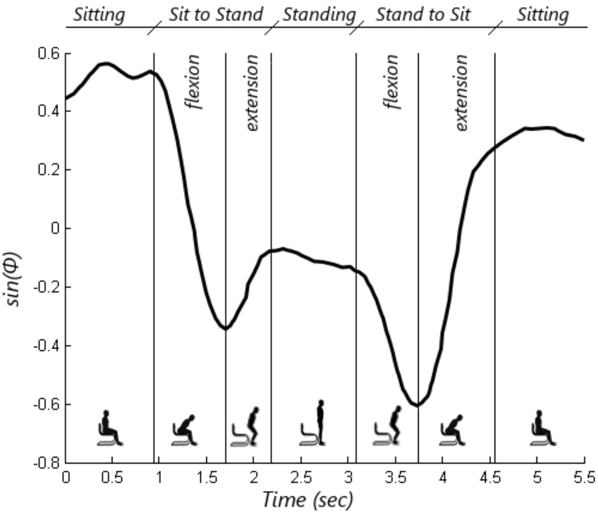

Figure 1. The wavelet transform of the sine of the trunk angle, dw_sin(ϕ), is shown during the main sub-phases of a complete STS cycle, preceded and followed by a sitting epoch.

The start of the sit-to-stand was defined as the end of the plateau before the first dip in dw_sin(ϕ). Similarly, the end of the sit-to-stand was defined as the start of the plateau after the first dip in dw_sin(ϕ). The start of the stand-to-sit was defined as the end of the plateau before the second dip in dw_sin(ϕ) and the end of the of the stand-to-sit was defined as the start of the plateau after the second dip in dw_sin(ϕ). Plateaus were identified where the slope of dw_sin(ϕ) was smaller than 0.1. After automated identification of all phases (sit-to-stand and stand-to-sit) and sub-phases (flexion and extension), durations, coefficients of variation of all durations (CV) and maximum angular velocity were calculated. Only subjects who completed all 5 repetitions were included in the analysis of the CV.

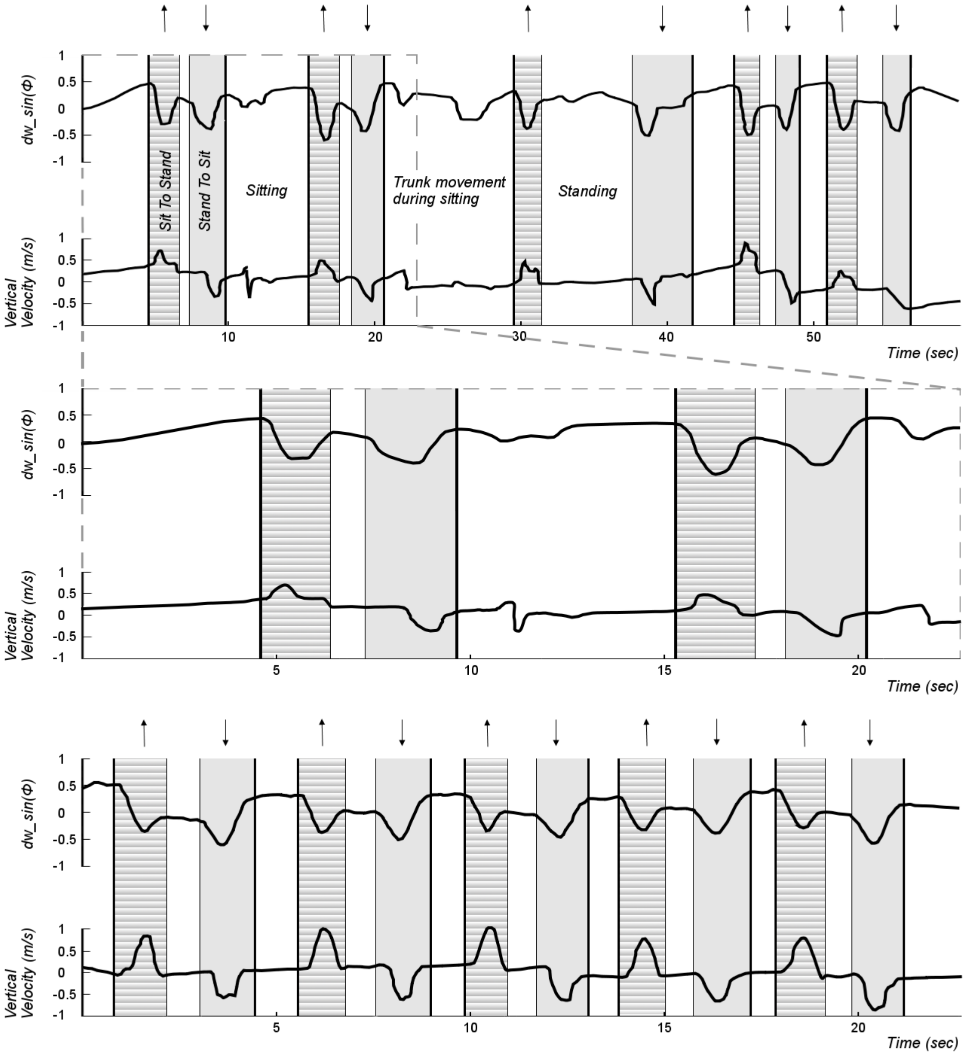

Figure 2. Typical example of five repeated STS cycles of an older adult (top) and a young adult (bottom). In the top panel dw_sin(ϕ) is shown; in the bottom panel the vertical velocity is shown. Standing up is indicated by ϕ, sitting down is indicated by ϕ. Variability of the signals of the OA is high and of the YA is relatively low.

To evaluate feasibility of the automated method, we documented the % of STS movements that correctly identified using the BFS and compared that to those identified by the observer.

Statistical analysis

Due to the small sample size and non-normal distribution of some measures, parameters are described using median, minimum and maximum values. Differences in outcomes between OA and YA were analyzed using the Mann-Whitney U test ($p < 0.05$) (SPSS version 17.0).

RESULTS

All 16 young controls were able to complete the 5 STS cycles. Twelve of the OA completed all 5 STS cycles, three completed at least 1 cycle. The data of all subjects were included in the analysis of duration and angular velocity.
Table 1 Durations (seconds), maximum angular velocity (ϕ max, in degrees per second), and coefficient of variation of durations (percentage) of the 5 repeated sit-to-stand cycles of the young and older adults.

Durations [sec]		**Younger Adults**			**Older Adults**			**p-value***
		Median	**Min**	**Max**	**Median**	**Min**	**Max**	
Sit-to-stand	Duration	1.45	1.14	2.58	1.98	1.65	3.49	<0.001
	Flexion duration	0.73	0.63	0.88	1.06	0.74	1.64	<0.001
	Extension duration	0.72	0.49	1.74	1.1	0.82	1.94	<0.001
Standing	duration	0.33	0	0.74	1.35	0.57	6.57	<0.001
Stand–to-sit	Duration	1.47	1.18	2.28	2.59	1.34	3.21	<0.001
	Flexion duration	0.69	0.46	0.91	1.31	0.65	1.87	<0.001
	Extension duration	0.79	0.71	1.37	1.06	0.69	1.68	0.024
Sitting	Duration	0.33	0.06	0.7	3.1	0.36	9.71	<0.001
Angular Velocities [°/sec]								
Sit-to-stand	ω maxflexion	124.62	90.04	192.7	91.62	57.31	125.46	<0.001
	ω maxextension	57.22	20.7	98.9	54.67	25.57	93.33	0.323
Stand-to-sit	ω maxflexion	79.68	50.32	117.63	40.93	22.99	72.71	<0.001
	ω maxextension	102.15	60.42	138.22	107.31	65.65	170.29	0.527
Coefficient of Variation [%]								
Sit-to-stand	Duration	7	2	15	26	7	42	<0.001
	Flexion duration	8	5	16	19	9	41	<0.001
	Extension duration	11	3	33	40	7	85	0.003
Standing	Duration	40	5	96	55	26	121	0.08
Stand-to-sit	Duration	8	3	39	19	7	51	0.001
	Flexion duration	12	2	36	22	9	44	0.005
	Extension duration	10	3	61	18	11	79	<0.001
Sitting	Duration	36	8	69	57	38	140	0.002

*Significance is calculated using the Mann-Whitney U test ($p < 0.05$).

From the 12 OA who completed the 5 repetitions, 3 had failed efforts to rise from the chair. All (100%) of the failed attempts were detected as such by the software and all successful transitions were correctly identified. Figure 2 illustrates an example of the dw_sin(ɸ) of the trunk angle and the vertical velocity of five STS cycles of a typical OA and YA. The variability of the signal and the durations of the phases of the older adult are high. Nonetheless, all sit-to-stand and stand-to-sit transitions were correctly detected by the software without manual interference.

All durations were significantly longer for the OA (Table 1). The median of the summed time of standing and sitting was 4.45 seconds and 0.66 seconds for OA and YA, respectively, representing 49% and 18% of the total STS cycle time. The maximum angular velocity was lower for the OA during the flexion phases of sit-to-stand and stand-to-sit than for the YA ($p<0.001$), but not during the extension phases. All but one (standing phase) of the CV scores were significantly higher for OA than for YA (Table 1).

DISCUSSION AND CONCLUSIONS

The present findings demonstrate that automated analyses of repeated STS data captured using a single BFS is feasible. The software was able to correctly detect durations and maximum angular velocity of all successfully completed sit-to-stand and stand-to-sit cycles.

The automated detection also identified many features of the STS that were different in this small sample of older and young adults. Future work is needed to identify parameters that are most sensitive to aging and intervention. Duration parameters were chosen to differentiate between the duration of different phases. The angular velocity parameters were chosen because in other studies they relate to moments, which might be critical for successful STS transition. CV parameters were chosen because they might show loss of automation. The initial findings suggest that these three different sets of parameters may have clinical utility.

Further validation in a larger sample size and in patients who may have more disturbed STS patterns are needed to confirm the present findings and identify the most relevant parameters. Nonetheless, the results of this first fully automated analysis of instrumented repeated STS movements demonstrate that several STS parameters can be identified that provide a basis for a more precise, quantitative study of STS performance, in clinical practice.

Conflict of interest statement

R.C.v.L. is the owner and E.A is employee of McRoberts B.V. This company is manufacturer of the DynaPort.

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Methodological aspects

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VALIDATION OF SEAT-OFF AND SEAT-ON IN REPEATED SIT-TO-STAND MOVEMENTS USING A SINGLE-BODY-FIXED SENSOR

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Abstract

The identification of chair rise phases is a prerequisite for quantifying Sit-to-Stand movements. The aim of this study is to compare seat-off and seat-on detection using a single body fixed sensor (BFS) with chair switches. A single sensor system with three accelerometers and three gyroscopes (DynaPort® Hybrid) was fixed around the waist. Synchronized on-off switches were placed under the chair. Thirteen older adults were recruited from a residential care home and fifteen young adults were recruited among college students. Subjects were asked to complete two sets of five trials each. Six features of the trunk movement during seat-off and seat-on were calculated automatically, and a model was developed to predict the moment of seat-off and seat-on transitions. The predictions were validated with leave-one-out cross-validation. From the 15 young and 13 older adults who did 2 sets of 5 trials, in only 2 trials (0.7%) feature extraction failed. Estimation of seat-off was successful in young and old adults with a mean error for the optimal combination of features during the cross-validation of 0 ms and a mean random error of 51 ms. Estimation of seat-on was successful in young and old adults with a mean error of the best predictor during the cross-validation of -3 ms and a mean random error of 127 ms. The results of this study demonstrate that seat-off and seat-on of repeated sit-to-stand can be semi-automatically detected in young and old adults using one body-fixed sensor system with an accuracy of 51 ms and 127 ms, respectively. The use of the ambulatory instrumentation is feasible for non-technically trained personnel. This is an important step in the development of an automated method for quantification of STS movements in clinical practice.

Keywords: seat-off, seat-on, sit-to-stand, assessment, accelerometer, gyroscope
(Some figures may appear in colour only in the online journal)

1. INTRODUCTION

Sit-to-stand (STS) tasks are frequently used as a test of motor function in clinical populations (Guralnik et al 2011, Penninx et al 2000, Volpato et al 2008, Guralnik et al 1994, Rolland et al 2006). In current clinical practice, the total time to perform this task is used as the outcome variable, while several studies suggest that valuable information may be obtained by assessing the duration of the different phases of the task (Najafi et al 2002, Ikeda et al 1991, Lord et al 2002, Janssen et al 2002). The identification of chair rise events is a prerequisite for such an analysis. STS events of particular interest are seat-off and seat-on because these mark the transitions to and from an intrinsically stable three-point support (i.e. sitting) and a dynamically stable two-point support (i.e. standing) (Riley et al 1991). Leaving the chair seat is a critical factor for a successful STS. It yields higher peak hip contact pressures and requires greater moment and range of motion at the knee than gait or stair climbing (Hughes et al 1996). The seat-off has been used to separate STS sub-phases (Schenkman et al 1990, Riley et al 1991, Lindemann et al 2007) and to synchronize different strategies of STS (Doorenbosch et al 1994, Hirschfeld et al 1999).

The gold standard for the identification of the moment of seat-on and seat-off is to measure the vertical loading on the chair using seat switches (Kralj et al 1990), a force platform under the chair (Pai and Rogers 1990, Alexander et al 1991, Hirschfeld et al 1999, Zijlstra et al 2010) or load-cells (Papa and Cappozzo 1999). If an instrumented chair is not available, foot–floor reaction forces are used to estimate the moment of seat-off. Several features of the ground reaction force signals have been used to predict seat-off in previous studies: (1) time of peak of horizontal ground force (Kralj et al 1990); (2) time of peak of vertical ground force (Riley et al 1990); (3) time of 100% body weight vertical ground force (McGibbon et al 2004).

Since the early 1990s, body-fixed sensors (BFS) have increasingly been used to measure kinematic and kinetic parameters (Veltink and van Lummel 1994). BFS have several advantages. Miniaturizing electronics has made it possible to develop small and light devices including sensors to capture accelerations and angular velocities in three orthogonal planes. These devices are unobtrusive and can be positioned anywhere on the body with low patient awareness. Advances in ergonomic design and fixation methods have improved patient acceptance (Regueiro et al 2011) and enabled some patients to wear the BFS system for several weeks. This makes it possible to move from the lab to daily life settings.

Previous studies using BFS during the analysis of STS movements have demonstrated the ability to: (1) identify the beginning and end of STS transitions, with one gyroscope fixed to the chest (Najafi et al 2002) and with accelerometers and gyroscopes fixed to the trunk (Giansanti and Maccioni 2006); (2) decompose accelerometric signals on the trunk and thigh (Janssen et al 2005); (3) combine two accelerometers and one gyroscope to improve the accuracy to measure trunk and thigh angles (Boonstra et al 2006); (4) reconstruct the trunk trajectory (Giansanti et al 2007); (5) analyze the peak power (Zijlstra et al 2010), (6) discriminate between healthy and frail elderly (Ganea et al 2011) and (7) fully automated analysis of instrumented repeated STS movements (van Lummel et al 2011).

The objectives of this study were: (1) to develop an automated approach for quantifying the seat-off and seat-on during STS using a single sensor located at the waist and (2) to determine the validity of this approach in young and older adults, using switches under the chair as reference.

2. METHODS

2.1. Subjects

In this cross-sectional study, 13 older adults (OA) were recruited from a residential care home (age: 85.3±6.4 years; height: 168.4±9.3 cm; weight: 74.0±11.0 kg); they had to be able to perform at least 5 repeated STS movements. In addition, 15 young adults (YA) were recruited among college students (age: 20.7±1.4 years; height: 183.2±8.7 cm; weight: 72.9±9.2 kg). The young subjects had no history of neuromuscular or musculoskeletal disorders. The protocol had been approved by the ethics committee of the Faculty of Human Movement Sciences of VU University Amsterdam and all participants signed informed consent.

2.2. Equipment

A BFS system (DynaPort® Hybrid, McRoberts, The Hague, The Netherlands) was inserted in an elastic belt and positioned on the lower back at the height of the second lumbar vertebra, which is close to the body’s center of mass (CoM) in the standing position. The small and light measurement system (87×45×14 mm, 74 g) contains three pre-calibrated seismic accelerometers (STM: sensor range □} 2 g, resolution 1 mg) and three pre-calibrated gyroscopes (EPSON: range □} 100 ◦ s–1, resolution 0.0069 ◦/s–1) and has a sampling rate of 100 samples/s. The accelerometer signals have been shown to be highly reproducible (van Hees et al 2009). Raw data were stored on a Micro-SD card. The device can connect with a computer from a distance of up to 100 m via Bluetooth. The supporting acquisition software can start and stop the sensor system and send event markers to store analysis intervals with the data. Sensor data and chair switch data are shown in figure 1.

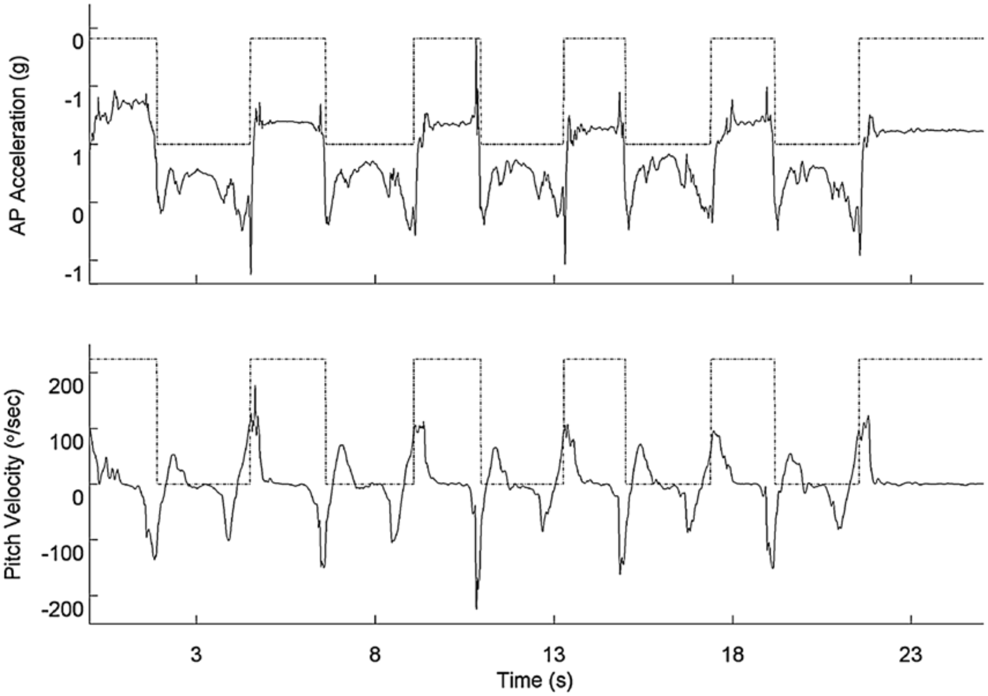

Figure 1. Example of signals and event markers of a complete assessment of an old adult. In the top panel the acceleration data (g) and in the bottom panel the gyroscope data (°/s) are shown. The colored areas are the two intervals of the repeated STS.

Four on/off switches were connected to a second DynaPort device and positioned under the corners of a plywood sheet placed underneath the chair. The adjustable thresholds were set at 98.1 N. The two DynaPort devices were synchronized using a special cable set. The sensors were connected with the cables in standby mode and started with a button. After the start of the measurement, the cables were removed.

2.3. Procedures

As illustrated in figure 2, subjects were asked to perform two sets of 5 STS cycles at self-selected speed. A STS cycle is comprised of standing up (a-c), standing including stabilizing (d-e), sitting down (f-g) and sitting (h) (see Figure 2). Five STS cycles contain five periods of standing up, standing and sitting down and four sitting periods. A standard chair without arm rests (height 42 cm) was used. All trials were videotaped from the side to enable post-hoc visual inspection of successful and failed attempts. Subjects were free to swing their arms but were instructed to avoid pushing off from the chair with their hands because this meant the switches under the chair remained on and a seat off could not be detected. If necessary, subjects were allowed to push off from their own legs.

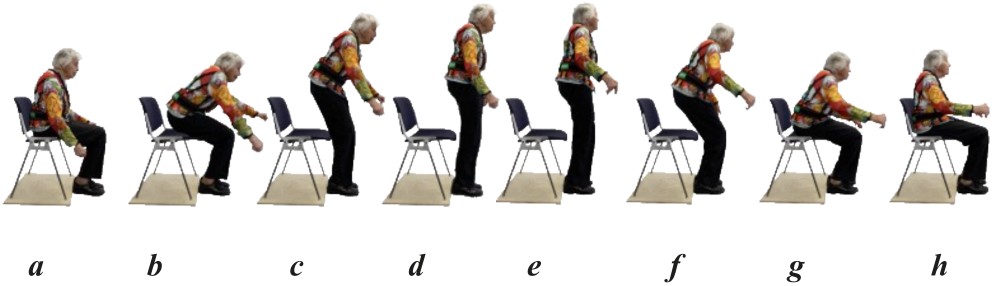

Figure 2. A STS cycle is comprised of standing up (a-c), standing including stabilizing (d-e), sitting down (f-g) and sitting (h)

2.4. Data analysis

Seat-off was detected when the chair switches underneath the two back corners of plywood were off. Seat-on was detected when three of four switches were on. Dedicated software was developed in Matlab (Mathworks, Natick MA, USA) to detect seat-off, seat-on, and to analyze trunk movements using the accelerations and angular velocities. The acceleration and the angular velocity in the sagittal plane were used to calculate the trunk pitch angle (Williamson and Andrews 2001). The effect of the angular displacement was removed from the raw accelerations using the following equations:

$$a_{\text{angle\_V}} = \sin\left(05\,\pi - \frac{\varphi}{180\,\pi}\right) \tag{1}$$

$$a_{\text{true\_V}} = a_{\text{measured\_V}} - a_{\text{angle\_V}} \tag{2}$$

where ϕ is the angle of the accelerometer with respect to the vertical. Next, αtrue_V and αtrue_AP were integrated to derive vertical and anterior–posterior (AP) velocities. Additionally, a discrete wavelet transformation was performed on the sine of the trunk angle (Najafi et al 2002). Finally, the derivative of this signal was calculated to estimate the angular velocities.

On these signals, peak detection was performed to derive the following features as predictors of seat-off and seat-on, respectively (see figure 3)

1. Maximum trunk vertical acceleration (aCC_max)
2. Minimum and maximum trunk angular velocity (ωmin and ωmax)
3. Maximum and minimum horizontal trunk velocity (vAP_max and vAP_min)
4. Maximum and minimum vertical trunk velocity (vCC_max and vCC_min)
5. Minimum of the wavelet transformed sine of the trunk angle (Wsin(α)min)
6. Minimum and maximum of the derivative of Wsin(α): (DWsin(α)min and DWsin(α)max)

Each predictor had an offset relative to the reference values obtained from the chair switch signals (see figure 3). The average offset (over all trials recorded) was subtracted from the predictor variable to obtain an estimate of the seat-off or seat-on event. To increase the precision and robustness of the estimation, a combined estimate was made based on the weighted average of the individual estimates. The weight for each predictor in the model was based on the variability of the estimates obtained with the single predictors as described by equations (5) and (6):

$$a_{\text{angle\_AP}} = \mathrm{COS}\left(05\,\pi - \frac{\varphi}{180\,\pi}\right) \tag{3}$$

$$a_{\text{true\_AP}} = a_{\text{measured\_A}} \quad \mathrm{P} - a_{\text{angle\_AP}}, \tag{4}$$

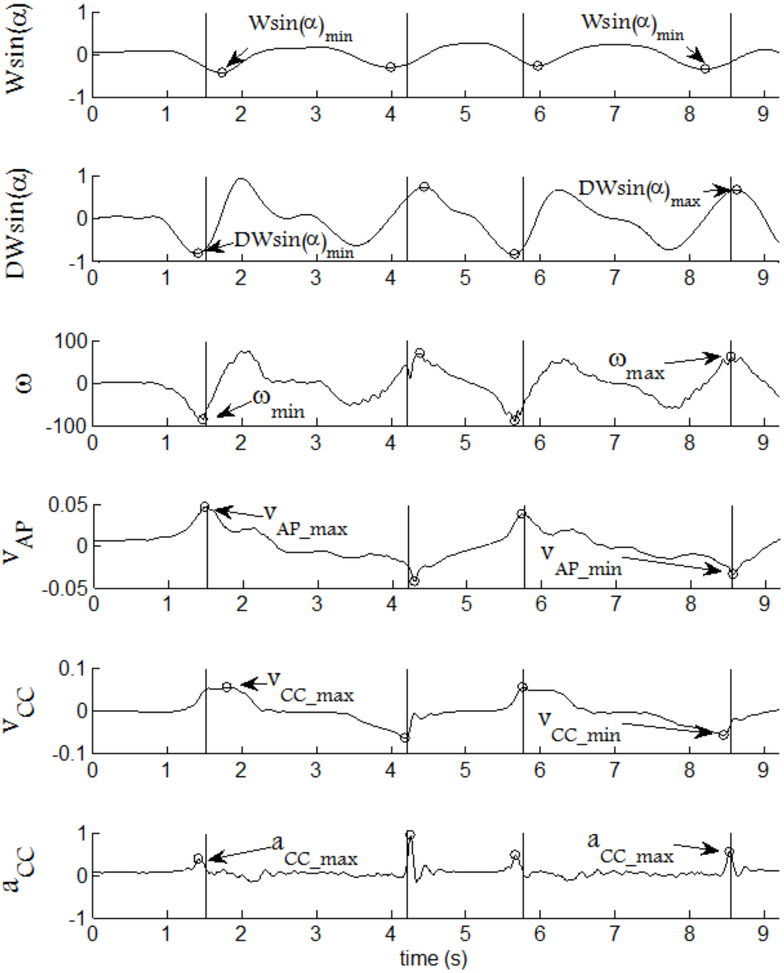

Figure 3. Example of signals of two STS repetitions from one old adult used for feature extraction. The circles (o) represent the estimation of the seat-off and seat-on. Vertical lines represent the seat-off and seat-on as detected by the chair switches.

Each predictor had an offset relative to the reference values obtained from the chair switch signals (see figure 3). The average offset (over all trials recorded) was subtracted from the predictor variable to obtain an estimate of the seat-off or seat-on event. To increase the precision and robustness of the estimation, a combined estimate was made based on the weighted average of the individual estimates. The weight for each predictor in the model was based on the variability of the estimates obtained with the single predictors as described by equations (5) and (6):

$$w_i = \frac{1}{\mathrm{SD}_i} \tag{5}$$

$$\mathrm{weight}_i = \frac{w_i}{\Sigma_w}, \tag{6}$$

where SD is a vector containing the standard deviations of the estimates based on single predictors. Note that the larger the standard deviation, that is, the larger the uncertainty for that estimate, the lower the weight. Two models were created, one with all predictor variables combined (combined all) and one with the two best single predictors (combined optimal), i.e. the predictors that yielded the offset with the lowest mean and standard deviation. For both models, all the data of both young and older adults were used.

2.5 Statistical analysis

We determined mean differences between the estimated and reference event times. The mean difference was subtracted from the estimated event times and the standard deviation of the resulting estimates was determined as an indicator of precision.

Cross-validation, sometimes called rotation estimation, was used for assessing how the results of the analyses generalize to an independent data set. This method is mainly used in settings where the goal is prediction, and one wants to estimate how accurately a predictive model will perform in practice (Kohavi 1995). Cross-validation can be done in several ways. Leave-one-out (Stone 1974 and Geisser 1975) is one option and it is more efficient than creating a hold-out set. Therefore, the predictions were validated with leave-one-out cross-validation. This involves using a single observation from the original sample as the validation data, and the remaining observations as the training data. This is repeated such that each observation in the sample is used once as the validation data.

3. RESULTS

From the 15 YA and 13 OA who did 2 sets of 5 trials, 253 trials (90.4%) were analyzed successfully; feature extraction failed in only two trials (0.7%). Two OA were not able to stand up and were excluded. Eighteen trials were removed due to chair sensor problems (YA, 10 and OA, 8). A chair sensor problem means that the seat-off or the seat- on was not correctly detected, because the sensor-ground contact failed, or the sensor was switched on due to standing on the plywood, or the subject pushed off from the chair with the hands. Seven YA performed four instead of five trials. Two trials of OA were removed due to failed feature extraction.

Figure 3 presents a typical example of the signals from which features were extracted as predictor variables. The mean offsets relative to seat-off and seat-on and the concomitant standard deviations for the 6 predictors are presented in figure 4. The vertical acceleration (av_max) was found to be imprecise because often there were no clearly detectable peaks in the signal. Therefore, av_max was not further used in the analysis.

In general the variability of the timing of the predictors relative to seat off was much lower in YA than in OA and predictions of the seat off were less variable than predictions of seat-on.

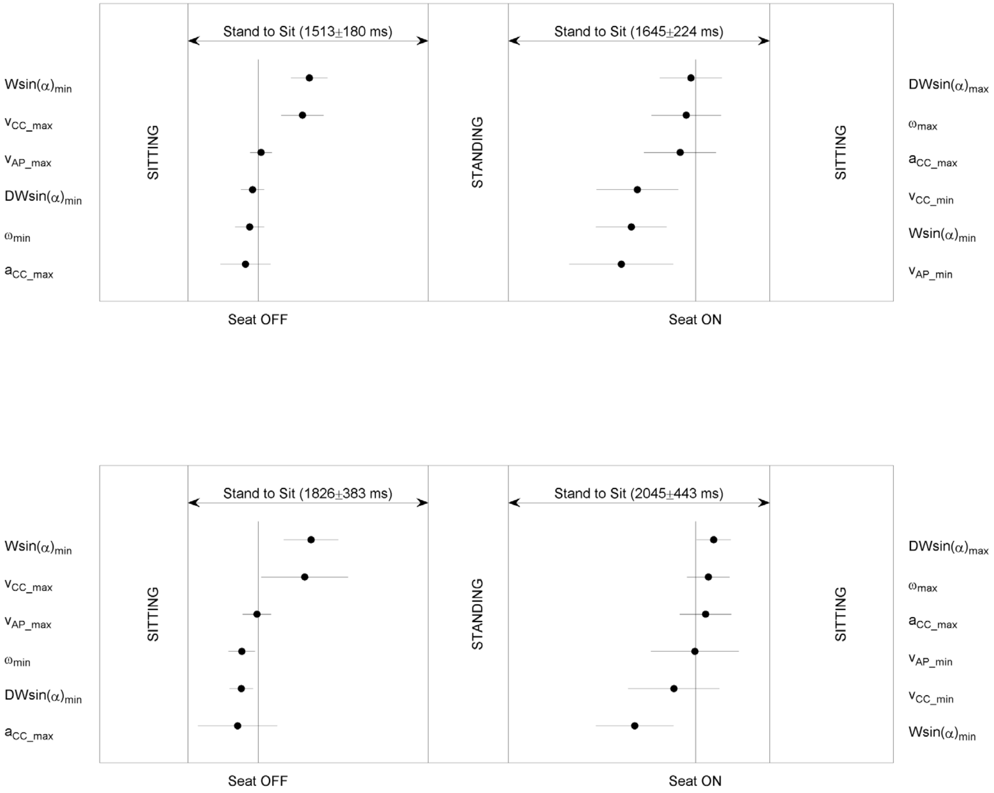

Figure 4. Offset (•) and SD (---) of the timing of each of the predictors relative to seat-off and seat-on. In the upper panel the results for the young adults (133 trials) and in lower panel the results for the old adults (120 trials) are shown. The continuous vertical lines represent the separation between the phases of the STS cycle, the shorter vertical lines represent the moments of seat-off and seat-on.

3.1 Seat-off

The timing difference between seat-off and the peak in horizontal trunk velocity (vAP_max) had the smallest offset and variability and DWsin(α)min was the second best predictor of seat-off. The mean error and mean absolute error of: 1) the five single estimates, 2) the estimate based on all five features and 3) the estimate based on the features with the lowest mean absolute error (vAP_max and DWsin(α) min) are presented in table 1. As can be seen, the last model (Italic) yielded the best results, with a negligible mean error and the smallest absolute error of 49 ms.

The best two single predictors and the model using the best two predictors were used in the leave-one-out cross-validation. The mean error and the mean absolute error are shown in table 2. The best predictor was the model using the best two predictors, with a mean error of 0 ms and mean absolute error of 51 ms.

Table 1. Mean (and SD) values of the error absolute error of the seat-off estimates based on single predictors and the two models combining several predictors (ms).

	DWsin(α) min	Wsin(α) min	ωmin	vAP_max	vCC_max	Combined all	Combined optimal
mean error (ms)	0 (69)	0 (122)	0 (73)	0 (69)	0 (186)	0 (74)	0 (66)
mean abs error (ms)	51 (50)	94 (77)	63 (47)	56 (40)	161 (109)	58 (45)	49 (44)

The model using the combined features vAP_max and DWsin(α)min was used in the leave-one-out cross-validation. The mean error was 0 m and the mean absolute error 51 ms (Table 2).

Table 2. Mean (and SD) values of the error absolute error of the seat-off estimates based on single predictors and the two models combining several predictors in the cross-validation (ms).

	DWsin(α)min	vAP_max	Combined optimal
mean error (ms)	1 (72)	0 (71)	0 (68)
mean abs error (ms)	52 (52)	58 (42)	51 (46)

3.2 Seat-on

The timing difference between seat-off and DWsin(a)$_{min}$ had the smallest offset and variability and Wsin(α)$_{min}$ was the second best predictor of seat-off. The mean error and mean absolute error of (1) the 5 single estimates, and (2) the model based on all 5 features are presented in table 3. The combined models did not improve the first prediction using only DWsin(α)$_{max}$, which had a negligible mean error
of -3 ms and an absolute error of 127 ms.

The best two single predictors and the model using the best two predictors were used in the leave-one-out cross-validation. The mean error and the mean absolute error and are shown in Table 4. The best predictor was DWsin(α)max, with a mean error of -3 ms and mean absolute error of 127 ms.

Table 3. Mean (and SD) values of the error and absolute error of the seat-on estimates based on single predictors and the model combining all predictors (ms).

	DWsin(α) max	**Wsin(α) min**	**ωmax**	**vAP_min**	**vCC_min**	**Combined all**	**Combined optimal**
mean error (ms)	0 (157)	0 (213)	0 (171)	0 (311)	0 (261)	0 (170)	0 (166)
mean abs error (ms)	124 (101)	159 (144)	133 (112)	324 (130)	233 (146)	135 (108)	130 (105)

Table 4. Mean (and SD) values of the error and absolute error of the seat-on estimates based on single predictors and the model combining all predictors in the cross-validation (ms).

	DWsin(α)max	**Wsin(α)min**	**Combined optimal**
mean error (ms)	-3 (163)	0 (221)	-3 (176)
mean abs error (ms)	127 (105)	163 (150)	136 (113)

4.1. Automated approach of STS quantification

In this study, a method was developed to estimate seat-off and seat-on in STS task based on a single body-fixed sensor system placed on the trunk. Six features of the trunk movement during seat-off and seat-on were calculated automatically. In two trials of OA the automatic analysis failed. Both trials were removed manually. So a fully automated approach is not yet realized.

4.2. Seat-off prediction

Estimation of seat-off was successful with a mean error of the optimal model during the cross-validation of 0 ms and a mean random error of 51 ms (Table 2). The total duration of the sit-to-stand in our study was 1670 ms. In other studies the duration of the sit-to-stand of old adults varied between 1440 ms and 2950 ms (Najafi et al., 2002; Lindemann et al., 2007). Based on the durations measured in this study the random estimation error for the final model of seat-off was 3.1% of the total sit-to-stand duration.

The mean maximum horizontal velocity is the parameter closest in time to the seat-off (figure 5). Bernardi et al. (2004) used the peak horizontal velocity to define the end of the flexion momentum phase, referring to Riley et al. (1991). This is also the method used to detect the moment that the bottom leaves the chair. The maximum angular velocity (Figure 5) precedes and induces the horizontal velocity. The angular velocity of the trunk generates the momentum, which is necessary to displace the centre mass from the chair to the feet.

The timing and the order of occurrence of events identified during sit-to-stand was almost identical for the young and older adults (Figure 5). This could indicate that the strategy was similar. It could also be explained by the fact that the sit-to-stand is a constrained movement. The standard deviation of the timing of these events relative to seat-off was higher in the older adults than in the young adults (Figure 5).

We found only one study validating seat-off detection (McGibbon et al., 2004). In that study, predictions were based on signals of a force plate underneath the subject's feet, a method that would be less applicable in practice given the costs involved. Moreover, only healthy subjects with a mean age of 30 years were included. The overall absolute error was 4.5 ms. Hence we can conclude that McGibbon's method is more precise. However in our study young and old adults living in a care home were included and a single body fixed sensor system was used, which appears more versatile and suitable for clinical applications.

4.3. Seat-on prediction

Estimation of seat-on was successful with a mean error of the optimal model during the cross-validation of -3 ms and a mean random error of 136 ms (Table 4). Estimation of seat-on revealed that DWsin(α)max (-3 respectively 127 ms) is a better predictor than the combined features (Table 4). The total duration of the stand-to-sit in our study was 1845 ms. In the literature durations of 2810 ms to 4080 ms have been reported (Najafi et al., 2002; Ganea et al., 2011). Based on the durations measured in this study, the random estimation error for the best predictor of seat-on was 6.9% of the total stand-to-sit duration.

The timing of the mean values during stand-to-sit shows several differences. All trunk features of the young adults occurred before seat-on and in the old adults half of the mean features occurred after seat-on. Also the order of the features shows several differences. Especially the minimum horizontal velocity (vAP_min) was an early feature in young adults, but occurred close to seat-on in old adults. This may be explained by differences in movement strategy between age groups. To improve the prediction of the seat-on separate models could be developed for different age groups. However, at present this would require arbitrary choices regarding age thresholds in application of the estimation procedure and therefore such an approach can only be developed when data over a wide range of ages are available.

4.4. Variance and STS strategies

The estimation error of the seat-on is markedly larger than the estimation error of the seat-off. A possible explanation for this can be found in the difference in execution (figure 5). Apparently, the old adults use different strategies for stand-to-sit which could negatively influence the prediction. Inspection of the videos supports this observation. Ageing is accompanied with loss of automation and physical capability due to decreasing coordination, force and confidence. This can result in changing stand-to-sit strategies, which might affect the magnitude of the variance of STS movement. Although the variance is used in the method as a weighting factor differences in execution of the STS contribute to the variance of the estimates. Future research should focus on the effect of different STS strategies (Doorenbosch et al., 1994; Hughes et al., 1996; Papa & Cappozzo, 2000; Mazzà et al., 2004; Manckoundia et al., 2006; Scarborough et al., 2007).

4.5. Leave-one-out methodology

In estimating the accuracy of the prediction, one would like to have an estimate with low offset and low variance. The accuracy (offset) is less important than the variance of the estimate or in other words the precision (Kohavi, 1995). McGibbon et al. (2004) used the hold-out method to validate estimates of seat-off. This method uses a subset of the test sample for learning and a subset for testing. The hold-out method makes inefficient use of the data (Kohavi, 1995). Therefore, in this study all data were used in the model to estimate the accuracy of the estimates. The differences in the standard deviation of the mean error and the mean absolute error between the model and the cross-validation were very small (Table 1-4). This implies that estimation errors are not very different for subjects that were not part of the group that the model was based on, implying that the prediction will be valid for new subjects.

4.6. Limitations

In this study a small amount of very young and very old adults were measured. With larger subject groups, stratified models for age and possibly for other variables such as gender could be developed in the future. In the interpretation of the results presented, it must be realized that the switches do not yield perfect estimates of the seat-off and seat-on events, which contributes to the estimation errors reported.

5. Conclusions

The results of this study demonstrate that seat-off and seat-on in a repeated sit-to-stand task can be estimated based on a semi-automatic procedure in young and old adults using a single body-fixed sensor system with a precision of about 50 ms and 127 ms, respectively. The use of the ambulatory instrumentation is feasible for non-technically trained personnel. This is an important step in the development of an automated method for quantification of STS movements in clinical practice.

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Methodological aspects

1

CHAPTER 2
Automated approach for quantifying the repeated sit-to-stand using one body fixed sensor in young and older adults

CHAPTER 3
Validation of seat-off and seat-on in repeated sit-to-stand movements using a single-body-fixed sensor

CHAPTER 4
Intra-rater, inter-rater and test-retest reliability of an instrumented Timed Up and Go (iTUG) test in patients with Parkinson’s disease

CHAPTER 4

Intra-Rater, Inter-Rater and Test-Retest Reliability of an Instrumented Timed Up and Go (iTUG) Test in Patients with Parkinson's Disease

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INTRA-RATER, INTER-RATER AND TEST-RETEST RELIABILITY OF AN INSTRUMENTED TIMED UP AND GO (ITUG) TEST IN PATIENTS WITH PARKINSON’S DISEASE

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ABSTRACT

Background

The ‘Timed Up and Go’ (TUG) is a widely used measure of physical functioning in older people and in neurological populations, including Parkinson’s Disease. When using an inertial sensor measurement system (instrumented TUG (iTUG)), the individual components of the iTUG and the trunk kinematics can be measured separately, which may provide relevant additional information.

Objective

The aim of this study was to determine intra-rater, inter-rater and test-retest reliability of the iTUG in patients with Parkinson’s Disease.

Methods

Twenty eight PD patients, aged 50 years or older, were included. For the iTUG the DynaPort Hybrid (McRoberts, The Hague, The Netherlands) was worn at the lower back. The device measured acceleration and angular velocity in three directions at a rate of 100 samples/s. Patients performed the iTUG five times on two consecutive days. Repeated measurements by the same rater on the same day were used to calculate intra-rater reliability. Repeated measurements by different raters on the same day were used to calculate intra-rater and inter-rater reliability. Repeated measurements by the same rater on different days were used to calculate test-retest reliability.

Results

Nineteen ICC values (15%) were ≥ 0.9 which is considered as excellent reliability. Sixty four ICC values (49%) were ≥ 0.70 and < 0.90 which is considered as good reliability. Thirty one ICC values (24%) were ≥ 0.50 and < 0.70, indicating moderate reliability. Sixteen ICC values (12%) were ≥ 0.30 and < 0.50 indicating poor reliability. Two ICT values (2%) were < 0.30 indicating very poor reliability.

Conclusions

In conclusion, in patients with Parkinson’s disease the intra-rater, inter-rater, and test-retest reliability of the individual components of the instrumented TUG (iTUG) was excellent to good for total duration and for turning durations, and good to low for the sub durations and for the kinematics of the SiSt and StSi. The results of this fully automated analysis of instrumented TUG movements demonstrate that several reliable TUG parameters can be identified that provide a basis for a more precise, quantitative use of the TUG test, in clinical practice.

INTRODUCTION

The ‘Timed Up and Go’ test (TUG) is a widely used measure of physical functioning (balance and mobility) in older people and in neurological populations, including Parkinson’s Disease (PD) [1–3)] It is a simple test that can be performed almost everywhere. The subject rises from an arm chair (Sit-to-Stand) , walks 3 meters, returns to the chair and sit down again (Stand-to-Sit). The score given is the time taken in seconds to complete the test [4,5].

When the subject wears an inertial sensor measurement system, the individual components of the TUG can be measured separately. For example, in early stages of PD information on the components of each task, such as gait, turns or postural transitions (e.g. angular velocity and angular displacement) could reveal specific mobility problems. This may provide relevant information on the quality of movements. This version of the TUG is called an instrumented TUG, abbreviated as iTUG.

A few studies have used the iTUG in patients with Parkinson’s Disease (PD). Weiss et al. [6,7] found that several specific iTUG features, for example the amplitude range and slope in the accelerometer signal in anterior-posterior direction during the Sit-To-Stand and Stand-To-Sit time intervals, were different between patients with PD and healthy controls. Zampieri et al. [8] found differences between untreated patients with PD and healthy controls in several iTUG movement parameters, such as arm swing, cadence, trunk rotations, and turning velocity. Buchman et al. [9] reported that sub-tasks of the TUG were related to Parkinsonian signs and Herman et al. [10] and Mirelman et al. [11] demonstrated in PD patients that particular cognitive domains were related to iTUG subtasks. These studies suggest that the iTUG may be useful for studying mobility in patients with PD, to detect and quantify subtle differences in mobility and function and is only available using instrumentation. Further research should investigate the potential of the iTUG to identify PD, to monitor the progression of PD over time, and to asses the response and benefits to different therapeutic interventions.

Essential for these applications of the iTUG are good measurement properties. A high reliability is required to enable the measurement of small differences between patients with PD and healthy controls or changes in iTUG parameters over time. Measurement error may occur due to differences in attachment of the belt containing the accelerometers, differences in instructions given by the rater, or differences in behavior of the subjects over time. Subjects are usually instructed to walk at their comfortable speed, but the actual speed can fluctuate.

Little research has been performed on the measurement properties of the iTUG. As far as we know, only one study on the reliability of the iTUG with inertial sensors in PD patients has been reported. Salarian et al. found moderate to good intra-rater reliability for different iTUG parameters, in a sample of 18 subjects, 9 patients with PD and 9 controls [12].

The aim of this study therefore was to determine intra-rater, inter-rater and test-retest reliability of the iTUG in PD patients. The hypothesis was that test-retest reliability would be lower because patients with patients with Parkinson show unpredictable fluctuations of the disease [13].

METHODS

Setting

Measurements were conducted at the outpatient clinic and ward of the Department of Neurodegenerative Diseases of the Center for Neurology of the University of Tübingen, the Gertrudis Klinik, Biskirchen, and a Physical Therapist Practice in 's-Gravenzande, The Netherlands. In order to establish if the patients were able to communicate well with the investigator and to understand and comply with the requirements of the study, clinical examination and absence of diagnosis of dementia was used. All patients provided written informed consent. The study protocol was approved by the Ethics Committee of the Medical Faculty of the University of Tübingen.

Patients

Twenty eight patients with a diagnosis of Parkinson according to UK Brain-Bank criteria [14] were recruited. Mean age was 67.1 years (SD ± 8.3) and 22 patients were male. Median Hoehn & Yahr score was 3 (range 2-4). Patients needed to be able to walk 10 meters independently without ambulatory aids or assistance. Patients were tested during their subjective ''on'' phase. using their regular medication regimen [15].

Procedures

All patients performed the iTUG five times on two consecutive days. On day 1, the first rater (A or B) explained and demonstrated the procedure. Then he attached the belt with the sensor and started the measurement by giving the start signal and operating the Remote Control (described below). One test trial (O) was performed in order to familiarize the patient with the procedure. This trial was not used for analysis. Morris et al [3] also removed the results of the first trial because it was abnormally slow. Then a second and third trial (AA or BB) were performed. After that, the first rater removed the belt. The second rater reattached the belt and the patients again performed two trials. After 24 hours, the whole procedure was repeated. Two raters (EvH and MH) performed all tests (raters A and B). The patients were assigned randomly to the test leaders. All possible combinations are visualized in table 1.

Table 1. Order of measurements: O is a test trial. A is rater 1 and B is rater 2

Day 1	**Day 2**
OAABB	OAABB
OAABB	OBBAA
OBBAA	OAABB
OBBAA	OBBAA

Measurements

Participant's trunk movements were measured with a small and light (87×45×14 mm, 74 grams) inertial sensor measurement system (DynaPort Hybrid, McRoberts, The Hague, The Netherlands), which was inserted in an elastic belt and positioned on the lower back near the spine. The device measured acceleration and angular velocity in three directions at a rate of 100 samples/s. Several Sit-to-Stand (STS) parameters can be identified that provide a basis for a more precise, quantitative study of STS performance in clinical practice [16,17]. The patients started the TUG while sitting on a regular, stable chair, with a height of 43-46 cm, without armrests. Patients were instructed to sit with their back against the back of the chair, feet placed on taped markers on the floor directly in front of the chair, with a distance of 43 cm between the feet and arms resting in their lap. Patients were instructed to rise from the chair (without using their arms) after the rater gave the starting signal, comfortably walk the clearly marked distance of 3 meter, turn around a cone, walk back to the chair and sit down with their back against the chair. The 3 meter walking distance was measured from the front of the chair to the middle of the cone. Markers in the signals of the inertial sensors were set at the start and the end of every trial using a remote control (McRoberts B.V.) which uses Bluetooth to connect with the DynaPort sensor. The rater also used a stopwatch to measure the time needed to perform the TUG, from the starting signal until the subject sat down on the chair again with the back against the back of the chair.

Signal analysis

The iTUG was analyzed using commercially available software (DynaPort MoveTest, The Hague, The Netherlands). The total iTUG time was determined, as well as the following separate time intervals: sit to stand duration, walking first 3 meter duration, turning around the cone duration, walking second 3 meter duration, and turning before sitting duration and stand to sit duration. From the sit to stand and the stand to sit the separate flexion and extension durations were calculated. The maximum angular velocity during turning around the cone was calculated.

Start and end temporal events of the sit to walk and walk to sit phases were determined using peak detection of a low-pass filtered vertical acceleration signal. Maximal flexion angles of the sit to walk and walk to sit were determined using the trunk angle signal [18]. End and start temporal events of the sit to walk and walk to sit phases were determined as the first peak of the vertical acceleration signal after and before the maximum flexion angles and above the mean of the vertical acceleration signal. Global turning phases were determined using the low-pass filtered and squared angular velocity around the vertical axis. Start and end temporal events of the turning phases were determined using threshold detection based on low-pass filtering, squaring and differentiation of the angular velocity around the vertical axis.

From the trunk kinematics maximum angular velocity and angular displacement of the flexion and extension phase were calculated during the sit to stand movement and the stand to sit movement (figure 1).

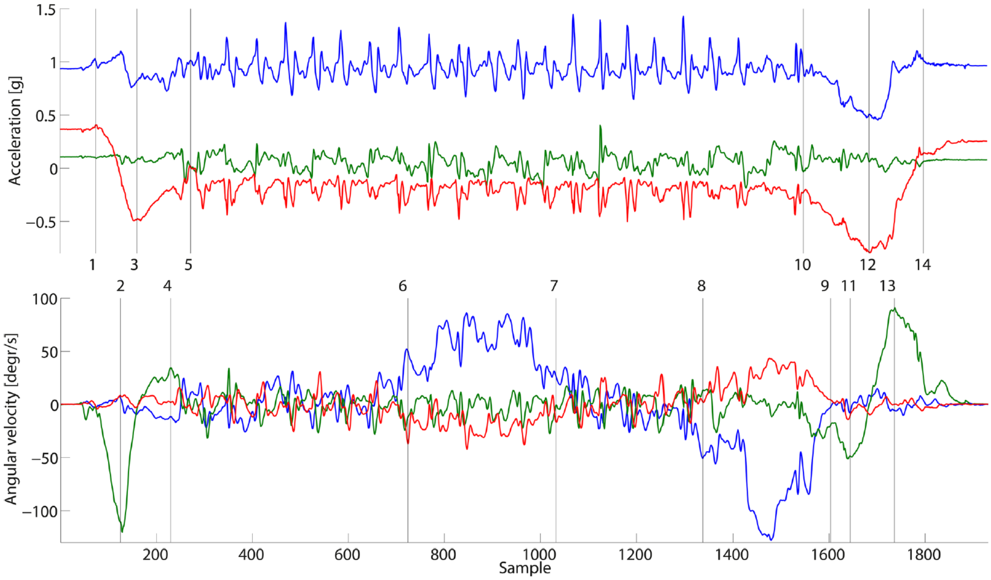

Fig 1. Raw data of the accelerometers on top and the gyroscopes at the bottom. 100 samples is one second. Blue are the vertical axes. green are the medio-lateral axes and red are the anterior-posterior axes. The numbers at the vertical lines correspond with the following events: 1 = Start SiSt. 2 = Maximum trunk flexion velocity SiSt. 3 = Maximum trunk flexion angle SiSt. 4 = Maximum trunk extension velocity SiSt. 5 = End SiSt. 6 = Start turn 1. 7 = End turn 1. 8 = Start turn 2. 9 = End turn 2. 10 = Start StSi. 11 = Maximum trunk flexion velocity StSi. 12 = Maximum trunk flexion angle StSi. 13 = Maximum trunk extension velocity StSi. 14 = End StSi.

Statistical analyses

Statistical differences between stopwatch and iTUG timing during Day 1 and Day 2 were tested using the dependent 2-group Wilcoxon Signed Rank Test, because most parameters were not normally distributed.

Measurement error was expressed in the Standard Error of Measurement (SEM) and the Smallest Detectable Change (SDC). The SEM value was derived from the error variance in the ICC formula. The SDC was calculated as $1.96*\sqrt{2}*SEM$, which can be interpreted similar as the limits of agreement of the Bland and Altman method [19]. The Standard Error of Measurement (SEM) and the Smallest Detectable Change (SDC) of all variables (durations and kinematics) were presented in the same unit of measurement as the variable itself, for straightforward interpretation.

A single measures, two-way mixed model, type absolute intra-class correlation coefficient was used to calculate ICCs [20,21]. Intra-, inter-rater and test-retest reliability are expressed in Intra-class Correlation Coefficients (ICCs). The following equations for the ICC were applied. Each term refers to a variance component: p = patient, o = observer and m = moment.

Intra-rater reliability: $$\frac{\sigma_p^2 + \sigma_{po}^2 + \sigma_{pd}^2}{\sigma_p^2 + \sigma_{po}^2 + \sigma_{pm}^2 + \sigma_{pd}^2 + \sigma_{residual}^2}$$

Inter-rater reliability: $$\frac{\sigma_p^2 + \sigma_{pm}^2 + \sigma_{pd}^2}{\sigma_p^2 + \sigma_{po}^2 + \sigma_{pm}^2 + \sigma_{pd}^2 + \sigma_{residual}^2}$$

Test-retest reliability: $$\frac{\sigma_p^2 + \sigma_{po}^2 + \sigma_{pm}^2}{\sigma_p^2 + \sigma_{po}^2 + \sigma_{pm}^2 + \sigma_{pd}^2 + \sigma_{residual}^2}$$

The familiarization trials (O) were not analyzed. Repeated measurements by the same rater on the same day (AA or BB) were used to calculate intra-rater reliability. Repeated measurements by different raters on the same day (AB or BA) were used to calculate inter-rater reliability. Repeated measurements by the same rater on different days (A-A or B-B) were used to calculate test-retest reliability.

We used thresholds, instead of significance, to asses reliability because they were less depending from the sample size. ICC's were rounded at two decimals. An ICC of ≥ 0.90 was considered as excellent reliability, an ICC of ≥ 0.70 - < 0.90 was considered as good reliability, an ICC of ≥ 0.50 - < 0.70 was considered as moderate reliability, an ICC of ≥ 0.30 - < 0.50 was considered as poor reliability, an ICC of > 0.30 was considered as very poor reliability.

Data were analyzed using SPSS 20 for Windows (SPSS Inc., Chicago, USA).

Results

Stopwatch timing was different from the iTUG timing for both raters on Day 1 and Day 2 ($p<0.001$) and between ICC's calculated for Day 1 and Day 2 for the stopwatch and iTUG timing ($p<0.001$). The results for descriptive statistics of the durations, the SEM and the SDC are shown in Table 2.

Table 2. Mean, Standard deviation, Minimum, Maximum, Standard Error of Measurement and Smallest Detectable Change of the total time of the stopwatch, total time of the iTUG and individual components of the iTUG in seconds.

	Mean (s)	SD (s)	Min (s)	Max (s)	SEM (s)	SDC (s)
Total durations						
Stopwatch	11.80	3.11	7.80	18.54	0.61	1.69
iTUG	11.38	2.97	6.89	17.63	0.56	1.55
Sit-to-Stand						
SiSt Total	1.73	0.51	0.89	3.13	0.10	0.27
SiSt Flex	0.91	0.32	0.48	1.84	0.06	0.17
SiSt Ext	0.83	0.31	0.30	1.71	0.06	0.16
Walks and Turns						
Walk 1	2.19	0.82	0.95	4.24	0.16	0.43
Turn 1	2.65	0.57	1.84	4.39	0.11	0.30
Walk 2	1.81	0.66	0.76	3.18	0.13	0.35
Turn 2	2.33	0.48	1.71	3.82	0.09	0.25
Stand-to-Sit						
StSi Total	2.01	0.56	0.73	3.24	0.11	0.30
StSi Flex	1.03	0.39	0.24	1.71	0.07	0.20
StSi Ext	0.98	0.28	0.48	1.73	0.05	0.14

The results of descriptive statistics of the angular range (θflex), the maximum angular velocity (ωmax), the standard error of measurement (SEM), and the Smallest Detectible Change (SDC) are shown in table 3.

Table 3. Descriptive values, SEM and SDC of the angular range (θ) in degrees (°) and the maximum angular velocity (ωmax) in degrees per second (°/s) of the individual components of the TUG.

		Mean	SD	Min	Max	SEM	SDC
Sit-to-Stand							
SiSt Flex	θflex (°)	41.26	9.91	27.39	61.35	1.87	5.19
SiSt Flex	ωmax (°/s)	82.08	21.75	51.40	122.06	4.11	11.39
SiSt Ext	θflex (°)	21.20	7.45	5.86	41.39	1.41	3.90
SiSt Ext	ωmax (°/s)	32.63	10.00	17.77	58.03	1.89	5.24
Turns							
Turn 1	ωmax (°/s)	136.60	40.94	74.85	224.25	7.74	21.45
Turn 2	ωmax (°/s)	142.27	38.59	82.27	226.89	7.29	20.21
Stand-to-Sit							
StSi Flex	θflex (°)	18.90	8.00	4.13	32.12	1.51	4.19
StSi Flex	ωmax (°/s)	33.29	11.47	14.90	53.84	2.17	6.01
StSi Ext	θflex (°)	41.02	6.53	32.17	55.57	1.23	3.42
StSi Ext	ωmax (°/s)	77.32	14.42	56.82	110.62	2.73	7.55

The results of the intra-rater, inter-rater and test-retest reliability are shown in table 4. Total duration, as measured with a stopwatch and as calculated from the kinematics were both highly reliable.

Table 4. Intra-rater, inter-rater and test-retest reliability of the TUG durations (s) and the trunk kinematics expressed in angular displacement of the flexion (θflex) and the extension (θext) phase and the maximum angular velocity (ωmax) of the TUG (n=28).

Durations Intra-rater reliability (ICC) of iTUG durations and stopwatch duration												Total duration
	SitSt	Flex	Ext	Walk 1	Turn 1	Walk 2	Turn 2	StSit	Flex	Ext	iTUG	TUG
Day 1	0.57	0.61	0.56	0.80	0.89	0.88	0.80	0.75	0.77	0.85	0.95	0.96
Day 2	0.62	0.37	0.57	0.88	0.89	0.86	0.89	0.81	0.78	0.79	0.98	0.97
Inter-rater reliability (ICC) of iTUG durations and stopwatch duration												Total duration
	SitSt	Flex	Ext	Walk 1	Turn 1	Walk 2	Turn 2	StSit	Flex	Ext	iTUG	TUG
Day 1	0.52	0.58	0.56	0.84	0.90	0.91	0.80	0.74	0.73	0.77	0.95	0.96
Day 2	0.61	0.27	0.57	0.90	0.91	0.86	0.89	0.74	0.73	0.85	0.96	0.95
Test-retest reliability (ICC) of iTUG durations and stopwatch duration												Total duration
	SitSt	Flex	Ext	Walk 1	Turn 1	Walk 2	Turn 2	StSit	Flex	Ext	iTUG	TUG
Day 1	0.47	0.59	0.42	0.86	0.84	0.71	0.71	0.75	0.67	0.73	0.88	0.90
Day 2	0.50	0.60	0.36	0.80	0.88	0.83	0.76	0.62	0.53	0.58	0.89	0.90
Kinematics Intra-rater reliability (ICC) of iTUG trunk kinematics												
	Sit to Stand Flex	Sit to Stand Ext	Turn 1	Turn 2	Stand to Sit Flex	Stand to Sit Ext						
	θflex	ωmax	θflex	ωmax	ωmax	ωmax	θflex	ωmax	θflex	ωmax		
Day 1	0.86	0.83	0.85	0.74	0.89	0.77	0.80	0.77	0.60	0.83		
Day 2	0.91	0.80	0.83	0.32	0.92	0.87	0.79	0.52	0.74	0.76		
Inter-rater reliability (ICC) of iTUG trunk kinematics												
	Sit to Stand Flex	Sit to Stand Ext	Turn 1	Turn 2	Stand to Sit Flex	Stand to Sit Ext						
	θflex	ωmax	θflex	ωmax	ωmax	ωmax	θflex	ωmax	θflex	ωmax		
Day 1	0.83	0.56	0.85	0.83	0.90	0.78	0.82	0.66	0.70	0.59		
Day 2	0.90	0.79	0.74	0.49	0.91	0.88	0.73	0.60	0.62	0.72		
Test-retest reliability (ICC) of iTUG trunk kinematics												
	Sit to Stand Flex	Sit to Stand Ext	Turn 1	Turn 2	Stand to Sit Flex	Stand to Sit Ext						
	θflex	ωmax	θflex	ωmax	ωmax	ωmax	θflex	ωmax	θflex	ωmax		
Day 1	0.59	0.66	0.47	0.38	0.84	0.83	0.63	0.52	0.45	0.47		
Day 2	0.60	0.52	0.47	0.39	0.88	0.73	0.53	0.41	0.33	0.18		

Nineteen ICC values (15%) were ≥ 0.9 which is considered as excellent reliability. Sixty four ICC values (49%) were ≥ 0.70 and < 0.90 which is considered as good reliability. Thirty one ICC values (24%) were ≥ 0.50 and < 0.70, indicating moderate reliability. Sixteen ICC values (12%) were ≥ 0.30 and < 0.50 indicating poor reliability. Two ICT values (2%) were < 0.30 indicating very poor reliability. The results clearly show that the reliability of total duration (range 0.88-0.95) and walk 1 and 2 (range 0.71-0.90) and turn 1 and 2 (range 0.71- 0.91) is better than the reliability of the other parameters. Furthermore, the intra-rater and the inter-rater reliability were equal but the test-retest reliability was a bit lower.

Discussion

In this study, intra-rater, inter-rater, and test-retest reliability were assessed in 28 patients with Parkinson's disease. The intra-rater, inter-rater and test-retest reliability for the total duration, the walking and turning parts were good to excellent. Moderate reliability was found for the SiSt and StSi durations. The intra-rater and inter- reliability of the trunk kinematics showed good to excellent reliability. The test-retest reliability of the trunk kinematics showed moderate reliability for the SiSt and StSi and good reliability for the turns. In general the test-retest reliability was a bit lower than intra-rater and inter-rater reliability.

The attachment of the sensors, the instruction of the raters and the automated analysis of the individual components seem to have a small effect on the reliability because differences between intra-rater and inter-rater reliability were very small for the durations as well as the kinematics. The small differences between the intra-rater and the inter-rater scores were also comparable for the shorter sub parts of the TUG. Estimates of movement characteristics may suffer from errors due to discrepancies in accelerometer location. Rispens et al. [22] has shown that the differences in vertical sensor locations (L2-L5) on gait characteristics are small but some gait characteristics are more sensitive for mediolateral differences. This suggests that the sensors have to be attached accurately on the spine.

The data show a slightly lower test/retest reliability of most duration and kinematic parameters compared to the intra/rater and the inter/rater reliability. This shows that the behaviour of the subjects during consecutive days has more influence on the reliability than the behaviour of the raters. This could be affected by fluctuations of the movement symptoms of patients with PD.

We found seven other studies on the reliability of the normal TUG (studies on modified versions were omitted) [3,5,23–27] of which only one study was performed in PD patients [3]. One additional study was found on the reliability of an iTUG in PD patients and healthy controls [12]. The results of these studies are summarized in Table 5. These studies generally also show high inter- and intra-rater reliability of total TUG time. Test-retest reliability was low (ICC=0.56) in the large study of Rockwood et al. [25]. However, the test-retest interval in this study was very large (mean 112 days), the tests were administered under different circumstances, and by different raters. Thus, despite the large sample size, the quality of this study is considered to be poor. Morris et al. (3) found an inter-rater reliability of 0.87-0.99 for total TUG time in Parkinson patients, which is comparable to our study (inter-rater ICC=0.88-0.98). In the study of Salarian et al. [12] a poor intra-rater reliability (ICC=0.04) was found for sit to stand duration, and high intra-rater reliability was found for turns (ICC=0.89) and turn to sit (ICC=0.84). We found a moderate intra-rater reliability for sit to stand duration on day 1 (ICC=0.57), as well as on day 2 (ICC=0.62). We also found higher intra-rater reliabilities for the turning parameters (ICC=0.80-0.92). An explanation for this finding is that the turning phase can be detected from the available signals much easier than the other phases of the test.

Table 5. Results from earlier reliability studies.

Ref	**TUG type**	**subjects**	**n**	**Intra-rater reliability (different days)**	**Inter-rater / reliability (same day)**	**Test-retest reliability (different days and different raters)**	**Intra-rater LoA* (sec)**	**Inter-rater LoA (sec)**	**Mean ± SD or median (range) sec**
[5]	TUG	Elderly with a variety of medical diagnoses	20 22	ICC=0.99	ICC=0.99		± 10	± 10	(11-128)
[19]	TUG	Unilateral lower limb amputation	32	r=0.93	r=0.96		1.6 ± 10.2	0.5 ± 9.2	24.5 (9-102)
[18]	TUG	Community-dwelling elderly	1115			ICC=0.56			14.0 (4-165)
[17]	TUG	Community-dwelling elderly	30	ICC=0.93-0.99		ICC=0.93-0.99			13.3
[16]	TUG	Elderly with impaired mobility	28	ICC=0.68					
[20]	Mean of 2 TUGs	Inpatients on an orthopaedic rehabilitation ward	24			ICC=0.80			22-104
[3]	TUG	PD patients	12		“Off” phase ICC=0.87-0.99 “On” phase ICC=0.99 **				“Off” phase 15-21 (10-45) “On” phase 13-15 (9-25)
[8]	iTUG	Early PD patients and healthy controls	12+12	Sit to stand ICC=0.04 Turn ICC=0.89 Turn to sit ICC=0.84 (same day)					10.8 ± 0.5

In the Salarian study [12], the only study in which inertial sensors have been used, intra-rater reliability has been studied. The walking part was longer (7 meter) than in the original TUG. The number of patients with PD was very low (n=9) and the duration of the disease of the patients short (H & Y score between 1 and 2.5).

Moreover, because both patients (n=9) and healthy controls (n=9) were included, the variability among subjects was larger. This artificially increases the reliability and decreases the generalizability of the results to future applications of the test in patients with PD only [28].

The results of our study should be interpreted with caution because of the relatively small sample size. We intend to collect more data in future studies. In addition, we intend to analyse more parameters, such as gait parameters and postural transitions (e.g. cadence, and number of steps). This may provide relevant information about the quality of movement. For example, in early stages of PD information on the components of each task, such as gait or postural transitions, could reveal specific mobility problems. The total duration taken with a stopwatch was a bit longer and the SD, SEM and SDC were larger than for the total iTUG duration (Table 2). Little is known about the accuracy of manually recorded time during performance tests. More research comparing these differences is necessary. There might be a difference between the start signal of the test leader and the start of the movement because of different reaction times of the participants. The observed difference may also be related to the accuracy of the test leader, who has to mark the start and stop of the movement and supervise the participant simultaneously.

In conclusion, in patients with Parkinson's disease the intra-rater, inter-rater, and test-retest reliability of the individual components of the instrumented TUG (iTUG) was excellent to good for total duration and for turning durations, and good to low for the sub durations and the kinematics of the SiSt and StSi. The results of this fully automated analysis of instrumented TUG movements demonstrate that several reliable TUG parameters can be identified that provide a basis for a more precise, quantitative use of the TUG test, in clinical practice.

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Author contributions

Conceived and designed the experiments: RVL MH WM CBT. Performed the experiments: RVL SW MH. Analyzed the data: RVL SW FG CBT contributed reagents/materials/analysis tools: SW JVD FG CBT. Wrote the manuscript: RVL JVD CBT

Conflict of interest

RVL is a PhD student at the VU University Amsterdam and director of McRoberts and SW is an employee of McRoberts. This does not alter our adherence to PLOS ONE policies on sharing data and materials.

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Clinical value

2

CHAPTER 5

The Instrumented Sit-to-Stand Test (iSTS) has greater clinical relevance than the manually recorded Sit-to-Stand Test in older adults

CHAPTER 6

Older adults with low muscle strength stand up from a sitting position with more dynamic trunk use

CHAPTER 7

A new scoring method to quantify the instrumented Sit-to-Stand test in older adults

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research article

THE INSTRUMENTED SIT-TO-STAND TEST (ISTS) HAS GREATER CLINICAL RELEVANCE THAN THE MANUALLY RECORDED SIT-TO-STAND TEST IN OLDER ADULTS

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RUNNING PAGE HEADLINE
Instrumented Sit-to-Stand Test in Older Adults

ABSTRACT

Background.
The ability to rise from sitting to standing is critical to an individual's quality of life, as it is a prerequisite for functional independence. The purpose of the current study was to examine the hypothesis that test durations as assessed with the instrumented repeated Sit-To-Stand (STS) show stronger associations with health status, functional status and daily physical activity of older adults than manually recorded test durations.

Methods. In 63 older participants (mean age 83 ±6.9 years, 51 female), health status was assessed using the European Quality of Life questionnaire and functional status was assessed using the physical function index of the of the RAND-36. Physical performance was measured using a wearable sensor-based STS test. From this test, durations, sub-durations and kinematics of the STS movements were estimated and analysed. In addition, physical activity was measured for one week using an activity monitor and episodes of lying, sitting, standing and locomotion were identified. Associations between STS parameters with health status, functional status and daily physical activity were assessed.

Results. The manually recorded STS times were not significantly associated with health status (p=0.457) and functional status (p=0.055), whereas the instrumented STS times were (both p=0.009). The manually recorded STS durations showed a significant association to daily physical activity for mean sitting durations (p=0.042), but not for mean standing durations (p=0.230) and mean number of locomotion periods (p=0.218). Furthermore, durations of the dynamic sit-to-stand phase of the instrumented STS showed more significant associations with health status, functional status and daily physical activity (all p=0.001) than the static phases standing and sitting (p=0.043-0.422).

Conclusions. As hypothesized, instrumented STS durations were more strongly associated with participant health status, functional status and physical activity than manually recorded STS durations in older adults. Furthermore, instrumented STS allowed assessment of the dynamic phases of the test, which were likely more informative than the static sitting and standing phases.

Key words: physical function, physical performance test, chair stand, activity monitoring, wearables, accelerometers, gyroscopes.

INTRODUCTION

The ability to rise from sitting to standing is a prerequisite for functional independence. Elderly who are unable to stand up from a chair without support are at risk of becoming more inactive and thus of further mobility impairment. The Sit-to-Stand (STS) transition is considered one of the most mechanically demanding physical activities in daily life [1]. Leg power has been associated with functional status [2] and functional ability [3]. Normal daily activities such as stair climbing and rising from a chair cause very high contact pressures in the human hip as measured in vivo [4]. STS transitions require the development of substantial muscle power [5] and consequently many older adults perform such transitions close to their maximal ability [6,7].

STS transitions are widely used as a test in clinical research and practice. The test is used either as stand-alone test or as part of the Short Physical Performance Battery (SPPB) [8]. Within the SPPB patients are invited to perform five STS transitions as quickly as possible with the time to perform these five repetitions being the test result. The SPPB has been shown to correlate with the amount of daily physical activity]9], the likelihood of future disability [10], the use of hospital services [11], nursing home admission [8] and mortality [12]. There is good evidence linking aging and COPD [13]. Also in pulmonary rehabilitation the use of the repeated STS [14] receives growing interest.

More detailed investigations of STS transitions, focusing on the nature of the dynamic STS phases, have been performed in laboratory settings using video-based 3D movement registration systems and force-plates [1,15,16]. However, such investigations are (too) time-consuming, complex and expensive for routine clinical usage. Inertial body fixed sensors provide an alternative approach to the laboratory to examine STS transitions in greater detail than manual STS recordings. This method has been used in this study and we call it the instrumented STS (iSTS). The present study was conducted to examine the merits of this alternative method, relative to the standard, hand-clocked STS test.

Several studies have shown that the durations and kinematic properties of the various STS phases can be successfully analysed using inertial body-fixed sensors [17,18]. Seat-off and seat-on detection in repeated sit-to-stand movements can be accomplished with sufficient accuracy for an objective measurement of task duration [19]. In a previous study, dynamic (standing up and sitting down) as well as static (standing and sitting) phases of the test could be determined [20]. Furthermore, in this study, age-related differences in STS performance were evident for all sub-phase durations. All STS phases (i.e., sit-to-stand, standing, stand-to-sit and sitting) were significantly longer and more variable in older compared to young adults [20]. In a small study (n=11) it was shown that duration and variability of trunk movement during sit to stand could distinguish between elderly with high fall-risk and elderly with low fall-risk [21]. More recently, it has been suggested that parameters characterizing the rising phase of the STS cycle may be used to detect early frailty in clinical environments [22]. Indeed, several STS parameters showed significant differences between higher and lower functioning elderly as assessed by using a self-reported score of limitations in activities of daily living [23].

Compared to conventional manually recorded total test durations, fully automated analysis of repeated STS movements (e.g. durations, maximum angular velocity and angular displacement of STS sub-phases) may provide increased accuracy and ability to provide greater detail about the movement and hence may have added value.

The hypothesis of the current study was that test durations as assessed with the instrumented repeated STS show stronger associations with health status, functional status and daily physical activity of older adults than manually recorded test durations. To the best of our knowledge this is the first publication that investigated these associations.

METHODS

Study population
Older participants were recruited from residential care facilities and the surrounding community. Eligible persons were aged 64 years and older, had a Mini-Mental State Examination (MMSE) [24] score > 18 out of 30 points, to include a wide range of cognitive abilities, and were able to walk 20 meter without cardiac or respiratory complaints. The medical ethical committee of the VU University Medical Centre Amsterdam approved the protocol for the study (#2010/290) and all participants provided written informed consent.

Measures of participant characteristics
Participants were visited at home by a PhD student before the start of the project to explain the aim and procedure of the project, to collect baseline characteristics (age, gender, weight, height and body mass index) and cognition (MMSE) [24], and to ask the participant to sign informed consent.

Measures of health status and functional status
Health status was assessed using the European Quality of Life questionnaire (EQ-5D-3L) [25]. This descriptive system comprises the following 5 dimensions: mobility, self-care, usual activities, pain/discomfort and anxiety/depression. A visual analogue scale records the respondent's self-rated health. Functional status was assessed using the physical function index of the of the RAND-36 [26,27], which examines limitations in 10 activities related to mobility and physical movements.

Physical performance
Physical performance was measured using the complete Short Physical Performance Battery (SPPB) protocol [10]. The SPPB is an objective assessment tool for

evaluating lower extremity functioning in older persons and comprises measures of standing balance, walking speed, and ability to rise from a chair. For the chair stand participants were first asked to stand up from a straight-backed chair placed next to the wall, one time, without using their arms. If successful, participants were asked to rise from a chair with their arms crossed over their chest for five repetitions of standing up and four repetitions of sitting down, performed as fast as possible, and ending in a standing position. The manually recorded time was calculated as the duration of these 4.5 STS cycles. The 4 complete STS cycles were used for the instrumented analysis. The main reason to analyse 4 complete iSTS cycles instead of 4.5 STS cycles is technical in nature: drift correction of the raw signals is easier when the sensors end in the same position as they started. Furthermore, automatic detection of a complete STS cycle is more robust. Measuring the complete 4.5 STS made it also possible to automatically calculate the conventional STS sub-score of the SPPB.

The upper body makes the most significant contribution to both the vertical and the forward displacement of the centre of mass during standing up [1]. These upper body movements of the participants were measured using a small and light (87×45×14 mm, 74 grams) inertial sensor measurement system (DynaPort Hybrid, McRoberts, The Hague, The Netherlands). Acceleration and angular velocity were measured in three directions at a rate of 100 samples/s. The device was inserted in an elastic belt fixed around the waist near the spine over the undergarments and if possible beneath outer clothes. In this position it was unobtrusive, easy to fasten and least hampering the participant's movements. This position near the centre of mass was chosen to measure whole body movements. The sensor location has been extensively used in geriatric settings [19,20,28] and the reliability of the measurements in a geriatric setting has been shown to be high [29].

The protocol for the test was implemented on a computer, which communicated with the measurement system via Bluetooth. The test leader used a remote control to send event markers to the protocol in the computer. The first marker was sent at `go` and the final marker was sent when the participant had straightened up completely for the fifth time. The assessor was standing close to the participant for reasons of safety. This manually recorded time was stored through the software. The signal analysis software automatically analysed the durations and the kinematic characteristics of the phases of the STS. This method, has been demonstrated to be valid [17,19,28] and reliable in a geriatric setting. ICCs were good to excellent for all variables in the total sample (0.80–0.94). The intra-observer group (50%) showed a higher number of excellent ICCs (≥.9) compared to the inter-observer subgroup (10%). SEM% was low for all variables (6.9–12.7%). The MDC95% ranged between 19.2–34.4% and more variables ≤30% were found in the intra- (80%) compared to the inter-observer group (60%) [29].

Signal analysis

The measurement of 3-dimensional accelerations and angular velocities of the trunk allowed a detailed analysis of the different phases of the STS movement. Data were analysed using commercially available software (MoveTest, McRoberts, The Hague, The Netherlands).

Figure 1 shows the filtered acceleration and angular velocity signals. In the upper panel, the up and down arrows indicate the standing up and sitting down phases, respectively. The sitting and standing phases were marked in grey.

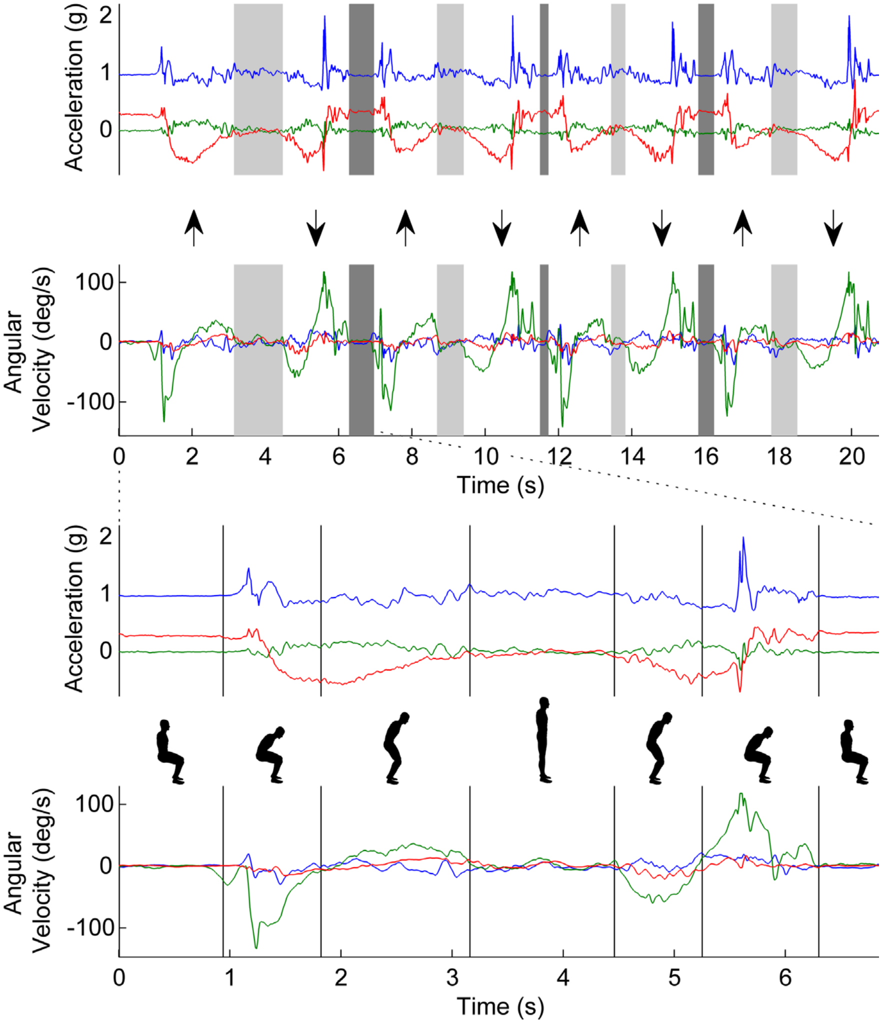

Figure 1. The top panel shows the time series of acceleration (green-mediolateral; red-anterior-posterior; and blue-vertical) and angular velocity (blue-pitch; green-yaw; and red-roll) over the main phases of the STS cycles. The up-arrows indicate standing up (SiSt) and the down-arrows indicate sitting down (StSi). The grey vertical bars demarcate the standing and sitting episodes. In the bottom panel the first complete STS cycle is depicted and magnified.

The acceleration and the angular velocity were used to calculate the trunk angle [30] in the sagittal plane (flexion/extension). "True vertical acceleration" was estimated by removing the influence of the trunk angle from the vertical acceleration signal. Finally, vertical velocity was calculated by integrating this signal. This method has been described in more detail elsewhere [19]. Successful STS cycles were identified by an upward movement followed by a downward movement as identified by the vertical velocity. Drift and noise were removed from the trunk angle using discrete wavelet transform [21]. The local minima in this "cleaned up" signal were used to detect a change in trunk rotation direction. Each STS cycle contains 2 of such local minima which separate the flexion and extension phases of the trunk during sit-to-stand (SiSt) and Stand-to-Sit (StSi) (Figure 1, lower panel). The start of the sit-to-stand was defined as the end of the plateau before the first local minimum in the trunk angle. Similarly, the end of the sit-to-stand was defined as the start of the plateau after the first local minimum in the trunk angle. The start of the stand-to-sit was defined as the end of the plateau before the second local minimum in the trunk angle and the end of the of the stand-to-sit was defined as the start of the plateau after the second local minimum in the trunk angle. From the iSTS phases (SiSt, St, StSi and Si) mean durations, mean range of motion, mean maximum angular velocity and coefficient of variation (CoV) were calculated. CoV was expressed as the ratio of the standard deviation and the mean over the 4 repetitions times 100%. Only the durations and sub-durations were compared with the manually recorded time events in this study.

Physical activity

Physical activity was measured using a small and light activity monitor (51×84×8.5 mm, 45 grams), which was attached centrally over the lower back with an elastic belt around the waist (DynaPort MM, McRoberts BV, The Hague, The Netherlands). Participants were asked to wear the activity monitor continuously for one week (i.e., 24/7) except during activities involving immersion of the body in water (e.g., when taking a shower). The monitor consisted of three orthogonal accelerometers (resolution: 0.003 g). Raw accelerometer signals were stored at a sampling rate of 100 samples/s. Reproducibility of the raw signals has been shown to be good to excellent. Intra- and inter-instrumental intraclass correlation coefficients (ICC) were all 0.99 and the intra-instrumental coefficients of variance were smaller than 1.13% [31].

The collected accelerometer data were analysed using commercially available software (MoveMonitor, McRoberts BV, The Hague, The Netherlands). First, the distribution of physical activity classes (lying, sitting, standing, locomotion, shuffling) and non-wearing was determined. Next, total duration, number of periods, and mean duration per period were calculated for these physical activity classes. The validity of such activity classifications has been demonstrated in both lab [32] and field [33,34] studies and one week of measurement has been shown to yield highly reliable results [35].

Statistics

Continuous variables with a normal distribution were presented as mean and standard deviation (SD). If a skewed distribution (non-Gaussian) was found, the median and interquartile range (IQR) were determined. The STS durations were dichotomised, using a median split, in a slower and a faster performing group. These two groups were compared with regard to health status, functional status and daily physical activity (i.e., mean duration of sitting periods, mean standing duration and mean number of locomotion periods). Differences in outcomes between slow and fast performers were analysed using the Mann–Whitney U-test (SPSS Inc, Chicago, Illinois, USA). P-values below 0.05 were considered statistically significant.

RESULTS

Fifty-seven out of sixty-three older adults (mean age 84 years; SD ±11) produced complete data. Six participants were unable to complete the entire STS test and were excluded from the analysis. Four were unable to stand up with arms crossed and two were unable to finish the 5 repetitions. The mean duration of data collection for the SPPB (gait, balance and chair stand) was 6.5 minutes (SD 2.9 minutes). Total measuring time of the STS part of the SPPB exclusive putting on the equipment was 2.1 minutes. Mean time to prepare the STS was 1.2 (SD 0.86) minutes. Mean measurement time of the STS was 0.4 (SD 0.36) minutes. Removing the equipment took on average 0.3 (SD 0.36) minutes. These durations were collected during the study. In clinical practice, data collection might take more time. The duration of uploading and analyzing the data were not measured. Average wearing time of the activity monitor was 6.80 days with a minimum of 5.4 days. Mean wearing duration was 23.2 hours per day (96.7%).

The demographic, clinical and physical function parameters of the participants are shown in Table 1. The mean score for health status was 0.8 (±0.2). This was a bit higher than the normal scores as measured in the U.S. national health measurement study. People older than 74 years had a mean score of 0.7 [27]. The mean score for functional status was 57.3 (SD ±22.6), which is somewhat lower than measured in a clinical setting (36). In this study participants were younger (74 years ± 5.7) than in our study (84 years ± 11).

Table 1 shows that the maximum for the STS mean sub-durations was 3 to 4 times as large as the minimum. The maximum durations of standing and locomotion in daily life were 9 to 64 times as large as the corresponding minimum durations. The maximum numbers of periods of standing and locomotion in daily life were 21 to 51 times as large as the corresponding minimum values. This indicates that extremes in outcomes differ less in physical performance (i.e. capability or capacity) than in physical activity (i.e. behavioural) outcomes.

Table 1. Demographics, clinical characteristics, iSTS parameters and daily physical activity of the study population.

Characteristics	Mean (SD)	Min	Max	Max/Min
(N=57, 82% female, 44% care home)				
Demographics				
Age (year)*	84 (11)	64	97	2
Weight (kg)	73.6 (11.3)	50	98.8	2
Height (m)	165.6 (7.9)	149	180	1
BMI (kg/m2)	26.9 (4)	19.8	38.1	2
Clinical characteristics (points)				
EQ.5D (score)*	0.8 (0.2)	0.2	1	5
RAND-36 (score)				
Physical function	57.3 (22.6)	10	95	10
MMSE (score)*	28 (2)	20	30	2
iSTS mean parameters (seconds)				
SiSt duration*	1.7 (0.8)	1	3.1	3
SiSt flexion duration*	0.8 (0.2)	0.5	1.4	3
SiSt extension duration*	0.9 (0.4)	0.5	1.8	4
StSi total duration*	1.7 (0.6)	1	3.4	3
StSi flexion duration*	0.8 (0.4)	0.5	2	4
StSi extension duration*	0.8 (0.3)	0.5	1.5	3
Daily physical activity				
Duration				
Lying duration (hr)	10.1 (2.1)	3.9	15.7	4
Sitting duration (hr)*	9.1 (2.7)	5.5	16.5	3
Standing duration (hr)	2.44 (0.9)	0.6	4.8	9
Locomotion duration (min)*	48.5 (30.4)	2	127.4	64
Number of periods				
Lying periods (N)*	8.5 (5.6)	1.5	38	25
Sitting periods (N)*	103 (36)	17	330	19
Standing periods (N)*	640 (400)	72	1488	21
Locomotion periods (N)*	297 (150)	15	769	51
Mean duration of periods				
Mean lying period duration (hr)*	1.3 (0.6)	0.3	3.8	13
Mean sitting period duration (min)*	5.7 (3.0)	1.9	28.7	15
Mean standing period duration (s)*	12.4 (4.0)	7.2	37.0	5
Mean locomotion period duration (s)*	9.4 (2.5)	5.8	16.2	3

* Values are expressed as median (interquartile range)

Figure 2 shows the association between the manually recorded duration of the 4.5 STS and the duration of 4 STS as calculated using the instrumentation. All durations of the manually recorded data are longer because these include the 5th SiSt. The four outliers had markedly longer manually recorded durations.

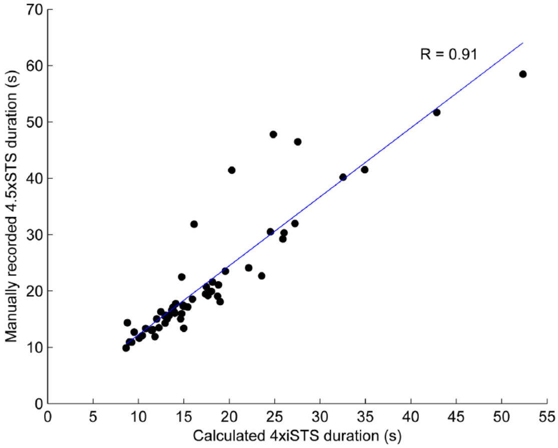

Fig 2. Associations between the durations (in seconds) of the manually recorded 4.5 x STS and the calculated 4 x iSTS.

Figure 3 shows a typical example of a fast (upper panel) and a slow performer (lower panel) of the STS. The fast performer shows a regular pattern of durations with relatively short standing (dark grey) and sitting periods (light grey). The slow performer, in contrast, shows greater variation in durations and very long standing and sitting durations. Standing up and sitting down durations were respectively 1.9 and 1.8 times longer for the slow performer. Sitting and standing duration were respectively 36 and 50 times longer for the slow performer.

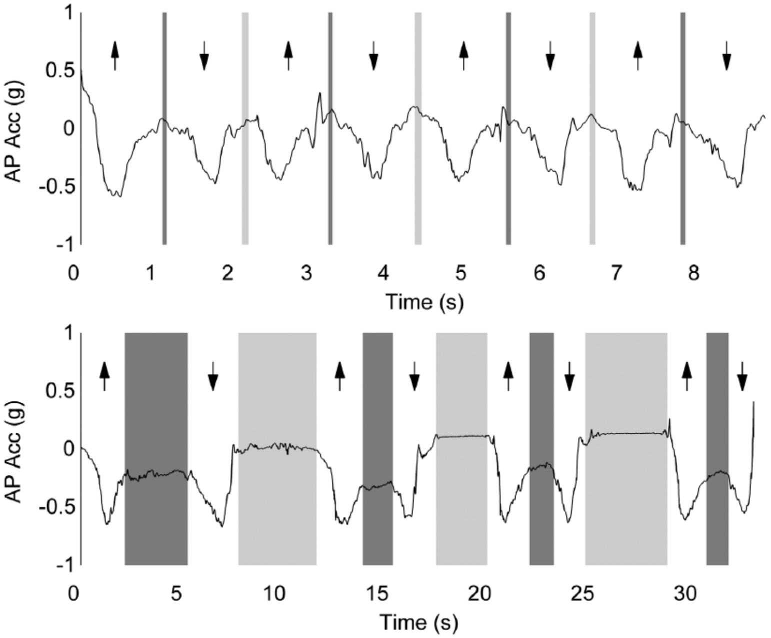

Fig 3. Anterior-posterior acceleration signal for two subjects. The ↑ arrows indicate standing up (SiSt) and the ↓ arrows indicate sitting down (StSi). The dark grey bars mark the standing duration, while the light grey bars mark the sitting duration. The upper panel shows a fast participant (9 seconds) with very short and regular standing and sitting durations. The lower panel shows a slow participant (33 seconds) with very long and less regular standing and sitting durations.

The association of manually recorded and instrumented STS outcomes with health status and functional status.

Table 2 shows the association of STS performance with health status (EuroQol) and functional status (RAND-36 Physical function). The manually recorded STS times were not significantly associated with health status (p=0.457) or functional status (p=0.055). In contrast, the 4 iSTS durations were associated highly significantly with health status and functional status (both p=0.009). All the 6 SiSt parameters showed significant or highly significant associations with health status and functional status (p=0.018 – 0.001). Two of the six StSi parameters showed significant associations with health status and functional status (p=0.049 and p=0.017).

Table 2. Associations of dichotomized STS and iSTS durations (seconds) by using a median split with health status (EuroQol) and functional status (RAND-36 Physical function).

		Health status			**Functional status**		
		EuroQuol 5D-3L			**RAND-36 physical function**		
		fast	**slow**	**p-Value**	**fast**	**slow**	**p-Value**
		performer			**performer**		
	Manually recorded						
↕	Duration 4.5xSTS	0.79	0.76	p = 0.457	64.8	51.2	p = 0.055
	Movement duration						
↕	Duration 4xiSTS	0.85	0.71	p = 0.009	65.9	47.5	p = 0.009
	Sub-phase durations (mean of 4 STS cycli)						
↗	SiSt duration	0.85	0.67	p = 0.001	67.7	44.2	p = 0.001
→	SiSt flexion duration	0.81	0.71	p = 0.015	64.4	47.5	p = 0.018
↑	SiSt extension duration	0.85	0.68	p = 0.001	68.5	44.5	p = 0.001
↔	Stance duration	0.80	0.75	p = 0.243	63.3	51.6	p = 0.097
↘	StSi duration	0.80	0.71	p= 0.237	63.7	50.0	p = 0.049
↓	StSi flexion duration	0.82	0.72	p = 0.017	63.0	51.4	p = 0.100
→	StSi extension duration	0.81	0.72	p = 0.150	60.2	53.7	p = 0.384
↔	Sit duration	0.79	0.75	p = 0.422	62.2	50.6	p = 0.091

↕	Including sit to stand, standing, stand to sit and sitting time
↕	4.5xSTS means 4 complete cycles and one SiSt ending in a standing position (SPPPB)
↕	4xSTS means 4 complete STS cycles, ending in a sitting position
↗	SiSt, including flexion and extension phase of standing up
→	SiSt, including flexion phase of standing up
↑	SiSt, including extension phase of standing up
↔	stance duration between standing up and before starting to sit down
↘	StSi, including flexion and extension phase of sitting down
↔	sit duration between sitting down and before standing up

The association of manually recorded and instrumented STS outcomes with physical activity behaviour

Table 3 shows the associations between slow and fast STS performers (independent variable) with daily physical activity parameters (dependent variables). The faster performing group showed shorter mean duration of sitting periods, longer duration of standing and more locomotion periods. From the manually recordings durations only mean sitting period duration were significant. All movement duration of the 4 iSTS cycles showed highly significant differences between slow and fast performers (p = 0.001 – 0.002) for all physical activities. All nine SiSt associations showed highly significant associations with daily physical activity parameters. SiSt flexion and the extension durations showed significant associations (p = 0.001 – 0.010) with daily physical activity parameters. From the flexion and the extension duration during StSi only one of the 6 parameters showed a significant association with daily physical activity parameters.

Table 3. Associations of STS durations dichotomized by using a median split with dichotomized daily physical activity (mean sitting duration, mean standing duration and mean number of locomotion periods.

		Sitting			**Standing**			**Locomotion**		
		mean period duration (m)			duration of standing (m)			number of periods (n)		
		fast	slow	p-Value	fast	slow	p-Value	fast	slow	p-Value
		performer			performer			performer		
	Manually recorded									
↕	Duration 4.5xSTS	323	428	p = 0.042	156	139	p = 0.230	349	310	p = 0.218
	Movement duration									
↕	Duration 4xSTS	287	486	p < 0.001	169	123	p = 0.001	385	265	p = 0.002
	Sub-phase durations (mean of 4 STS cycli)									
↗	SiSt duration	286	487	p < 0.001	169	122	p = 0.001	387	263	p = 0.001
→	SiSt flexion duration	300	472	p = 0.003	166	126	p = 0.005	376	274	p = 0.010
↑	SiSt extension duration	297	474	p = 0.005	167	125	p = 0.003	386	264	p = 0.002
↔	Stance duration	332	439	p = 0.043	154	137	p = 0.200	349	302	p = 0.212
↘	StSi duration	304	468	p = 0.008	161	131	p = 0.040	368	282	p = 0.018
↓	StSi flexion duration	342	429	p = 0.218	152	140	p = 0.480	360	290	p = 0.106
→	StSi extension duration	322	449	p = 0.026	157	134	p = 0.109	361	289	p = 0.113
↔	Sit duration	324	447	p = 0.092	157	134	p = 0.218	356	295	p = 0.099

↕	Including sit to stand, standing, stand to sit and sitting time
↕	4.5xSTS means 4 complete cycles and one SiSt ending in a standing position (SPPPB)
↕	4xSTS means 4 complete STS clycles, ending in a sitting position
↗	SiSt, including flexion and extension phase of standing up
→	SiSt, including flexion phase of standing up
↑	SiSt, including extension phase of standing up
↔	stance duration between standing up and before starting to sit down
↘	StSi, including flexion and extension phase of sitting down
↔	sit duration between sitting down and before standing up

DISCUSSION

As expected, the associations with health status, functional status and physical activity between slow and fast STS performers were overall more significant for movement durations as determined with the iSTS than for manually recorded durations. The most plausible reason for this finding is that movement durations can be calculated more accurately when using iSTS than when recorded manually. The 4 outliers in the manually recorded durations may reflect such inaccuracies (see Figure 2). There might be a difference between the start signal of the test leader and the start of the movement because of different reaction times of the participants. The observed difference may also be related to the accuracy of the test leader, who has to mark the start and stop of the movement and simultaneously supervise the participant. In the present study, a third reason could be the difference between evaluating over 4.5 or 4 STS cycles. Observations of participants performing the test suggested that for some participants it was confusing to start in a sitting position and end in a standing position. They stopped after 4 cycles and had to be reminded to end in a standing position. Another reason might be the duration of the stabilization phase. In the official Short Physical Performance Battery Protocol and Score Sheet the end of the 5th StSi is when "he/she has straightened up completely for the fifth time" [37]." We used the raw signals to analyze the duration of the standing phase between the SiSt and the StSi. The variability of the duration expressed in the coefficient of variance of the standing phase has shown to be significant different comparing young and older adults [21]. This could be the fourth reason for the observed differences in duration between manual recording and instrumented detection.

A recent study aimed at determining the reliability of the instrumented timed up and go (iTUG) revealed no significant difference in reliability between manual recording and instrumented detection of total duration [37]. More research comparing manually and iSTS duration is necessary, especially for the shorter sub-durations.

Overall, the SiSt transition, which is performed against gravity, showed the strongest association with health status, functional status and daily physical activity. This might be related to the relatively old participants included in this study (median 84 years). The slower group on SiSt performance was significantly older (80.3 versus 85.6, p = 0.003).

Although we did not measure muscle mass, the corresponding degree of sarcopenia might also influence this outcome [38]. After all, it is estimated that after the 50th year of life muscle mass and thus muscle force decrease with 1 to 2% per year, implying that the muscle mass of the participants was reduced considerably [39], which would limit their ability to stand up [6].

The difference between the associations of health status, functional status and PA with iSTS and STS revealed that the iSTS reflects more accurately the subject's status than manually recorded STS durations, which are commonly used in clinical research and practice. These findings and insights provided by the associations are recapitulated in the following section along with their theoretical and practical implications.

Associations between iSTS, health status and functional status.
As already concluded, the iSTS durations showed stronger and more significant associations with self-reported health status and functional status than the manually recorded duration of the total test. Faster STS performers on the iSTS test exhibited higher scores for health status and functional status, which was not evident for the manually recorded durations. This difference could be due to the fact that clinically relevant information is mainly present in the dynamic phases of the STS (SiSt and StSi) and not in the static phases (St and Si), while the latter are included in the manually recorded time events but to a lesser extent in total iSTS and not in the durations of the dynamic phases. Slower performance of the complete STS cycle can be strongly influenced by longer durations of sitting and standing (Figure 3).

Associations between iSTS outcomes and physical activity
As already concluded, the iSTS durations showed stronger and more significant associations with daily physical activity (mean duration of sitting periods, mean standing duration and mean number of locomotion periods) than the plain STS durations. Six of the seven iSTS parameters showed significant to strongly significant associations with the mean period durations of sitting measured in daily life. Faster performers showed shorter duration of sitting periods, longer standing durations and more locomotion periods. Recent studies have suggested that breaking up prolonged sitting may improve glucose metabolism and represent an important public health and clinical intervention strategy for reducing cardiovascular risk [40–43] and mortality [44].

Guralnik already stated in 1989: "Furthermore, performance tests may not give specific information on whether the identified limitations have any relevance to the actual activities or needs of the individual, or how well an individual with a limitation in a specific test item might have adapted to his or her individual environment (p. M143)" [45]. The activity monitor used in our study made it possible to compare in detail the physical performance outcomes with the individual's physical activities in daily life because it provides detailed information about sedentary as well as active behaviour.

Practical implications

Losing the ability to stand up without support has great implications for independent living. This is also evident in our data, which show clear associations between the ability to perform the STS and the amount and kind of daily activity. Therefore, in geriatric rehabilitation and physical activity programs, STS function should be considered as part of the training and the method discussed in this study may prove helpful for both diagnostic and evaluative purposes. This is in line with the plea of Guralnik [45] and Studenski [36] to include physical performance measures in the clinical setting. The instrumented STS test might be helpful for selecting appropriate and optimal interventions based on the patient's physical performance profile and physical activity behavior and their associations [9].

We anticipate that future development will focus on the most important advantage of using body worn sensors, namely that they permit remote monitoring of 'habitual' STS behavior. This highlights the wider application of the findings of this study given that health status is related to the STS movement measured by a body worn sensor, the timing of which may be identified remotely and documented longitudinally.

It is also interesting to consider whether this association presented in the current study between STS times derived from body worn monitors and health status is retained when extracting STS repetitions from community ambulation data. The present data indicate that both self-perception of physical health and physical status are associated with, and potentially cause, slower and less successful STS performance, but also that these factors may affect the duration of STS phases differently. Previous studies have focussed specifically on the relation between the duration of repeated STS and knee muscle strength in terms of maximal force or power [6,46,47]. The development of muscle power is mainly required during the dynamic ascending phase of the STS transition. Further research should explore the associations of different phases of the iSTS with muscle strength and physical activity in daily life. The TENDO analyzer is an easy to use device that aims to measure power during the SiSt movement. This device might be used for such studies [48,49].

Strength and limitations

iSTS may be readily applied in clinical settings. The single module instrumentation can be easily attached over undergarments and if possible beneath outer clothes in a manner that is unobtrusive to the subject. In this way the risk that the device is displaced is minimized. The awareness of being assessed is low because the instrumentation is not visible for the patient. Data collection is fast and with the remote control the test leader can stay close to the participant. The online connection of remote control makes it possible for one test leader to simultaneously collect data and watch over the participant as it is no longer necessary to read out the stopwatch and write down the times. The raw data are stored in the computer, which improves traceability and can be used for quality management. The automated analysis of the data provides detailed insight into the quality of the movements. The data are stored in a database, which makes it easy to use the clinical data for management and research purposes.

The high-resolution physical activity data, and consequently the ability to identify activity classes, provides more insight into health status, functional status and daily physical activity and its association with STS performance than using a single overall measure of acceleration.

The diversity of subjects is in general a positive aspect of the present study, with ages ranging from 66 to 97, BMI ranging from 20 to 38 and 44% recruited from residential care facilities. However, it is a concern that the number of subjects included in the analysis (N=57) was relatively small. Although the present work represents a promising first step towards more detailed kinematic analyses of STS transitions, there is a clear need to collect reference data to compare sub-groups of older adults. Moreover, the present analysis focussed mainly on the duration of different STS phases. The range of motion, maximum angular velocity and the coordination between the different STS phases in terms of their relative timing have to be studied in greater detail in future studies, which are also needed to confirm the validity of the present findings and insights. A limitation of this study is that only cross-sectional data were collected. Future studies will have to reveal if the instrumented STS has added value in longitudinal and intervention projects. The applicability of iSTS in a busy clinical environment remains to be demonstrated. Nevertheless, given its advantages and increased user-friendliness, we believe the method holds good prospects of finding wider application.

Conclusions

Detailed outcomes of the instrumented STS were more strongly associated with health status, functional status and physical activity than manually recorded duration, and are thus likely to provide added value in clinical testing of older adults. Furthermore, iSTS revealed that the durations of the dynamic STS phase against gravity (SiSt) were markedly stronger associated with health status, functional status and daily physical activity than the total duration of the repeated STS. Participants with a better STS performance showed shorter mean sitting periods, longer mean standing durations and a higher mean number of locomotion periods in daily life, suggesting a more active lifestyle. Collectively, these findings suggest that a fully automated analysis of instrumented repeated STS movements may have greater clinical relevance compared to a manually recorded version of the test and may help to identify STS parameters that provide a basis for a more precise, quantitative studies of STS performance in clinical settings and clinical research. Fully-automated analyses means that the raw data collected during the STS measurement are uploaded to a webserver and analyzed automatically and that outcomes are stored in a database which can be used to generate reports.

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CONFLICT OF INTEREST

RCvL is the owner of McRoberts, while SW and EA are employees of this company, which is the manufacturer of the DynaPort device and the MoveTest and MoveMonitor products that were used in the present study. The other authors have no conflict of interest.

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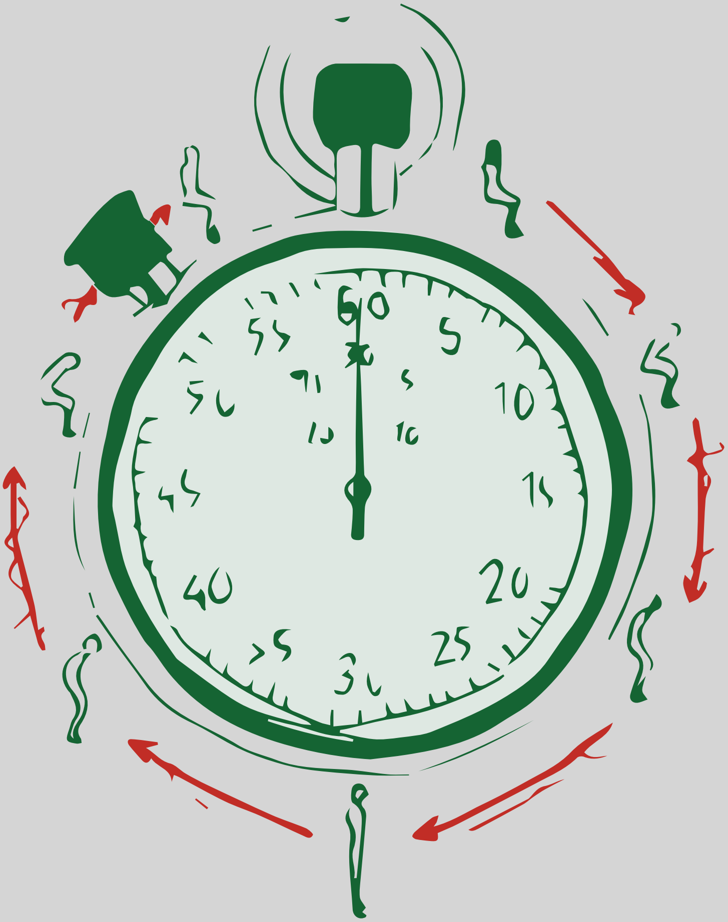
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Clinical value

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CHAPTER 5
The Instrumented Sit-to-Stand Test (iSTS) has greater clinical relevance than the manually recorded Sit-to-Stand Test in older adults

CHAPTER 6
Older adults with low muscle strength stand up from a sitting position with more dynamic trunk use

CHAPTER 7
A new scoring method to quantify the instrumented Sit-to-Stand test in older adults

CHAPTER 6

Older adults with weaker muscle strength stand up from a sitting position with more dynamic trunk use

Older adults with weaker muscle strength stand up from a sitting position with more dynamic trunk use.
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OLDER ADULTS WITH WEAKER MUSCLE STRENGTH STAND UP FROM A SITTING POSITION WITH MORE DYNAMIC TRUNK USE

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Key words: physical function, physical performance test, chair stand, sit to stand transfer, wearables, inertial sensors, accelerometers, gyroscopes.

RUNNING PAGE HEADLINE
Muscle strength and STS strategy

ABSTRACT

Introduction

The ability to stand up from a sitting position is a prerequisite for older adults to live independently. Previous research using video-based 3D movement registration and measurement of ground reaction forces in laboratory settings has quantified sit-to-stand movements (STS) to better understand their dynamics. Body-fixed inertial sensors provide an alternative approach for quantifying STS movements that can also be used outside the laboratory, including the clinic. The present study's aim was to investigate whether measurements with body-fixed sensors, as a clinically applicable tool, can yield parameters that are more informative regarding changes in STS kinematics with reduced muscle strength in older adults than the total duration of the STS.

Method

Twenty-seven healthy older adults, living in sheltered housing and the community participated in this cross-sectional study. Handgrip strength was assessed using a dynamometer and subjects were asked to stand up from three heights of a height adjustable chair at their preferred speed. The trunk movements were measured using a small and light inertial sensor measurement system fixed with an elastic belt around the waist and placed over the spine. Durations, angular range and maximum angular velocity of STS phases, as well as the vertical velocity of the extension phase, were calculated. Backwards elimination using GEE was used to identify which covariate best predicted the kinematics.

Results

The present results showed that older adults with less handgrip strength stand up with greater flexion of the trunk. After seat-off this group also showed greater trunk extension with a higher maximum angular velocity, indicating a more dynamic use of the trunk. Handgrip strength was the strongest predictor of this effect.

Conclusions

Older adults with weaker handgrip strength employed a different strategy to stand up from a sitting position making more dynamic use of the trunk during the extension phase. Trunk kinematics was more sensitive to muscle strength than durations were to muscle strength.

INTRODUCTION

The ability to stand up from a sitting position is a prerequisite for older adults to live independently. Having difficulty performing this task may also reduce their physical activity levels. Older adults with a better sit-to-stand (STS) performance showed shorter sitting periods, longer standing periods and a higher number of locomotion periods in daily life, suggesting a more active lifestyle [1]. In community-dwelling older adults, sedentary behavior was associated with increased risk of sarcopenia [2] and mortality [3–5]. In addition, difficulty in rising from a sitting position may directly increase the risk of injury, since STS transfers were found to be responsible for 41% of all falls in nursing homes [6]. Functionally limited elderly individuals with higher quadriceps muscle strength showed a higher dynamic stability when performing the STS at preferred speed [7].

Previous research using video-based 3D movement registration and measurement of ground reaction forces in laboratory settings has quantified STS to better understand its dynamics. The STS involves a transition from an intrinsically stable three-point support to a dynamically stable two-point support [8]. Schenkman et al. distinguished four phases of the STS: the flexion momentum phase, the momentum transfer phase, the vertical extension phase, and the stabilization phase [9]. Riley et al. found the momentum transfer phase, which starts with the lift off from the seat of the chair, to be the most demanding phase [8]. Several studies have reported different strategies of standing up [10–12]. In general, functionally impaired elderly stand up with greater flexion of the upper body [13]. It has been suggested that the aim of this so-called flexion strategy might be to achieve a better postural stability, and it has therefore been called a stabilization strategy [10]. Older adults using the stabilization strategy appear to be placing more importance on stability during the rise than do momentum transfer strategists [14]. Changing to another strategy seems to be an adaptation of older adults, which might be attributed to their lower extremity strength.

The time needed to stand 10 times from a standard chair was used to assess lower extremity muscle strength and to evaluate treatment [15]. Likewise, several authors have used the STS test as a proxy for muscle strength [16,17]. More recently the time to rise from a chair 5 times as quickly as possible was included in the Short Physical Performance Battery to assess lower extremity function [18].

Body-fixed inertial sensors, which have been used since the early nineties, provide an alternative approach to quantify the STS [19–23]. The results of fully automated analysis of instrumented STS (iSTS) movements demonstrate that several STS parameters can be identified that provide a basis for a more precise, quantitative study of STS performance in clinical practice [24]. Repeated STS performed as fast as possible, showed stronger association with health status, functional status and physical activity with automatically detected iSTS sub-durations than manually recorded STS durations, implying greater clinical relevance of iSTS as compared to STS [25]. Furthermore, iSTS allowed assessment of the dynamic phases of the test, which are likely more informative than the static sitting and standing phases [25]. We used a body-fixed sensor, because several studies have shown that this method is valid and applicable in clinical practice. The single module instrumentation can be easily attached in a manner that is unobtrusive to the participants and the reliability of the measurements in a geriatric setting has been shown to be high [26].

Handgrip strength (HGS) is frequently measured as a proxy for overall muscle strength. We will use muscle strength as a synonym for HGS. Approximately 25% of all 80-year-olds have a HGS of more than 2.5 standard deviations below the gender specific peak mean of HGS in the general population [27]. Low muscle strength is associated with cognitive decline, impaired functional status and mortality [28] and is therefore an important indicator of health status.

The aim of this study was to investigate whether measurements with body-fixed sensors, as a clinically applicable tool, can yield parameters that are more informative regarding changes in STS kinematics with reduced muscle strength in older adults than the total duration of the STS. It was hypothesized that adults with less handgrip strength would be inclined to use a STS strategy with more dynamic use of the trunk, as reflected in greater range of motion and greater angular velocity of the trunk.

METHODS

2.1. Participants

Twenty-seven healthy older adults, living in sheltered housing and in community (13 females; mean age: 74.7 ± 8.5 years; mean weight: 76.8 ± 13.2 kg; mean height: 172.2 ± 8.2 cm), participated in this cross-sectional study. The protocol had been approved by the ethics committee of the Department of Human Movement Sciences of the Vrije Universiteit Amsterdam (ECB 2014-3M). Prior to testing, all participants provided written informed consent.

2.2. Instrumentation and data acquisition

Trunk movements during STS were measured using a small and light (87×45×14 mm, 74 grams) inertial sensor measurement system (DynaPort Hybrid, McRoberts, The Hague, The Netherlands), which was fixed with an elastic belt around the waist and placed over the spine (Fig. 1). This device measured acceleration and angular velocity in three directions at a rate of 100 samples/s (Fig. 2). A single device was used because this is more practical for clinical use than multiple devices. The position near the center of mass was chosen to reflect whole body movement [29]. Furthermore, at this position the sensor was unobtrusive, easy to fasten and did not hamper the participant's movements.

Figure 1. The therapist stayed in close proximity to the patient. The protocol was implemented on a computer. With a remote control start and end of every STS was marked and stored with the raw data.

2.3. Test protocol

Participants were asked to stand up at their preferred speed from a height adjustable chair. Practice was allowed if needed. After getting up, they were required to stand still for 10 seconds. Each participant performed two STS movements from three different chair heights: 100%, 90% and 80%. The 100% chair height was defined according to Schenkman et al. [9], with the chair adjusted such that the participant's thighs were horizontal and knee- and foot angle in a position preferred to stand up. The three chair heights were determined prior to performing the trials. The STS protocol was implemented on a computer, which randomly assigned the order of the chair height conditions. The markers of the remote control were stored with the raw signals at the start and end of each trial, rendering automatic data analysis feasible. The three height conditions were performed with the arms folded in front of the trunk. When participants were not able to perform a certain condition, it was skipped and the next condition was offered.

2.4. Signal analysis

The measurement of 3-dimensional accelerations and angular velocities of the trunk allowed a detailed analysis of the different phases of the STS movement (Fig 2).

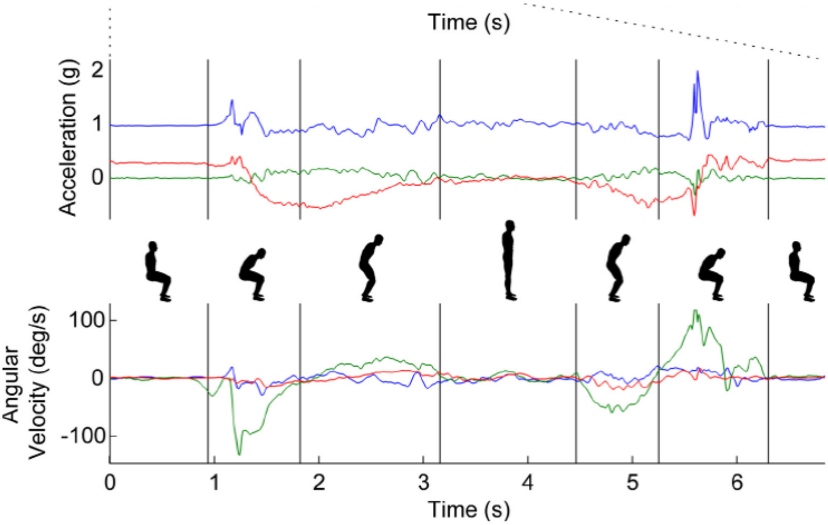

Figure 2. The top panel shows the time series of raw acceleration (green-mediolateral; red-anterior/posterior; and blue-vertical, the lower panel shows the angular velocity (blue-pitch; green-yaw; and red-roll) signals; the insets illustrate the main phases of the STS movement, which are separated by vertical lines in both graphs.

The acceleration and the angular velocity in the sagittal plane were used to calculate the trunk pitch angle [30]. Drift and noise were removed from the trunk pitch angle using the discrete wavelet transform [19]. The dips in the trunk angle were used to detect a change in trunk rotation direction. The start of the STS was defined as the end of the plateau before the first dip in the trunk pitch angle. Similarly, the end of the sit-to-stand was defined as the start of the plateau after the first dip in the trunk pitch angle. 'True vertical acceleration' was estimated by removing the influence of the trunk pitch angle from the vertical acceleration signal. The vertical velocity was derived by integrating this signal.

The following events were defined: start of the trunk movement, end of the trunk flexion phase, and end of the trunk rising phase [31] (Fig 2). After automated identification of start and end of the STS and the flexion and extension phases, the duration, angular range and maximum angular velocity of these phases as well as the vertical velocity of the extension phase were calculated.

The mean of the two repetitions was used for statistical analysis. Data were analyzed using commercially available software (MoveTest®, McRoberts®, The Hague, The Netherlands).

2.5 Hand grip strength (HGS)

HGS of both hands was measured using a digital handgrip dynamometer (Takei A5401) following a standardized protocol. Participants were standing in the upright position with their arms alongside the body. The handle was adjusted to fit the hand size. They were asked to squeeze the dynamometer with as much force as possible. Maximal HGS was measured twice for both hands with brief pauses between each measurement. The mean of all 4 measurements was considered the HGS.

2.6. Statistical analysis

Normally distributed characteristics were presented as mean and standard deviation (SD). Skewed (non-Gaussian) distributed continuous variables were presented as median and interquartile range (IQR).

Checks for normality

Sit-to-Stand parameters were checked for normality using the Kolmogorov-Smirnov test. Out of a total of 24 parameters, 8 were not normally distributed. Total STS duration and the duration of the flexion phase did not meet the criteria for normality for all three seat heights. For these duration parameters skewness and kurtosis ranged from 2.0 to 2.1 and from 3.0 to 5.9 respectively. The remaining two parameters that were non-normally distributed were maximum angular velocity during the flexion phase at the 80% chair height ($D(24) = 0.187$, $p < .05$) and the duration of the extension phase at the 90% seat height ($D(25) = 0.206$, $p < .05$)

Analysis

All outcome variables were analysed using Generalized Estimating Equations (GEE), to test whether they were associated with HGS. GEE was chosen instead of conventional least-squares regression, because it can cope with missing values and takes into account that observations within a data set are dependent. In our study, these were the different seat heights for all subjects. Body length and weight, age and gender were analysed as potential confounders. For HGS and these potential confounders main effects were calculated. Because the effect of handgrip force was the main interest and because an interaction between strength and task difficulty is plausible, the interaction between handgrip strength and seat height was also included in the initial model. The first iteration of the GEE analysis included HGS, HGS x seat height and all potential confounders. A backward elimination method was used to eliminate non-significant predictors. Seat height was always included in the model as this was the within-subject variable. All analyses were conducted using SPSS v. 21.0.

RESULTS

From the 27 participants 24 completed the entire protocol. One participant was unable to stand up from the 80% chair height, and two were unable to stand up from both the 90% and 80% chair heights. All participants were included in the analysis. Participant characteristics and descriptive statistics are presented in Table 1.

Table 1. Descriptive statistics of the study population

n	27
percentage male (n)	55.6% (15)
Age (years)	70.0 (16)
Height (cm)	173.4±7,4
Weight (kg)	77.1±13.2
BMI (kg/m2)	25.6±3.8
Hand Grip strength (kg)	29.2±10.1

Note: Data represents the mean ± SD or median (IQR).

The results of the STS outcomes are presented in Table 2.

Table 2. Durations (s), angular range (ϕ in °), maximum angular velocity (ωmax in °/s) and vertical velocity (vmax in m/s) during flexion and extension of the Sit-to-Stand movement for the three seat heights. Model effects of Generalized Estimating Equations are displayed for the condition factor Seat Height and for the included covariates.

				Model effects (p-value) of GEE						
	Seat Height			Covariates						
	100%	90%	80%	Seat Height	HGS	Seat Height *HGS	Length	Weight	Age	Gender
Sit-to-Stand										
Duration	1,60 (0,50)	1,65 (0,38)	1,70 (0,35)	0,097	0,015					
Flexion phase										
Duration	0,76 (0,15)	0,81 (0,10)	0,82 (0,18)	0,071						
Angular range	38,08±7,58	39,28±7,92	42,13±8,96	0,003	<0,001		0,019			
Angular velocity	113,18 (55,20)	117,10 (40,89)	119,31 (66,77)	0,201					0,004	
Extension phase										
Duration	0,84 (0,34)	0,91 (0,33)	0,87 (0,22)	0,062	0,003					
Angular range	29,40±9,26	32,00±9,82	32,83±11,49	0,002	<0,001	0,001				
Angular velocity	57,47±14,47	61,04±16,83	65,92±20,64	<0,001	<0,001	0,002			0,026	
Vertical velocity	0,59±0,15	0,62±0,18	0,67±0,15	<0,001	0,011		0,048		0,025	0,005

Notes: Data represents the mean ± SD or median (IQR). An empty cell means that the covariate was eliminated prior to the last GEE iteration and hence no p-value was calculated.

Sit-to-Stand

There was a no significant effect that the STS duration was longer for lower seat height (p=0.097). HGS was the only covariate showing that weaker subjects had a longer STS duration (p=0.015).

Flexion phase.

There was no significant effect of seat height on flexion duration (p=0.071). Angular range increased with lower seat height (p=0.003) and there was a significant effect of the covariates HGS (p<0.001) and body length (0.019). Age was the only covariate showing a significant effect for maximum angular velocity (p=0.004).

Extension phase

The duration of the extension phase tended to be longer for lower seat height (p=0.062) and was significant for HGS (p=0.003). Angular range was larger for lower seat heights (p=0.002) and for the covariates HGS (p<0.001) and the interaction seat height/HGS (p=0.001). Maximum angular velocity was larger for lower seat heights (<0.001) and the covariates HGS (p<0.001), seat height/HGS (p=0.002) and age (p=0.026) showed significant effects. Vertical velocity was larger for lower seat heights (p<0.001) and the covariates HGS (p=0.011), body length (p=0.048), age (p=0.025) and gender (0.005) showed significant effects.

The most important outcomes are visualized more in detail in the scatterplots (Figure 3).

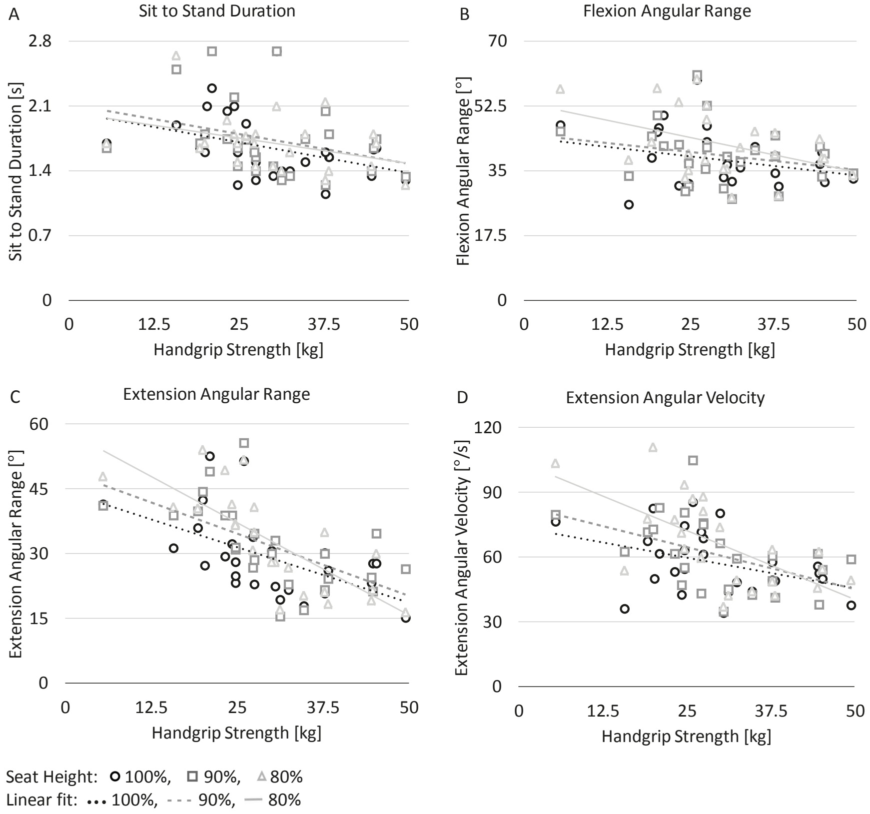

Figure 3. Scatter plots display values of the 4 STS parameters and handgrip strength at 3 different seat heights. The left upper panel (A) shows the total duration of the SiSt phase. The right upper panel (B) shows the angular range during the STS flexion phase. The left lower panel (C) shows the angular range during the STS extension phase. The right lower panel (D) shows the maximal angular velocity during the STS extension phase.

The four plots show the relation between handgrip strength on the horizontal axes and respectively duration and 3 kinematic variables on the vertical axes. The left upper panel (A) of this figure shows the total Sit-to-Stand durations, which are traditionally used as the only outcome parameter. The plot clearly shows that stronger subjects were faster during the STS. The right upper panel (B) shows that stronger subjects had a smaller flexion angular range. The left lower panel (C) shows that the weaker subjects had a much higher extension angular range and this effect increases for lower seat heights. The right lower panel (D) shows a comparable effect for the maximum angular velocity. Weaker subjects showed a greater maximum angular velocity and this effect was stronger for lower seat heights.

DISCUSSION

The present results showed that older adults with less handgrip strength stand up with greater flexion of the trunk. Forward trunk movement can be used to transport the body centre of mass towards the new base of support formed by the feet and to gain kinetic energy, which in the subsequent phase is converted to vertical movement. This requires a lower moment around the knee and consequently lower leg strength than performing a STS movement with less trunk flexion [11,32]. The weaker subjects also showed greater trunk extension with a higher angular velocity after seat-off, indicating a more dynamic use of the trunk. Similarly, Hughes et al. showed that functionally impaired elderly, when rising from the lowest chair that they could still stand up from, increased peak hip flexion velocity and decreased their mean center of mass/base of support (COM/BOS) separation at lift-off [13].
The present results may be taken to imply that older adults with lower muscle strength use this strategy to compensate for their loss of muscle strength. However, this does not mean that all weaker individuals adjusted their STS strategy in performing the STS movements. Objective methods to detect different strategies of STS may help to individualize instructions to improve STS transfers and measure intervention effects in clinical settings. This might be an argument to use such measurements in the clinic.

The present findings further demonstrated that kinematic outcomes were more sensitive to detect differences between muscle strength than durations. Duration outcomes did not show a significant difference between lower and higher muscle strength, whereas all kinematics during extension showed a significant effect of HGS. The hypothesis that older adults with lower muscle strength stand up with more dynamic use of the trunk was thus confirmed.

From all covariates HGS proved, using backwards elimination, to be the strongest predictor of the durations as well as the kinematic outcomes. Older adults with lower muscle strength thus seemed to change to a different trunk strategy with more dynamic use of the trunk. Instead of calling this a flexion strategy, which refers to the increased trunk flexion during sitting, we prefer to follow Hughes et al. and use the term stabilization strategy instead, because this term indicates that movements in which very little momentum is generated were made to increase stability [13].

In all likelihood, the adjustment to a larger angular range and a higher maximum angular velocity observed in the weaker HGS group represents a compensation for reduced lower limb strength.

The chair used in the present study was adjustable to a lower seat height. Standing up from a lower seat height occurs in daily life, for example when standing up from a sofa. However, the seating area of a sofa is longer, but with a backward slope and a compliant seat [33]. Hence, standing up from a sofa might be even more difficult. We did not measure lower extremity strength but used HGS as a proxy for global muscle strength instead. It has been shown that lower extremity muscle power was no better than knee extension torque or handgrip strength in the early identification of poor mobility [34].

A limitation of this study is that using the arms during STS was excluded by the protocol, because arm movements might help to compensate for lower leg strength. The reason is that we wanted to focus on the association between HGS and trunk movements. Future research could focus on the manner in which arm movements might be used to support STS dynamics.

To our knowledge, only a few studies to date have demonstrated the added value of using the instrumented STS in interventions [35,36]. The cross-sectional design of the present study precluded an analysis of how the STS strategy changes over time as muscle strength decreases. Longitudinal studies should shed more light on this issue.

Physical performance tests that include the STS, such as the Timed Up and Go [37] and the repeated STS as a sub test of the Short Physical Performance Battery [38], measure the duration of the total test and provide no information about the sub-durations and STS kinematics. The duration of the static periods (standing and sitting) during the 5x repeated STS represents at least for some older adults a great part of the total duration [25]. The present findings demonstrate that kinematic parameters of standing up might be useful for clinical practice. Trunk range of motion, maximum angular velocity and vertical velocity might be used to identify STS strategies in clinical practice and to evaluate interventions.

This means that the total STS duration as measured with a stopwatch provides incomplete information about the dynamic phases of the STS, which are particularly relevant when the trunk has to be displaced against gravity. STS transitions require the development of substantial muscle power and consequently many older adults perform such transitions close to their maximal ability [39,40].

This study and previous studies have shown that muscle strength is likely an important determinant of successful standing up from a sitting position [7]; however, besides strength training also the training of STS transfer skills may be a useful element in interventions aimed at preventing loss of mobility in older adults and patients [41]. Improvement of the technical performance of the STS might be more sustainable than strength training, which is an often used intervention to improve STS performance. Analysis of STS strategy using body fixed sensors is a potential candidate to better understand how older adults could improve their STS ability and measure changes over time objectively.

CONCLUSION

Older adults with weaker handgrip strength employed a different strategy to stand up from a sitting position with more dynamic use of the trunk during the extension phase. Trunk kinematics was more sensitive to muscle strength than durations were to muscle strength.

CONFLICT OF INTEREST STATEMENT

RCvL is the owner and JE, MN, SW are employees of the company McRoberts BV, which is the manufacturer of the DynaPort.

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Clinical value

2

CHAPTER 5
The Instrumented Sit-to-Stand Test (iSTS) has greater clinical relevance than the manually recorded Sit-to-Stand Test in older adults

CHAPTER 6
Older adults with low muscle strength stand up from a sitting position with more dynamic trunk use

CHAPTER 7
A new scoring method to quantify the instrumented Sit-to-Stand test in older adults

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A new scoring method to quantify the instrumented Sit-to-Stand test in older adults

A NEW SCORING METHOD TO QUANTIFY THE INSTRUMENTED SIT-TO-STAND TEST IN OLDER ADULTS

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Key words: physical function, physical performance test, chair stand, sit to stand transfer, wearables, inertial sensors, accelerometers, gyroscopes.

RUNNING PAGE HEADLINE
Development of a new STS score

ABSTRACT

Background
Since the Sit-to-Stand (STS) transition is considered one of the most mechanically demanding physical activities in daily life, age-related loss of muscle mass may imply that with an ageing population more people will face problems standing up.

Objective
The aim of this study was to develop a scoring system for the instrumented STS, including sub-scores based on durations, kinematics and their variation, reducing the dimensionality considered based on the relationships between variables. We aimed for scores on interval scales from 0-100, to be able to measure small changes in STS capability and to provide a readily understandable score for end-users.

Design
Cross-sectional study to explore the possibility of developing a clinically relevant score in a population that is at risk of losing the capability to stand up from sitting.

Methods
Participants were recruited from three residential care facilities and the surrounding community to obtain sufficient variability in physical performance. Physical performance was measured with the repeated STS test. Detailed movement analysis was performed with one device fixed to the lower back housing accelerometers and gyroscopes. Outcomes comprised durations of sub-phases, kinematics and their variation. Exploratory factor analysis, with Varimax rotation, was applied to the normalized data to accomplish dimensionality reduction and to uncover latent patterns in the data. Scores were calculated as the sum of the normalized component scores weighted by the percentage of explained variance of each component.

Results
The exploratory factor analysis revealed 7 underlying factors in the 24 variables that were entered in the analysis. This procedure yielded normalized overall scores characterizing STS performance on an interval scale ranging from 0-100, where 0 reflects the lowest and 100 the highest score relative to the sample population.

Limitations
Longitudinal data and interventions are necessary to further validate the score developed in this paper and the assumption that it might be of clinical use.

Conclusions
Factor analysis allowed a reduction of the number of variables of the instrumented STS test and revealed the underlying structure of the factors. With these factors individual scores can be calculated and the patterns of these score appear to reveal clinically relevant insights.

INTRODUCTION

In about 100 years the mean life expectancy has increased from 40 to 80 years [1]. By the year 2025, 26 countries will have a life expectancy at birth of above 80 years [2]. Since the Sit-to-Stand (STS) transition is considered one of the most mechanically demanding physical activities in daily life [3], age-related loss of muscle mass [4] may imply that with ageing more people will face problems standing up. Losing the capability to stand up in turn might lead to avoidance of physical activity and an increase in sedentary behavior. Indeed, it has been shown that older adults with lower scores on performance tests, especially repeated STS transfers, spent more time lying down and showed longer sitting episodes [5]. Illustrating the importance of STS performance, recent studies have suggested that breaking up prolonged sitting may improve glucose metabolism and may represent an important public health and clinical intervention strategy for reducing cardiovascular risk [6–8] and mortality [9].

STS performance can be easily measured using standardized physical tests, such as the repeated chair stand test, which is part of the Short Physical Performance Battery (SPPB) [10]. In this test, participants are asked to stand up five times as quickly as possible, and are timed from initial sitting to reaching the standing position at the end of the fifth cycle. The total duration is the outcome of the chair stand test. Although total duration is valuable from an epidemiological viewpoint and might be useful to assign care, more informative outcomes from a clinical point of view can be obtained using instrumented STS tests [11–13].

A single device fixed to the lower back has been shown to provide details on the six sub-phases of the STS test (sit-to-stand flexion/extension, standing, stand-to-sit flexion/extension and sitting) and kinematic characteristics of the STS itself (trunk angular range and maximum angular velocity) [14]. The durations of the STS sub-phases in older adults were not only significantly longer, but also showed a higher variability over repeated cycles compared to young adults [14]. Furthermore the dynamic sub-phases of the test were more informative regarding health status, functional status and physical activity in older adults than overall duration and the durations of the static sitting and standing phases [13]. In addition, older adults with lower hand grip strength were found to use a different kinematic strategy to stand up from a sitting position with more dynamic use of the trunk during the extension phase (van Lummel, submitted). The question arises whether the set of outcomes realized in instrumented STS tests can be used to develop a new STS score and sub-scores that are more useful in personalizing, selecting and evaluating goals of interventions and in predicting the risk of losing the capability to stand up from sitting.

The number of variables that can be analyzed using inertial body fixed sensors during the repeated STS test is high and the variables have different units, which makes clinical interpretation difficult. The aim of this study was to develop a scoring system for the instrumented STS based on durations, kinematics and their variation, reducing the number of dimensions considered based on the relationships between variables. We aimed for scores on interval scales from 0-100, to be able to measure small changes in STS capability and to provide a readily understandable score for end-users.

METHOD

Participants

Seventy-nine participants were recruited from three residential care facilities and the surrounding community to obtain sufficient variability in physical performance. The medical ethical committee of the VU University Medical Center Amsterdam approved the study (#2010/290). Prior to testing, all participants provided written informed consent.

Movement task

Physical performance was measured using the chair test from the Short Physical Performance Battery (SPPB) [10]. Participants were first asked to stand up from a standard chair once without using their arms. If successful, participants were asked to rise, as fast as possible, with their arms crossed over their chest for five repetitions of standing up and four repetitions of sitting down, ending in a standing position. The flexion phase during the Sit to Stance movement (SiSt) and the extension phase during Stance to Sit movement (StSi) are called the horizontal phases (marked by horizontal arrows in Figure 1). The extension phase during SiSt and the flexion phase during StSi are called the vertical phases (marked by vertical arrows in Figure 1).

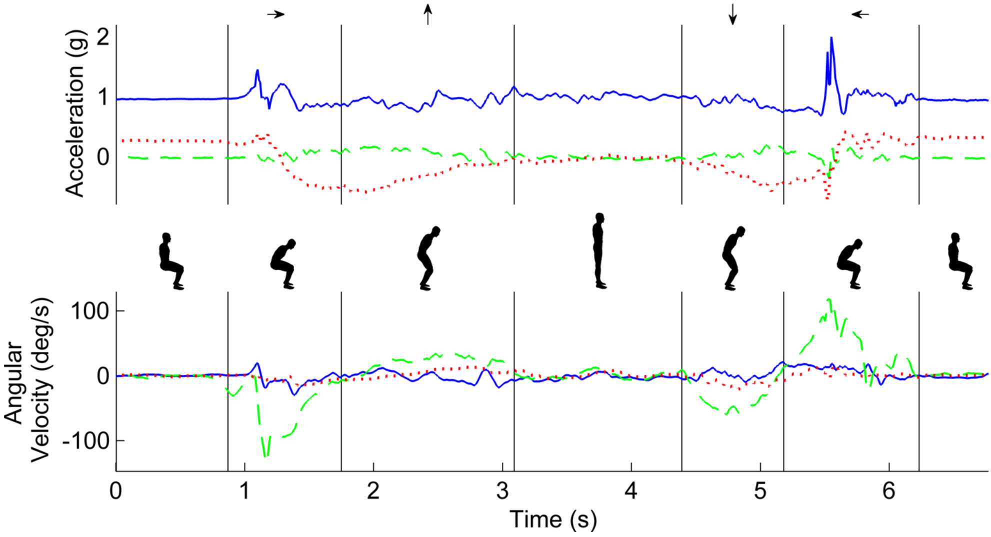

Fig 1. Time series of acceleration (green/dash—mediolateral; red/dots—anterior posterior; and blue/line—vertical) and angular velocity (blue/line—pitch; green/dash—yaw; and red/dots—roll) over the main phases of the STS cycle. The arrows indicate the horizontal (↔) and the vertical phases (↑↓).

Instrumentation

The trunk movements of the participants were measured using a small and light (87×45×14 mm, 74 grams) inertial sensor measurement system (DynaPort Hybrid, McRoberts, The Hague, The Netherlands), which was fixed with an elastic belt around the waist and placed over the spine (Fig 2). This device measured acceleration and angular velocity in three directions at a rate of 100 samples/s.

Fig 2. The test leaders attaches the measurement device. The device includes 3 accelerometers and 3 gyrocopes and has a wireless connection to the remote control of the test leader and the supporting computer with software controllling the test protocol.

The accelerometer signals have been shown to be highly reproducible [15]. High agreement of body-fixed-sensor detection of STS events with detection based on separate force plates below the feet and chair has been shown in older adults and patients with mild to moderate Parkinson's disease [16]. The body fixed sensor system (DynaPort) provides a reliable analysis of SiSt and StSi phases in geriatric patients, with a substantial improvement relative to the stopwatch approach currently used in clinical practice [17].

Signal analysis

Data were analyzed using commercially available software (DynaPort MoveTest, McRoberts, The Hague, The Netherlands). From the SPPB chair stand protocol four complete STS cycles were analyzed from the start of trunk movement in the first SiSt to the end of trunk movement in the 4th StSi. The episode selected ended with participants in the same sitting position as they started in, in order to improve the correction for drift of the gyroscopes. The measurement of 3-dimensional accelerations and angular velocities of the trunk allowed a detailed analysis of the different phases of the STS cycles. The acceleration and the angular velocity in the sagittal plane were used to calculate the trunk pitch angle. Signal processing consisted of two phases. In the first phase, the following temporal events were identified for the SiSt and StSi: start of the trunk movement, end of the trunk flexion phase, and the end of upward vertical phase. These events were determined using a calculated trunk pitch angle based on the accelerations and angular velocity in the sagittal plane as described by van Lummel et al. [14]. In the second phase, the temporal events were adapted using the trunk pitch angle as calculated with the algorithm proposed by Walgaard et al. [18].

After automated identification of all phases (sit-to-stand and stand-to-sit), sub-phases (flexion and extension) and kinematics (angular range and maximum angular velocity) of the 4 repeated STS cycles, the average durations and the variability of these phases and average kinematics within these phases were calculated. Additionally, the average sitting and standing durations were calculated.

Statistical analysis

Normally distributed characteristics are presented as mean and standard deviation (SD). Skewed (non-Gaussian) distributed continuous variables are presented as median and interquartile range (IQR).

To reduce the influence of outliers, for each variable, the 5th and 95th percentile of a normal distribution fitted to the pooled data of all participants was calculated. Data below the 5th percentile and above the 95th percentile were replaced by the values of the 5th and 95th percentiles, respectively. Subsequently, data were normalized by calculating z-scores.

The signal analyses resulted in 24 variables of three different types: durations, kinematics and coefficients of variation. Exploratory factor analysis was applied to the normalized variables to accomplish dimensionality reduction and uncover latent patterns in the data and to reduce the data set to a more manageable size, while retaining as much of the original information as possible. Only factors with an eigenvalue greater or equal to 1 were retained. Varimax factor rotation was applied such that factors loaded maximally on only one factor to improve interpretation. The aim was to develop a clear structure of factors and variables, which implies that only one type of variables was placed with each factor.

A score for each component was calculated by multiplying the standardized data with the component loadings and resulting scores were again normalized. The total score was calculated as the sum of the normalized component scores weighted by the percentage of explained variance of the component.

To interpret the latent patterns in the data, a factor loading of $\geq|0.60|$ was considered as high and a factor loading of $<|0.60|$ as moderate or low. A parameter was assigned to a factor when its loading was at least $|0.6|$ on this factor and when it had loadings of $< |0.60|$ on the other factors.

Results

Seventy-nine older adults participated in this study (67 females; mean age: 82.9 ± 7.9 years; mean weight: 72.7 ± 14.6 kg; mean height: 172 ± 18 cm). Descriptive statistics and STS parameters are presented in Table 1.

Table 1. Demographics and STS parameters of the study population.

Characteristics							
(N=79, Female 85%, Care Home 53%)							
		Mean	**SD**	**Median**	**IQR**	**Min**	**Max**
Demographics							
Age (year)				84	11	59	100
Height (m)				1.63	0.11	1.49	1.86
Weight (kg)				72.5	18.5	44	105
BMI (kg/m2)				26.6	6.0	15.3	38.2
Sit-to-Stand parameters							
4 STS cycles				14.92	11.38	8.67	52.51
Mean durations (seconds)							
Sit-to-Stand	Total			1.62	0.74	1.05	5.37
	Flexion			0.8	0.37	0.45	2.39
	Extension			0.8	0.36	0.47	3.25
Standing				0.24	0.54	0.04	2.23
Stand-to-Sit	Total			1.68	0.71	1.03	5.34
	Flexion			0.84	0.38	0.52	2.35
	Extension			0.84	0.32	0.45	2.99
Sitting				0.17	0.45	0.04	4.24
Mean angular range (degrees)							
Sit-to-Stand	Flexion	42.86	12.71			16.82	79.82
	Extension			31.29	12.45	10.11	74.42
Stand-to-Sit	Flexion	29.32	9.07			8.33	53.17
	Extension	40.89	12			16.1	65.84
Mean max. angular velocity (m/s)							
Sit-to-Stand	Flexion	108.81	38.33			35.56	195.49
	Extension			61.23	27.91	25.51	141.38
Stand-to-Sit	Flexion			61.58	40.38	16.76	118.6
	Extension	100.31	29.13			46.58	179.96

Coefficient of variation (%)							
Sit-to-Stand	Total			8.12	12.51	1.17	92.41
	Flexion			11.02	14.91	2.99	78.76
	Extension			9.93	13.52	1.55	134.56
Standing				35.36	33.16	7.41	138.83
Stand-to-Sit	Total			9.05	9.92	1.37	72.6
	Flexion			12.26	10.63	1.69	76.67
	Extension			10.28	9.92	1.23	135.73
Sitting				31.49	35.57	0	159.85

The participants in the present study had a mean age of 83 years and were recruited from care homes, sheltered housing, and the community, implying that the scores are relative to a group of participants at risk of losing mobility independence. The duration of the SiSt and the StSi was almost equal and this duration was almost equally divided between flexion and extension. Also notable is the high variability over the 4 repetitions of standing (CoV 35.36%) and sitting (CoV 31.49%).

Underlying factor structure

Factor analysis indicated that the 24 STS parameters could be grouped according to seven factors, meeting our criteria regarding factor loading, together accounting for 83% of the variance in the data (Table 2).

Table 2 Rotated component matrix using varimax rotation displaying the factor loadings of each variable on each factor. The 24 observed variables that were calculated from the raw signals mainly reflect seven underlying variables. These underlying variables are called factors.

		Duration	Kinematics		Duration	Coefficient of Variation		
		StSi and SiSt	Vertical	Horizontal	Si and St	StSi	SiSt	Sedentary
		1	**2**	**3**	**4**	**5**	**6**	**7**
Duration	stsi_ext	0,92	0,09	0,11	0,05	0,13	0,03	0,09
	stsi_tot	0,90	0,09	0,02	0,31	0,16	0,00	0,02
	sist_flex	0,84	0,08	0,12	0,10	0,19	0,27	0,06
	stsi_flex	0,78	0,08	0,09	0,49	0,16	0,02	0,02
	sist_tot	0,77	0,02	0,14	0,29	0,11	0,46	0,01
	sist_ext	0,68	0,01	0,19	0,43	0,07	0,42	0,02
Kinematics	sist_ext_range	0,04	0,91	0,05	0,08	0,05	0,02	0,03
	stsi_flex_range	0,05	0,89	0,19	0,11	0,16	0,04	0,05
	sist_ext_vel	0,48	0,75	0,20	0,21	0,03	0,08	0,09
	stsi_flex_vel	0,54	0,63	0,20	0,34	0,16	0,10	0,04
	sist_flex_vel	0,27	0,31	0,73	0,04	0,09	0,28	0,03
	stsi_ext_vel	0,15	0,17	0,73	0,11	0,13	0,08	0,25
	stsi_ext_range	0,54	0,28	0,67	0,02	0,02	0,11	0,25
	sist_flex_range	0,46	0,34	0,66	0,06	0,16	0,04	0,16
Dur	sit	0,27	0,08	0,06	0,89	0,17	0,04	0,01
	stand	0,25	0,09	0,07	0,89	0,03	0,14	0,04
CoV of duration	stsi_tot	0,28	0,22	0,02	0,09	0,86	0,13	0,00
	stsi_ext	0,17	0,22	0,05	0,05	0,77	0,05	0,13
	stsi_flex	0,20	0,42	0,04	0,08	0,73	0,17	0,05
	sist_tot	0,08	0,10	0,09	0,02	0,06	0,87	0,00
	sist_ext	0,20	0,23	0,11	0,06	0,14	0,77	0,03
	sist_flex	0,18	0,27	0,69	0,12	0,12	0,03	0,30
	stand	0,12	0,24	0,15	0,04	0,53	0,29	0,45
	sit	0,14	0,01	0,12	0,04	0,08	0,01	0,91
	eigenvalue	8,0	3,9	2,4	2,0	1,4	1,3	1,0
	% of variance	23,0	14,2	11,3	10,2	10,1	8,7	5,5
	cum of variance	23,0	37,2	48,5	58,7	68,8	77,5	83,0
Legend								
🟩	≥ |0.60|							

Two factors (1 and 4) included only durations. Factor 1 showed the highest percentage of explained variance (23%) and included the dynamic phases StSi and SiSt. Factor 4 included the static phases (sit and stand) and explained 10.2 % of variance. Two factors (2 and 3) included the kinematic parameters angular range and maximum angular velocity together explaining 25.5 % of variance. Factor 2 included the vertical phases when the subject was in an intrinsically unstable two-point support and factor 3 included the horizontal phase when the subject was in a stable 3-point support [3]. Three factors (5-7) included the coefficients of variation. Factor 5 included StSi, factor 6 included SiSt and factor 7 included the static phase sitting, together explaining 24.3 % of variance. These results suggest that the extracted seven factors reflected the three types of variables that formed the input for the analysis: durations (factors 1 and 4), kinematics (factors 2 and 3) and variability (factors 5, 6 and 7).

One CoV variable loaded on the horizontal kinematics factor 3 (sist_flex) and did not load on factor 6.

Individual factor scores

The distribution of the normalized individual factor scores of all participants is shown in Figure 3. These scores can be interpreted as reflecting STS functioning relative to that in the participant sample, with 0 indicating worst functioning and 100 indicating best functioning. The figure shows a small number of 6 participants with very low (< 20) and a small number of 2 participants with very high scores. The majority of participants shows gradual differences in scores between 24-90 points.

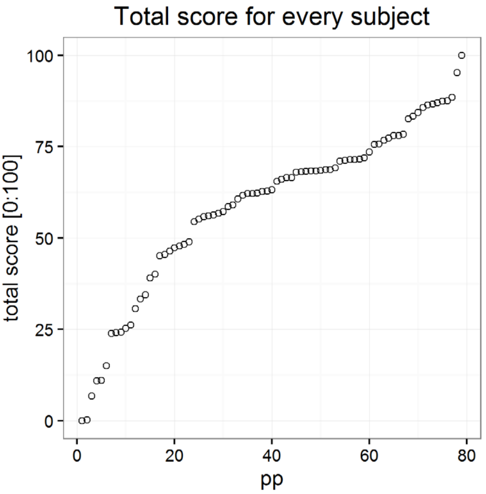

Figure 3. Distribution of individual factor scores of the 79 participants. The individual scores are normalized to the scores of the total sample.

Patterns of the factor loadings of individual participants

For every participant the individual factor loadings of the seven factors were calculated. We consider these the 7 dimensions of the STS score. To understand the potential relevance of these dimensions we present results of the participants with the same STS score and different patterns of scores over dimensions. Figure 4 shows 3 participants with a score of 87 with clear differences over dimensions. The participant represented by the blue (dashed) line shows low scores for kinematics (factors 2 and 3) and high scores for the other dimensions. The subject represented by the red (solid) line shows more uniform scores for all dimensions. The subject with the green line (small dashes) shows a pattern in between.

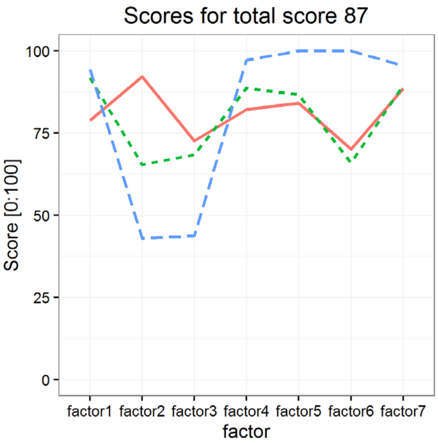

Figure 4. Typical example of three participants with a total STS score of 87 and different factor patterns.

Mean patterns of the factor loadings

We calculated the mean factor loadings for the four groups with scores between 0-25, 25-50, 50-75 and 75-100. The patterns of all subjects are presented in the supplement (Figure 1S). In figure 5 we show the mean patterns of the 4 goups.

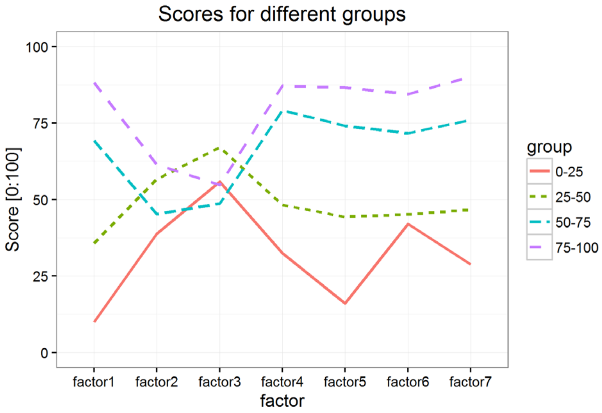

Figure 5. Mean patterns of the 7 factor scores for 4 groups of participants divided based on the individual total factor scores.

The pattern of the two groups with mean scores lower than 50 (red solid and green dotted lines) show a different pattern than the two groups with scores higher than 50 (blue dashed and purple dashed lines). For lower scores, factors 2 and 3 were relatively high and for the higher scores factors 2 and 3 were relative low. The mean scores for factors 2 and 3 did not show a difference between the 4 groups, while the other factor scores the pattern show a gradually increasing mean score for the 4 groups. This suggests that kinematic strategies used (factors 2 and 3) are independent from the overall performance of the STS test.

Discussion

In the present study, we sought to develop a new method to score the performance on the instrumented STS test. We determined a range of 24 variables reflecting duration and kinematics of phases of the STS tests as well as the variability of durations. Using factor analysis, we were able to reduce the number of variables and detect latent patterns. Based on the present results, we can conclude that a reduction of the number of variables, the primary aim the factor analysis, can be achieved. The 24 variables that were analyzed could be meaningfully grouped in 7 underlying factors. This procedure yielded normalized overall scores characterizing STS performance on an interval scale ranging from 0-100, where 0 reflects the lowest and 100 the highest score relative to the sample population. Different patterns of scores across the seven factors were shown for participants with the same total score.

Strength, balance and strategy

It is interesting that the durations of the vertical (↑ and ↓) as well as the horizontal (↔) phase merged into a single factor 1, while the kinematics during the vertical phases (↑ and ↓) were clearly separated from the horizontal phases (↔) and were expressed in two factors 2 and 3. Finally, three variability factors (5-7) could be distinguished for different phases of the STS cycle clearly separating the dynamic phases StSi and SiSt and the static phase sitting.

Several authors have emphasized strength as a determinant of STS performance by older individuals and by patients with stroke and Parkinson's disease [19–24]. In addition, balance control [19] and sensory function were mentioned as determinants of STS performance [25] as well as psychological factors including fear of falling [20,25]. We hypothesize that factor 1 is associated with strength and successful standing up [19,26]. Studies have illustrated the relevance of the use of different movement strategies for STS performance, for example as a compensation for impairments such a muscle weakness [27–30]. For example, impaired elderly stand up with more trunk flexion [31]. We suggest that factors 2 and 3 reflect the strategy of STS. Factor 4, the duration of the sedentary phases, might be associated with failed SiSt attempts, psychological (e.g. motivation) or cognitive aspects (e.g. cognitive processing speed and memory).

The variability of durations of dynamic (StSi, SiSt) and sedentary phases (Si) is reflected in factors 5-7. Variability of durations can have several causes e.g. pain, asymmetric lower limb dysfunction, low strength and impaired proprioception or peripheral tactile sensitivity [25]. Variability of gait has been associated with fall risk in community-dwelling older adults [32–34]. By analogy variability of STS repetitions, might be associated with risk of falling. Difficulty in rising from a sitting position may directly increase the risk of falling, since STS transfers were found to be responsible for 41% of all falls in nursing homes [35]. Low scores for factors 5-7 could thus be associated with the risk of falling during STS transfers. Further research is necessary to explore this innovative insight.

Mean patterns of factor loadings

In an earlier study [14], we have reported highly significant differences in STS durations and maximum angular velocities between older and young adults, but also significant differences of variability of STS duration between older and young adults. This suggests that slower movements, lower angular velocities as well as a high variability of successive repetitions of STS cycles are a characteristic of aging. For factors 1 (StSi and SiSt) and 4 (St and Si), low scores indicate longer durations. For factors 5-7, lower scores indicate higher variability. Low scores on these factors were associated with overall low scores and vice versa.

For factors 2 and 3, low scores indicate small ranges of movement and slow movements of the trunk. The mean scores on these factors seemed not associated with the overall STS score. These factors likely differentiate between different ways of standing up, which is not necessarily correlated to the duration of the STS test in this older population. Possibly individuals with sufficient muscle strength can stand up quite fast using an inefficient kinematic strategy, while individuals with low muscle strength may get up equally fast by using an efficient strategy. On the other hand, the information on strategy use may be clinically relevant. Bobbert et al. reported that an optimal kinematic strategy can substantially reduce the mechanical demands of the STS [30]. We therefore suggest that the kinematic strategy used in the STS may deserve more attention in interventions. Changing the strategy and ability of transferring from sitting to standing as a means to make more efficient use of the existing muscle strength could have a more sustainable impact. Further research might lead to better understanding of the individual patterns and show whether they can be used to identify potential impairments underlying a reduced ability to stand up and to evaluate the effect of interventions.

Conceptual framework

Conceptual frameworks define the concepts measured in empirical research in a diagram that presents a description of the relationships between items, dimensions, sub-dimensions, and the scores produced by a patient reported outcome instrument [36]. Here we use the result of the factor analysis of the repeated STS to propose a conceptual framework (Figure 6).

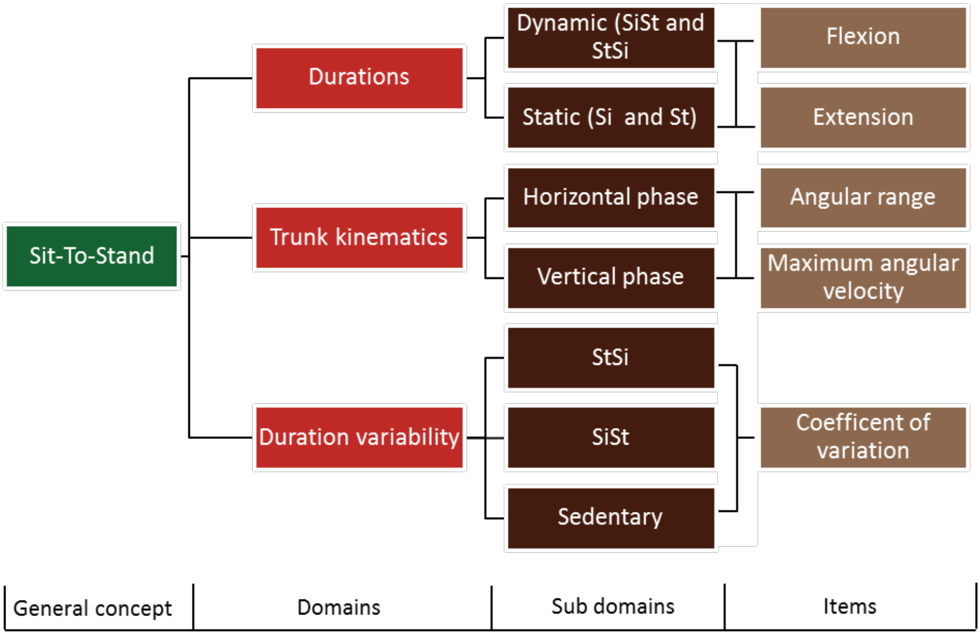

Fig 6. STS measures presented in a conceptual framework with durations, trunk kinematics and trunk variability as the domains of Sit-to-Stand performance.

In this framework the items are the 24 outcomes of the signal analysis, the subdomains are the 7 underlying factors resulting from factor analysis and the domains are the 3 clusters of factors that we identified based on conceptual considerations. Future studies will have to test the stability of this framework.

Limitations

The reliability of factor analysis is dependent on sample size [37]. In this study we included 79 subjects. A common rule suggests that the sample size should be a function of the number of variables. Factor analysis is based on the correlation matrix of the variables involved, and correlations usually need a large sample size before they stabilize. According to Osborne and Costello the best method to standardize the sample size is based on the subject to item ratio [38], which in the present study was 3 (74 subjects and 24 variables). This is considered as low. Guadagnoly et al. argue that the magnitude of the component loadings had the greatest impact on the stability [39]. At higher saturation levels (.06 ad .08) the influence of sample size is small. Factor loadings greater than 0.6 are reliable regardless of sample size, which was the case in our analysis by design. The number of variables per component is also important for stability. “If components possess four or more variables with loadings above .60, the pattern may be interpreted what ever the sample size used" (p. 274) [39]. Also MacCallum et al. conclude that the subject to item ratio appears not to be the sole determinant of stability of the results [40]. Contrary to this popular rule of thumb, level of communality plays a critical role. They should be higher than 0.6.

In this study, factors 1- 3 included 4 variables or more with a loading greater than 0.6 and can thus most likely be considered as stable. Factors 4 - 7 which included only 3 or less variables and should be considered as less stable.

Although the underlying factor structure seem to reveal interesting insights there are still several open questions. Duration and kinematic factors seem to be distinctive domains of the STS, but it is not yet completely clear what these factors reflect and how they are related. We hypothesized that kinematic factors (2 and 3) relate stronger to the way of performing the STS or the strategy of standing up, but further research is needed to substantiate this finding. Confirmatory factor analysis using a comparable population has to show the validity of the results. Longitudinal data and interventions are necessary to further validate the clinical relevance of the concepts shown in this paper.

CONCLUSION

Factor analysis was used to analyze the outcomes of an instrumented Sit-to-Stand test in older adults. Seven underlying factors were identified, representing 3 clusters of factors, presumably related to strength, balance and strategy. Individual STS scores and sub-scores for the seven factors were proposed on an interval scale of 0-100. A conceptual framework was proposed based on the 24 parameters derived from signals obtained with a single inertial measurement unit fixed to the trunk.

FUNDING

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CONFLICT OF INTEREST

RCvL is the owner of McRoberts, while SW, MN and JE are employees of this company, which is the manufacturer of the DynaPort device and the MoveTest product that were used in the present study. The other authors have no conflict of interest.

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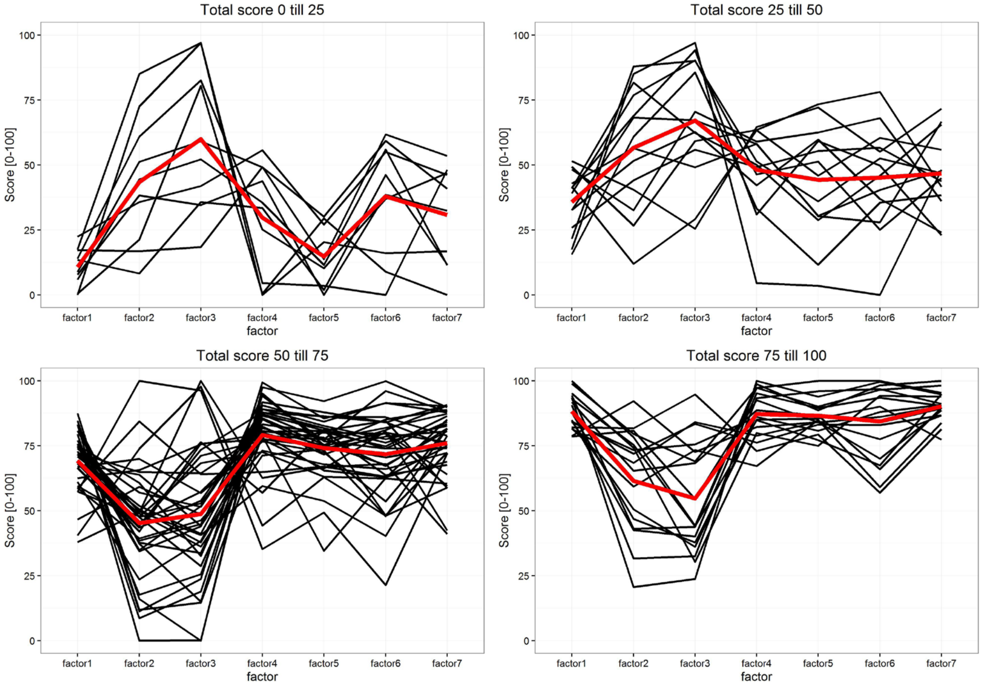
SUPPLEMENT

Figure 1S. Patterns of individual factor scores of all participants and average patterns (in red/thick line) divided in four groups with scores between 0-25, 25-50, 50-75 and 75-100.

Supporting information



3

Association Physical Performance – Physical activity

CHAPTER 8

Physical Performance and Physical Activity in Older Adults: Associated but Separate Domains of Physical Function in Old Age

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PHYSICAL PERFORMANCE AND PHYSICAL ACTIVITY IN OLDER ADULTS: ASSOCIATED BUT SEPARATE DOMAINS OF PHYSICAL FUNCTION IN OLD AGE

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ABSTRACT

Background
Physical function is a crucial factor in the prevention and treatment of health conditions in older adults and is usually measured objectively with physical performance tests and/or physical activity monitoring.

Objective
To examine whether 1) physical performance (PP) and physical activity (PA) constitute separate domains of physical function; 2) differentiation of PA classes is more informative than overall PA.

Design
Cross-sectional study to explore the relationships within and among PP and PA measures.

Methods
In 49 older participants (83±7 years; M±SD), performance-based tests were conducted and PA was measured for one week. Activity monitor data were reduced in terms of duration, periods, and mean duration of periods of lying, sitting, standing and locomotion. The relation between and within PP scores and PA outcomes were analysed using rank order correlation and factor analysis.

Results
Factor structure after varimax rotation revealed two orthogonal factors explaining 78% of the variance in the data: one comprising all PA variables and one comprising all PP variables. PP scores correlated moderately with PA in daily life. Differentiation of activity types and quantification of their duration, intensity and frequency of occurrence provided stronger associations with PP, as compared to a single measure of acceleration expressing overall PA.

Limitations
For independent validation, the conclusions about the validity of the presented conceptual framework and its clinical implications need to be confirmed in other studies.

Conclusions
PP and PA represent associated but separate domains of physical function, suggesting that an improvement of PP does not automatically imply an increase of PA, i.e. a change to a more active lifestyle. Differentiation of activity classes in the analysis of PA provides more insights into PA and its association with PP than using a single overall measure of acceleration.

INTRODUCTION

Physical function is increasingly recognized as a powerful factor in the prevention and treatment of a number of health conditions in older adults [1]. It is defined as one's ability to carry out activities that require physical actions, ranging from self-care (activities of daily living) to more complex activities that require a combination of skills, often with a social component or within a social context [2]. Physical function is a multidimensional concept, with four related subdomains: mobility (lower extremity function), dexterity (upper extremity function), axial ability (neck and back function), and ability to carry out instrumental activities of daily living [2]. Physical function is usually measured objectively with physical performance tests [3,4] and/or physical activity monitors [5,6].

The present study focuses on mobility as measured with physical performance (PP) tests. Over the past decades, various PP tests have been developed to assess the physical function of older adults. Typical outcome measures, such as the time to perform a supervised and standardized task, are straightforward to determine and objective, and therefore widely employed. In this study we used the timed Sit-to-Stand test (STS) [7], the Timed Up and Go test (TUG) [8,9], and the Short Physical Performance Battery (SPPB) [10]. Minimal meaningfull change of the SPPB in older adults has been reported [11].

Physical activity (PA) is defined as any bodily movement produced by skeletal muscles that requires energy expenditure [12]. PA is behavior that encompasses all forms of activity, including walking and cycling, active play, work-related activity, and active recreation such as working out in a gym, dancing, gardening and competitive sports. Self-report is the most commonly used method to measure PA in large observational studies. Yet with the advent of ambulatory movement registration techniques in the early nineties, PA is increasingly being measured by means of accelerometers cached in wearable devices. Such activity monitors allow objective assessment of the intensity, frequency, and duration of physical activity [5, 13]. The level of activity is expressed in activity counts and energy expenditure estimates [14]. In recent years, multi-axis accelerometers, recording both the magnitude and direction of accelerations, have become available, allowing detection of the orientation of the instrumented segment in question (e.g., the trunk) relative to gravity. Based on this feature, analysis methods have been developed to differentiate activities like sitting, standing, lying and locomotion [15]. We are unaware of any publications discussing the meaningful change of physical activity using activity monitors.

PP and PA are often used as outcome variables in (clinical) studies on effects of preventive or curative interventions aimed at improving physical function. In a recent review it was concluded that only limited evidence exists to support the effectiveness of pulmonary rehabilitation and pharmacotherapy in improving PA in Chronic Obstructive Pulmonary Disease (COPD) [16].

For measurements of patient reported outcome (PRO) endpoints, the Food and Drug Administration (FDA) recommends the use of appropriate conceptual frameworks, which explicitly define the concepts measured by a PRO instrument [17]. A PRO is any report of a patient's health status that comes directly from the patient without interpretation of the patient's response by a clinician or someone else. A systematic review of the use of patient reported measures of PA and related constructs concluded that selected instruments lacked justification in terms of such a framework [18]. Here, we propose a conceptual framework in which PP and PA represent associated but also separate domains of the mobility domain of physical function (Figure 1) and hence require different types of measurement.

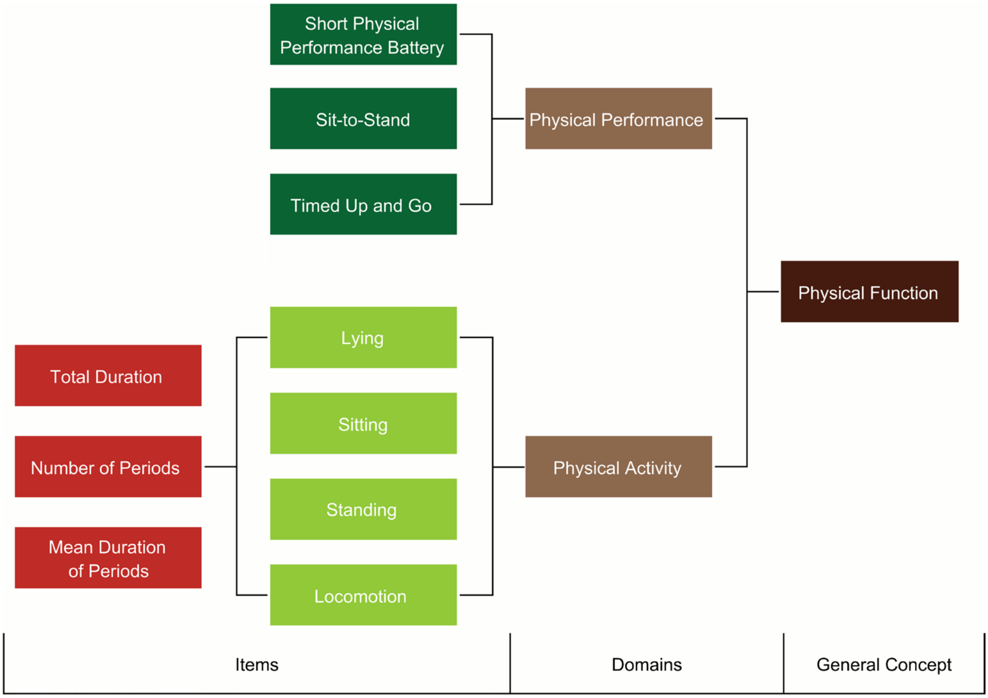

Fig. 1 Mobility measures presented in a framework with physicial performance and physical activity as domains of physical function. Activity classes are determined and for all types of physical activity total duration, number of periods and mean duration of periods are calculated.

The relationship between physical activity of community dwelling older adults and functional limitations, disability or loss of independence has previously been reviewed [19]. However, in this review, articles reporting associations between physical performance tests and physical activity were not included. In patients with COPD and healthy controls, a strong correlation (0.76) between the distance walked during a 6-minute walking test and the total walking time in daily life has been found [20]. Similarly, better scores on the Short Physical Performance Battery (SPPB) appeared to be associated with higher PA levels and mobility in healthy older men [21], although in another study poor correlations were found between

SPPB scores and time spent walking in daily life in healthy older people of both genders [22]. The correlation reported between the SPPB and activity counts was 0.48 [21] and while the correlation between the gait speed score of the SPPB and the amount walking in daily life was 0.35 [22]. These associations were relatively low and explain only the associations between PP and PA to a certain extent. In a recent study observations using a wearable device suggest that laboratory gait measurements do relate to daily-life walking, but are more indicative of an individual's 'best' performance, rather than their usual performance [23]. All of the studies provided some support that PP and PA are associated, but did not explicitly state or test the assumption that PP and PA are related but separate domains of physical function. As physical performance is ability and physical activity is behaviour, it could be assumed that they are related but also separate domains. To our knowledge, associations between objective PP tests and PA measures have not been systematically studied to date.

The primary aim of this study was to test this hypothesis by investigating the correlation and the latent variables between PP and PA measures in older adults. In addition, we tested the hypothesis that differentiation of activity classes and quantification of their duration, intensity and frequency of occurrence, provide more meaningful relations with physical performance, than a single acceleration measure (e.g. counts) expressing overall PA.

METHODS

Study population

For the purpose of this cross-sectional study, a convenience sample was recruited from both a residential care facility and the surrounding community in order to obtain sufficient variability in both PP and PA. Eligible persons were aged 70 years and older, had a Mini-Mental State Examination score [24] > 18 out of 30, and were able to walk 20 m without cardiac or respiratory symptoms. The medical ethical committee of the VU University Medical Center Amsterdam approved the protocol for the study (#2010/290), and all participants provided written informed consent.

Physical performance assessment

Participants' PP was measured by means of the 3×Sit-to-Stand (STS) [7], the TUG [9], and the SPPB [10]. Participants performed 3 STS cycles at a self-selected speed (start and end in a sitting position), while being free to swing their arms. A standard chair without arm rests was used. The patients started the TUG while sitting on a regular chair, with a height of 43-46 cm without armrests. Patients were instructed to sit with their back against the back of the chair, feet placed on the floor directly in front of the chair, and arms resting in their lap. Patients were instructed to rise from the chair (without using their arms) after the rater gave the starting signal, comfortably walk the clearly marked distance of 3 meter, turn around the cone, walk back to the chair and sit down with their back against the chair. The 3 meter walking distance was measured from the front of the chair to the middle of the cone. The SPPB consisted of measures of standing balance, walking speed, and ability to rise from a chair. For tests of standing balance, the subjects were asked to attempt to maintain their feet in the side-by-side, semi-tandem, and tandem positions for 10 seconds each. Walking speed was measured over a distance of 4 meters. Participants started standing still with their feet against a line. At a start signal they walked at self a chosen-speed and passed a second line at 4 meters distance and stopped at a line at 5 meters. The time of the faster of two walks was used for scoring. To test the ability to rise from a chair, a straight-backed chair was placed next to the wall; participants were asked to stand up and sit down five times as quickly as possible, and were timed from the initial sitting position to the final standing position at the end of the fifth stand. These three PP tests contained both preferred and maximum speed test variables; the 5×STS a subtest of the SPPB and the TUG were performed as fast as possible, whereas the 3×STS and gait as subtest of the SPPB were performed at preferred speed. All participants wore their regular footwear during all tests, and were allowed to use any mobility aid that they would normally use. However, the use of walkers or wheelchairs was precluded. These tests were administered by professionals with a background in kinesiology.

The protocol of the PP tests was implemented on a computer. Dedicated software allowed the test leader to send event markers with a remote control to start the measurements and store start and stop markers of the tests. The software used these markers to determine the duration of the 3xSTS and the TUG tests in seconds and calculate the SPPB scores for balance, walking speed, and chair rises. Five performance scores (from 0 to 4) were created for each SPPB test, with a score of 0 representing the inability to complete the test and 4 representing the highest level of performance [10].

Physical activity assessment

PA was measured using a small and light activity monitor (51×84×8.5 mm, 45 grams), which was attached centrally over the lower back with an elastic belt around the waist (DynaPort® MoveMonitor®, McRoberts, The Hague, The Netherlands) (Figure 2). Participants were asked to wear the activity monitor continuously for one week (day and night) with the exception of activities involving immersion in water (e.g. showering). The monitor consisted of three orthogonal accelerometers (resolution: 0.003 g) for sensing in three directions: longitudinal (x), mediolateral (y), and anterior–posterior (z). Raw accelerometer signals were stored at a sample rate of 100 samples/s. Instrumental reproducibility was examined using a shaker device. Intra- and inter-instrumental intraclass correlation coefficients (ICC) were 0.99 for both x- and y-directions [13]. The direction of the z-sensor could not be tested due to a lack of space on the shaker device for solid attachment of the accelerometers. However, the sensors are expected to have the same measurement quality. The intra-instrumental coefficients of variance were smaller than 1.13% [13], indicating that reproducibility of the raw accelerometer signals was high. The validity of the activity classifications has been demonstrated in both lab [25,26] and field [27,28] studies and one week of measurement has been shown to yield highly reproducible results [29].

Fig. 2 Participant wearing the activity monitor, located at the lower trunk.

Raw data were analysed using commercially available software (MoveMonitor© McRoberts). First, the distribution of PA classes (lying, sitting, standing, locomotion) was determined (Figure 3).

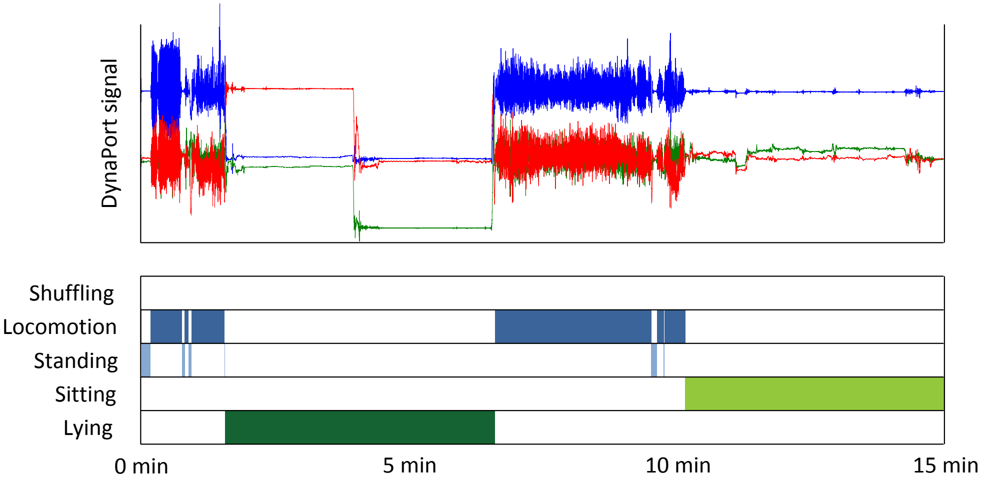

Fig. 3 Raw acceleration signals (top panel) and a Gantt chart of classes of activity (bottom panel). The blue or dark grey line represents longitidunal (x), green or light black mediolateral (y) and red or light grey anterior-posterior (z) axis of the accelerometer. During lying, the person turns from phrone to the left side.

Locomotion was defined broadly as all cyclic activity, including walking, stair walking and cycling. The basic ingredient of posture detection (discrimination between lying, sitting and standing) is threshold analysis on the trunk angle, as determined from the low frequency components of the accelerations. The basic ingredients of locomotion detection are threshold and frequency analysis. For each classified PA period, movement intensity (MI) was calculated. To this end, 3D accelerations were low-pass filtered to remove unwanted measurement noise and high-pass filtered to remove the effect of gravity. A fourth-order Butterworth band-pass filter was used, and cut-off frequencies were set at 0.2 and 8 Hz [13]. The Euclidean sum of the filtered 3D accelerations was used as the resultant acceleration. MI was defined as the average of the resultant acceleration during an interval and expressed in units of the acceleration due to gravity (g). Finally, for each class of activity, a week summary was made with the following variables: 1) total duration, 2) number of periods, 3) mean duration per period, and 4) weighted mean MI per period. MI was calculated per activity class and the values obtained were correlated with PP to see whether this results in more meaningful relations.

Statistical analysis

Spearman’s rank correlations coefficients were used to explore the relationships within and between PP and PA measures. P values <0.05 were considered statistically significant. Correlations were rounded at two decimals. A correlation of <0.30 is considered as very low, a correlation between ≥0.30 to 0.50 as low, a correlation between ≥0.50 to 0.70 as moderate, and a correlation between ≥0.70 to 0.90 as high. Factor analysis (FA) was used to detect structure in and relationships between variables and to test the construct validity of the proposed conceptual framework. The fundamental objective of FA is to group together those variables that are highly correlated with each other but relatively uncorrelated with the other variables; these groups are then regarded as potential evidence for an underlying factor structure [30]. FA procedures are more accurate when each factor is represented by multiple measured variables in the analysis. PA values correlating significantly with all PP values were included in the FA. To ensure that variables had roughly normal distributions, logarithmically transformed values of PP were used. All factor analyses consisted of a principal component analysis with varimax rotation. Kaiser's eigenvalue-greater-than-one rule was applied to determine the optimal number of factors to retain [31]. A variable was assigned to a factor when its loading was at least |.50| or higher on this factor and when it had no loading at |.50| or higher on another factor. Data were analysed using SPSS 20 for Windows (SPSS Inc., Chicago, USA).

RESULTS

Forty-nine older participants (mean age 82.8 years (SD 6.9), 37 female, 19 residential care, 34 walking aids) were included in the study. Participant characteristics and descriptive statistics are presented in Table 1.

Table 1. Descriptive statistics of all measures averaged over 49 participants. Physical Performance and Physical Activity outcomes are expressed in weighted mean, standard deviation (SD), minimum and maximum values.

			Mean	SD	Min	Max
Descriptive statistics						
	Age	Years	82.8	6.9	70	97
	Sex	Female / Male	38 / 11	-	-	-
	Weight	Kilogram	75.4	12.3	49.1	106
	Height	Centimeter	166	8.7	149	190
	BMI	Kg / m²	27.4	4.4	19.4	38.1
Physical Performance						
		3xSTS, mean per 1xSTS (s)	1.73	.60	.9	3.5
		TUG (s)	17.9	9.44	7.5	52.4
	SPPB	Balance score	2.49	1.36	0	4
		Gait score	2.59	1.08	0	4
		5xSTS score	1.29	1.02	0	4
		Total score (Balance+Gait+5xSTS)	6.37	2.86	1	12
Physical Activity						
	Lying	Total duration (hours/day)	10.6	1.96	6.34	15.7
		Periods (#/day)	9.59	5.36	4.00	30.0
		Mean period duration (min/day)	82.8	40.9	22.9	227
		Movement Intensity (g)	.006	.002	.003	.014
	Sitting	Total duration (hours/day)	9.62	1.88	5.87	13.4
		Periods (#/day)	96.9	37.0	17.0	210
		Mean period duration (min/day)	7.70	5.73	2.64	28.7
		Movement Intensity (g)	.017	.006	.007	.036
	Standing	Total duration (min/day)	132	53.6	21.6	244
		Periods (#/day)	619	328	53.0	1489
		Mean period duration (s/day)	15.5	8.50	7.78	51.7
		Movement Intensity (g)	.048	.012	.025	.088
	Locomotion	Total duration (min/day)	46.1	27.6	.46	113
		Periods (#/day)	272	164	7.00	770
		Mean period duration (s/day)	10.1	3.25	3.86	21.2
		Movement Intensity (g)	.149	.028	.101	.236

Note that the sum of the 4 PA durations in Table 1 (23,24 hours) is slightly different from the mean wearing time of the sensor (23.4 hours), due to a small category of unclassified activities.

The mean duration of data collection for the 3×STS and TUG was 3.8 minutes and 7.2 minutes for the SPPB. Average wearing time of the monitor was 6.88 days with a minimum of 6 days. Mean wearing duration was 23.4 hours per day (97%).

Are PP and PA associated?

The correlations between age, PP and PA are presented in Table 2. Age appeared only to have very low to low correlations with PP and with PA. The strength of the association between PP and PA is dependent on the activity type. Most PP outcomes significantly correlated low to moderately with 7 PA classes and very low and not significantly with 5 PA classes.

With the exception of total duration of lying and mean duration of locomotion the significant correlations between activity classes and scores of 3xSTS performed at a self-chosen speed were markedly lower than correlations of PA with SPPB-5xSTS performed at maximum speed (Table 2).

Table 2. Spearman rank correlations between Age, Physical Performance and Physical Activity measures. Physical performance measures includes 3xSTS, TUG, the three sub-scores and the total score of the SPPB. Physical activity scores include lying, sitting, standing and locomotion and from these total duration (Dur.), number of periods (#), mean duration of periods (Mean) and movement intensity (MI). Note that 3xSTS and TUG are expressed in seconds, where higher values indicate worse performance, whereas SPPB scores are expressed in scores of 0-4, where higher values indicate better performance.

	Age	Lying				Sitting				Standing				Locomotion				Total
		Dur.	Periods		MI	Dur.	Periods		MI	Dur.	Periods		MI	Dur.	Periods		MI	
			#	Mean			#	Mean			#	Mean			#	Mean		
Age		-.19	-.25	.19	-.07	.31	-.27	.32	-.31	-.13	-.27	.13	-.36	-.35	-.25	-.33	-.29	-.39
3xSTS	.29	.29	-.01	.15	-.06	.09	-.32	.33	-.21	-.29	-.40	.38	-.46	-.43	-.46	-.14	-.58	-.42
TUG	.27	.37	-.10	.24	.07	.22	-.53	.55	-.24	-.51	-.60	.40	-.53	-.55	-.69	-.01	-.55	-.49
SPPB																		
Balance	-.43	-.24	.14	-.21	-.06	-.17	.40	-.46	.20	.45	.51	-.22	.49	.55	.58	.24	.40	.39
Gait	-.36	-.31	.10	-.23	-.04	-.16	.35	-.38	.23	.37	.41	-.25	.34	.38	.48	.01	.44	.37
5xSTS	-.32	-.17	.06	-.12	-.02	-.30	.54	-.58	.39	.43	.62	-.50	.64	.63	.69	.11	.56	.62
Total	-.45	-.28	.14	-.24	-.06	-.25	.52	-.57	.32	.50	.61	-.36	.58	.61	.69	.15	.56	.54

Four PP scores (3xSTS, TUG, SPPB-Gait and SPPB-Total) showed significant low correlations (r = 0.28 to 0.37) with the total duration of lying, suggesting that participants with lower PP scores spent slightly more time lying. All PP scores correlated very low (r = -0,01 to -0.24) with the number and the mean duration of lying periods.

PP scores had very low to low correlations with total duration of sitting (r = 0.09 to -0.30). PP scores correlated low or moderately with the number and mean duration of sitting periods (r = -0.32 to -0.58). This indicates that participants with higher PP scores had more frequent sitting periods but of shorter duration.

PP scores showed low to moderate associations with the total duration and number of periods of standing and locomotion (r = -0.29 to 0.69), indicating that participants with higher PP scores stood and walked more often with more frequent interruptions.

PP scores showed very low correlations (r = -0.01 to 0.24) with mean duration of locomotion periods.

The correlations within the PA and the PP scores are presented in the online supplementary Table S3 and Table S4.

Are PP and PA separate domains?

The factor structure after varimax rotation revealed 2 factors (Table 3). Factor loadings for PP outcomes were low or moderate for factor 1 (0.147 to 0.465) and moderate or high for factor 2 (.590 to .846). Factor loadings for PA outcomes were high for factor 1 (0.843 to 0.925) and low for factor 2 (0.270 to 0.333). Factor 1 (PA) explained 48.8 % of the variance and factor 2 (PP) explained 29.6 % of the variance, adding up to a total of 78.4 %.

Is PP associated differently with the movement intensity of activity classes ?

The means of movement intensity (MI) for each class of activity are presented in Figure 4. The mean MIs of the sedentary activities lying (0.006 m/s2) and sitting (0.017 m/s2) were lower than the mean MIs of the more active classes standing (0.048 m/s2) and locomotion (0.149 m/s2). The weighted mean MI over all activities classes (0.020 m/s2) was close to the inactive classes, because these had a much longer total duration than standing and locomotion. The PP scores correlated markedly differently with the means of the MI per activity class: lying (0.02 to -0.07), sitting (0.20 to 0.39), standing (0.34 to 0.64), and locomotion (0.29 to -0.58)

Table 3. Rotated component matrix using varimax rotation displaying the factor loadings of each variable on each factor. The physical performance parameters include the duration of 3xSTS at self chosen speed, duration of he TUG and the three sub scores of the SPPB. The physical activity parameters include the number of sitting periods, the mean duration of the sitting periods, the total duration of standing, the number of standing periods, the total duration of locomotion and the number of locomotion periods. Note that 3xSTS and TUG are expressed in seconds, where higher values indicate worse performance, whereas SPPB scores are expressed in scores of 0-4, where higher values indicate better performance.

	Factor 1	**Factor 2**
Physical Performance		
3xSTS	-0.187	-0,782
TUG	-0.357	-0.824
SPPB BALANCE	0.465	0.590
SPPB GAIT	0.147	0.846
SPPB 5xSTS	0.438	0.609
Physical Activity		
Sitting periods	0.899	0.270
Sitting mean period duration	-0.875	-0.276
Standing total dur.	0.843	0.333
Standing periods	0.925	0.312
Locomotion total duration	0.901	0.277
Locomotion periods	0.908	0.304
% variance explained	48.8	29.6

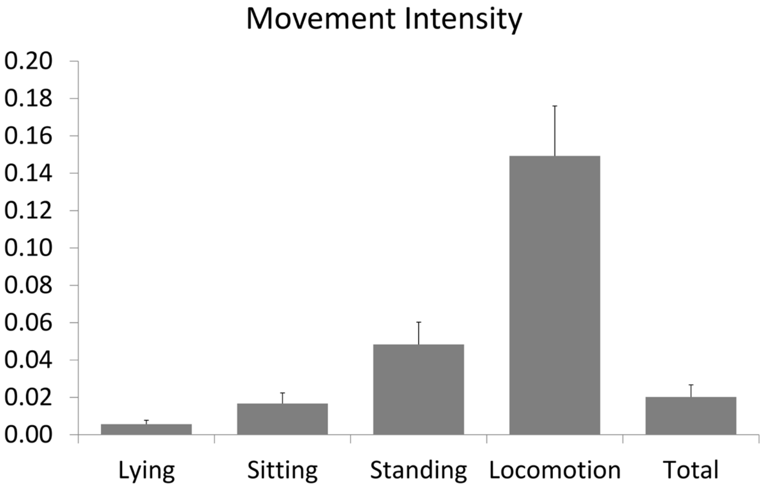

Figure 4. Mean Movement Intensity and standard deviations per class of activity. Differences between classes of activity were all significant (P < 0.01).

DISCUSSION

We aimed to validate a conceptual framework in which PP and PA constitute related but separate domains of physical function. To test this hypothesis we investigated the associations between objective PP and PA measures in older adults using rank order correlation and factor analysis. We also investigated the hypothesis that multiple different measures of PA provide more meaningful relations with PP than a single intensity measure expressing overall PA.

Are PP and PA associated?

In line with previous studies [5,21,22,23], we found clear correlations between PP measured with a range of performance tests and PA in daily life. Given the cross-sectional nature of the study, causation cannot be inferred and in fact causality may be circular in this case.

It was expected that sedentary activity classes (lying and sitting) would not correlate with PP, but the number and mean duration of sitting periods correlated somewhat higher than expected (0.32 to 0.58). With respect to the activity classes distinguished in the present study, the high and negative loadings of the mean durations of sitting periods (-0.875) on the PA factor (Table 3) seem to indicate that long mean durations of sitting periods are indicative of inactivity. The high positive factor loadings for the number of standing (0.925) and locomotion periods (0.908) might suggested that these measures are indicative of an active life style.

Relatedly, the number of locomotion and standing episodes were generally associated moderately to high with PP (Table 2). Nicolai and co-workers [22] also found a positive correlation between SPPB and total walking time in community living older adults, albeit lower than in our study (0.41 versus 0.61).

Sitting and lying showed a more complex pattern of correlations with PP. Overall, the participants with lower PP scores showed larger total durations spent lying down and longer mean durations of sitting episodes, suggesting a less active lifestyle in the less physically fit participants, which corresponds with the lower overall MI. These findings are consistent with Healy's [32] findings on the deleterious associations of prolonged sedentary time with cardio-metabolic and inflammatory biomarkers. Interrupting sitting time with short bouts of light or moderate-intensity walking lowers postprandial glucose and insulin levels in overweight adults. Breaking up sedentary time may be beneficial to reduce cardiovascular disease risk [33].

Remarkably, mean duration of walking periods did not correlate with the PP scores. This could be due to the low between-subject variance (3.2 s) of the mean duration (10.2 s) of walking periods, or to the fact that walking duration was predominantly determined by in-house distances.

An important finding was that PP scores from tests performed at a self-chosen pace correlated less with PA in daily life than scores from tests performed at maximum speed (Table 2). This finding is also supported by the relatively high correlations between PP tests performed at maximum speed and PA reported by Morie and co-workers [21], suggesting that PP tests performed at maximum speed more closely reflect physical capacity and skill with less interference from factors such as motivation to perform well during the test.

Are PP and PA separate domains?

Even though PP and PA were associated, factor analysis showed that PP outcomes loaded high on one factor and low on the other factor, while PA outcomes had opposed (i.e. low and high) loadings on these factors except for balance, which had low loading on PA and moderate loading on PP. Factor 1 consisted of all PA variables and factor 2 comprised all PP variables. The FA procedure is accurate given that each factor is represented by multiple measured variables in the analysis. The resulting factor structure is simple and separated PP from PA measures, which confirms our hypothesis that PP and PA may be considered as separate but associated domains of physical function.

Is PP associated differently with activity classes and the corresponding MI?

We showed that categorization and more detailed quantification of PA provides additional information on associations between PP and PA than the quantification of PA in terms of a single overall index of motor activity. Most activity monitors calculate activity counts or vector magnitude units over a period of time, usually over a fixed epoch of 15 seconds or one minute [14]. This method has the advantage of data reduction during the measurement, but the disadvantage that it does not allow one to differentiate classes of PA and calculate specific metrics per activity. The activity classes differed substantially in the level of activity as reflected in the MI and the total time, number of periods, and the mean duration per class of activity correlated differently with PP outcomes (Table 2). Therefore, it can be concluded that activity classification has added value over calculation of a single measure to assess physical activity.

MI as presented here expresses the weighted mean acceleration over short timeframes. The sample rate of 100 samples/s enables one to analyse a class of activity using the start and end of such an activity and calculate duration and MI per event in a very precise manner. This might be especially relevant for activity classes with short mean durations, such as the short periods of standing and locomotion in this study, with a mean duration of 15 and 10 seconds, respectively. As the correlations between PP and the MI per activity class were markedly different we can conclude that identification of activity classes reveals more specific associations between PP and PA, which remain hidden if only movement intensity is calculated.

Practical implications

The limited correlations between PP and PA revealed by the factor analysis suggest that an improvement of PP does not automatically lead to an increase of PA, i.e. a change to a more active lifestyle. This is supported by several studies on pulmonary rehabilitation showing that translating gains in exercise capacity to increased physical activity had mixed results [16]. This has led to the implementation of physical activity interventions as part of pulmonary rehabilitation [34]. Increasing activity levels may improve long-term outcomes. It is well known that it is difficult to change from an inactive life style to a more active life style. It is common practice in interventions aimed at improving physical function to focus on PP, while it is not clear at this point whether subjects undergoing such interventions will adopt a more active life style that could affect daily life in the long-term. Having the capacity to perform mobility related physical activities does not guarantee that this capacity is actually used. There is an important role for interventions aimed at increasing physical activity. Therefore, PA measurement could be used to give objective, specific and comprehensible feedback to patients about their physical activity level in clinical practice.

Strengths and limitations

We included a wide range of participants in this study, from normal to obese persons (BMI range 19.4 to 38.1), with ages ranging from 70 to 97, and individuals that were practically immobile (locomotion 0.46 min/day) to fairly mobile (locomotion 113 min/day). In general this heterogeneity represents a positive aspect of this study, however, it raises some concerns from a statistical point of view, given that extreme data points can have a strong effect on analyses based on correlation. We have examined this potential influence by inspecting the scatter plots of PP and PA variables. There were three outliers of inactive participants with very short walking durations, due to frequent use of a wheelchair. To evaluate the effects of these

outliers we performed an additional factor analysis without these 3 outliers (Table S1 of the online supplement). This comparison revealed only a small effect of these outliers on the strength and the distribution of PP and PA factor loadings.
A potential weakness of the study is that the use of walking aids (e.g. walkers and wheelchairs) was precluded during the performance tests, while these walking aids were frequently used in daily life. This could have influenced the performance of participants with and without walking aids differentially. To examine this possibility, an additional factor analysis was performed on both groups. The distribution and the factor loadings of the PP and PA variables over the two factors hardly changed compared to the initial analysis (results presented in Table S2 of the online supplement).

Another limitation of the study is the well-known inability of accelerometers to accurately detect stationary activities, to estimate physical load associated with carrying weights, and to correct for locomotion intensity on stairs and slopes. Additionally, due to a lack of waterproofing, the monitor could not be worn during water-based activities. So our study may have underestimated PA somewhat, but given our strict criteria regarding wearing time this effect was probably small.

The results of this study are based on an older population consisting of community dwelling as well as institutionalised participants who were not selected on the basis of a specific pathology. The results therefore cannot be generalized to other populations. Further studies should provide for example subjects of younger age, other geographic areas and other chronic diseases.

Exploratory factor analysis (EFA) as applied here has its limitations. Confirmatory factor analysis (CFA) which tests the goodness of fit of a pre-specified factor model, is considered to be better suited for construct validation, because it enables testing of adequacy of fit on the data to the postulated underlying construct [31]. However, the resulting factor structure exactly matched with the structure hypothesized in our conceptual framework. For independent validation, the conclusions about the validity of the presented conceptual framework and its clinical implications need to be confirmed in other studies.

CONCLUSIONS

Our results support a conceptual framework in which physical performance and physical activity are viewed as associated but separate domains of physical function. Activity monitors that allow differentiation of activity classes in the analysis of PA are providing new insights into PA and its association with PP.

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COMPETING INTEREST

Rob C. van Lummel is a PhD student at the Faculty of Human Movement Sciences (Vrije Universiteit Amsterdam) and the owner of McRoberts. Stefan Walgaard is an employee of McRoberts. This company is the manufacturer of the DynaPort.

AUTHOR CONTRIBUTIONS

RvL conceived the study idea, led the AGIS research consortium, contributed to data collection, contributed to the analysis, and drafted the first version of the report.

SW contributed to the data collection, was responsible for quality control of data, and contributed to the statistical analysis and revised the article.

MP led the FARAO research consortium, contributed to the data collection, and revised the article.

PE led and oversaw all activities related to the participants and revised the article. JGA contributed to the statistical analysis and critically revised the article for important intellectual content.

JHvD was responsible for the FARAO consortium, developed the analytical methodology, and revised the article and had final approval of the article.
PJB was responsible for the study, oversaw all activities and critically revised the article for important intellectual content, and had final approval of the article.

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SUPPORTING INFORMATION

S1 Table. Rotated component matrix using varimax rotation displaying the factor loadings of each variable on each factor. The left panel shows the results of all subjects. The right panel shows the results without 3 outliers with very short total locomotion duration. The physical performance parameters include the duration of 3xSTS in self chosen speed, duration of he TUG and the three sub scores of the SPPB. The physical activity parameters include the number of sitting periods, the mean duration of the sitting periods, the total duration of standing, the number of standing periods, the total duration of locomotion and the number of locomotion periods.

All subjects (n=49)	Factor 1	Factor 2
Physical Performance		
3xSTS	-0.187	-0.782
TUG	-0.357	-0.824
SPPB BALANCE	0.465	0.59
SPPB GAIT	0.147	0.846
SPPB 5xSTS	0.438	0.609
Physical Activity		
Sitting periods	0.899	0.27
Sitting mean period duration	-0.875	-0.276
Standing total duration	0.843	0.333
Standing periods	0.925	0.312
Locomotion total duration	0.901	0.277
Locomotion periods	0.908	0.304
% variance explained	48.8	29.6

Without outliers (n=46)	Factor 1	Factor 2
Physical Performance		
3xSTS	-0.131	-0.747
TUG	-0.275	-0.836
SPPB BALANCE	0.439	0.568
SPPB GAIT	0.008	0.864
SPPB 5xSTS	0.456	0.661
Physical Activity		
Sitting periods	0.923	0.164
Sitting mean period duration	-0.877	-0.178
Standing total duration	0.827	0.212
Standing periods	0.93	0.251
Locomotion total duration	0.908	0.212
Locomotion periods	0.912	0.273
% variance explained	59.3	16.8

S2 Table. Rotated component matrix using varimax rotation displaying the factor loadings of each variable on each factor. The left panel shows the results of subjects who did not use walking aids. The right panel shows the results for subjects who did use walking aids. The physical performance parameters include the duration of 3xSTS in self-chosen speed, duration of he TUG and the three sub scores of the SPPB. The physical activity parameters include the number of sitting periods, the mean duration of the sitting periods, the total duration of standing, the number of standing periods, the total duration of locomotion and the number of locomotion periods.

	No walking aids (n=12)	Factor 1	Factor 2
Phys.Performance	3xSTS	0,191	0,818
	TUG	-0,236	0,840
	SPPB BALANCE	0,258	0,320
	SPPB GAIT	0,155	-0,852
	SPPB 5xSTS	0,096	-0,686
Phys. Activity	Sitting periods	0,710	-0,499
	Sitting mean period dur.	-0,769	0,413
	Stading total dur.	0,873	0,094
	Standing periods	0,970	-0,062
	Locomotion total dur.	0,901	0,159
	Locomotion periods	0,934	-0,077
	% variance explained	60%	13%

Factor loading of ≥ 0,3 - < 0,50 highlighted light gray

Factor loading of ≥ 0,5 - < 070 highlighted gray

Factor loading of ≥ 0,7 - < 0,90 highlighted dark gray

	Walking aids (n=34)	Factor 1	Factor 2
Phys.Performance	3xSTS	-0,063	-0,754
	TUG	-0,374	-0,733
	SPPB BALANCE	0,619	0,444
	SPPB GAIT	0,159	0,776
	SPPB 5xSTS	0,346	0,601
Phys. Activity	Sitting periods	0,912	0,168
	Sitting mean period dur.	-0,868	-0,204
	Stading total dur.	0,834	0,278
	Standing periods	0,921	0,285
	Locomotion total dur.	0,894	0,205
	Locomotion periods	0,896	0,270
	% variance explained	45%	26%

Factor loading of ≥ 0,3 - < 0,50 highlighted light gray

Factor loading of ≥ 0,5 - < 070 highlighted gray

Factor loading of ≥ 0,7 - < 0,90 highlighted dark gray

S3 Table. Spearman rank correlations and significance between physical activity measures. Physical activity scores include lying, sitting, standing and locomotion and from these total duration, number of periods, mean duration of periods and movement intensity.

N = 49			PHYSICAL ACTIVITY										
					Sitting			Standing			Locomotion		
			Periods		Total duration	Periods		Total duration	Periods		Total duration		
PHYSICAL ACTIVITY			Number	Mean duration		Number	Mean duration		Number	Mean duration		Number	Mean duration
Lying	Total duration		0.417	-0.075	-0.645	-0.121	-0.082	-0.317	-0.296	0.137	-0.231	-0.276	-0.030
			0.003	0.610	0.000	0.406	0.575	0.026	0.039	0.347	0.110	0.055	0.838
	Periods	Number		-0.913	-0.410	0.277	-0.408	0.079	0.018	0.176	-0.110	-0.018	-0.154
				0.000	0.003	0.054	0.004	0.590	0.903	0.225	0.451	0.903	0.292
		Mean duration			0.240	-0.351	0.416	-0.219	-0.125	-0.121	0.068	-0.073	0.190
					0.097	0.014	0.003	0.130	0.391	0.406	0.640	0.616	0.190
Sitting	Total duration					-0.372	0.614	-0.205	-0.257	0.257	-0.301	-0.279	-0.157
						0.009	0.000	0.158	0.075	0.074	0.035	0.052	0.281
	Periods	Number					-0.936	0.800	0.780	-0.347	0.686	0.764	0.093
							0.000	0.000	0.000	0.015	0.000	0.000	0.523
		Mean duration						-0.742	-0.749	0.386	-0.697	-0.741	-0.170
								0.000	0.000	0.006	0.000	0.000	0.244
Standing	Total duration								0.743	-0.141	0.685	0.761	0.129
									0.000	0.334	0.000	0.000	0.378
	Periods	Number								-0.694	0.888	0.934	0.153
										0.000	0.000	0.000	0.294
		Mean duration									-0.641	-0.619	-0.171
											0.000	0.000	0.240
Locomotion	Total duration											0.869	0.449
												0.000	0.001
	Periods	Number											0.065
													0.657

Correlations of ≥ 0.3 and < 0.5 are highlighted in light grey, correlations of ≥ 0.5 are highlighted in grey

S4 Table. Spearman rank correlations between physical performance measures. Physical performance measures includes 3xSTS, TUG, the three sub-scores and the total score of the SPPB.

	PHYSICAL FUNCTION				
N = 49	TUG	SPPB BALANCE	SPPB GAIT	SPPB 5xSTS	SPPB TOTAL
PHYSICAL FUNCTION					
3xSTS	0.601	-0.385	-0.576	-0.546	-0.604
	0.000	0.006	0.000	0.000	0.000
TUG		-0.669	-0.810	-0.630	-0.843
		0.000	0.000	0.000	0.000
SPPB BALANCE			0.466	0.606	0.866
			0.001	0.000	0.000
SPPB GAIT				0.500	0.765
				0.000	0.000
SPPB 5xSTS					0.833
					0.000

Correlations of ≥ 0.3 and < 0.5 are highlighted in light grey, correlations of ≥ 0.5 are highlighted in grey

4

General discussion and summary

CHAPTER 9
General discussion

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CHAPTER 9

General discussion

GENERAL DISCUSSION

In this final chapter, we draw the balance sheet with regard to each of the aims that we set out to achieve. To this end, we first summarize the main findings that were obtained in each of the three content parts, followed by an evaluation of the degree to which the aim of the research of the part in question was achieved and a discussion of future research directions.

PART I. METHODOLOGICAL ASPECTS

Proper measurement is the cornerstone of both medical research and clinical practice. Although there is a trade-off between the quality of measurement that can be achieved using high-end equipment in the laboratory on the one hand and the affordability and feasibility of the equipment used in clinical practice on the other hand, it remains the case that also the latter type of measurements should be sufficiently accurate, reliable and valid to be of scientific and practical value. The research presented in this thesis was initiated by the introduction of a new automated method for quantifying repeated STS movements, using a single body-fixed sensor system located at the waist housing three accelerometers and three gyroscopes (Chapter 2). The discriminative validity of this instrumentation in quantifying seat-off and seat-on durations was examined in young and older adults, using switches underneath the chair for reference (Chapter 3). With the help of the new method, six features of the trunk movement during seat-off and seat-off were calculated automatically and a model was developed to predict the moments of the seat-off and seat-on transitions, which were subsequently validated using leave-one-out cross-validation. The results indicated that the moments of seat-off and seat-on could be adequately detected semi-automatically in young and older adults using a single body-fixed sensor with an accuracy of 51 and 127 ms, respectively. In a related project, the intra-rater, inter-rater and test-retest reliability of the new method in assessing separate components of the instrumented Timed-Up-and-Go (iTUG) was determined in patients with Parkinson's disease (PD) (Chapter 4). These three types of reliability proved to be excellent-to-good for total duration and turning durations, and good-to-low for the sub-durations and the kinematics of the sit-to-walk and walk-to-sit transitions. Collectively, the results of these studies not only demonstrated the usability, validity and reliability of an instrumented (i.e., single sensor-based) and automated assessment of (repeated) STS and TUG, but also highlighted its potential in identifying more detailed aspects of STS and TUG performances that by definition do not come in the visor of conventional clock-timing methods. Importantly, the ambulatory instrumentation in question proved to be usable not only by scientific researchers but also by non-technically trained personnel, implying that it strikes an adequate balance in the aforementioned trade-off between quality of measurement and clinical applicability.

Although the validity, reliability and accuracy of the single sensor-based instrumentation were found to be adequate from a scientific point of view, they could in principle all be improved by increasing the number and the type of sensor devices used, but this would make the sensor system and its use more complex, at the expense of the applicability of the device in a regular clinical context. Another relevant factor for the quality of measurements is the selected location of the device. In the present thesis, we chose for the lower back because this location is close to the Centre of Mass[1] (CoM), which is likely to better represent whole body movement than other locations [1] and to minimally distract the wearer's attention. However, as far as we know, these aspects have not been investigated and there are no studies that we are aware of in which different sensor locations are compared in terms of measurement accuracy and reliability. It has been shown, however, that gait characteristics are robust against limited repositioning of the sensors in the vertical direction, between L3 and L5, whereas repositioning around the waist should be avoided [2]. It can be expected that inaccuracy of sensor placement around the trunk might influence kinematic parameters (such as angular range and angular velocity) more than displacement in the vertical direction. Future studies are needed to determine the optimal placement of the sensor system and to evaluate the appropriateness of (the assumptions for) the lower back as the presently preferred location. In optimizing the boundary conditions for measuring with a single body-fixed sensor system, it is also important that the integration drift of the gyroscope is handled in an appropriate manner, which is easier to achieve when it is ensured that the sensor is in the same position at the start and at the end of the measurement. For the repeated STS it is therefore recommended that the measurement starts and ends with a sitting position.

During the past decades, sensors have seen a rapid development internationally, driven by technological innovations in the military and the automotive industry, from which the measurement and analysis of human movement has benefitted as a spin-off. Particularly the combination of accelerometers and gyroscopes has been important for the study of human movement, because this combination allows for accurate measurement of the orientation of segments of the human body with one or more inertial measurement units [3]. As a result of this development, we have now reached a point at which, in principle, all existing physical performance tests with demonstrated clinical value can be instrumented in such a manner that they can be automatically (or at least semi-automatically) recorded and analyzed. One may even go a step further and attempt to develop an arsenal of supervised performance tests that include all basic types of physical activity, including different ways of displacement e.g., horizontal and vertical) and rotation (e.g., turning), which might thus allow in the future for an integral assessment of a person's physical performance status. Turning this prospect into reality requires the further refinement of pertinent measurement instruments, the identification of optimal boundary conditions for measurement, including the starting and ending positions of the physical activities in question, and the processing and reduction of sensor outputs in outcome measures that are clinically interpretable and meaningful. It may very well be that in order to increase the latter aspect physiological measurements will have to be added to the ambulant registration of forces and motions. Patently, this perspective implies a much more encompassing and far-reaching program of research and innovation than presented in this thesis, which should be first and foremost seen as a demonstration of what is currently possible and as an indication of what will be possible in the future, rather than the final station of a past development.

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[1] The center of mass is the point where all of the mass of the object is concentrated.

PART II. CLINICAL VALUE

After having established the feasibility of the developed methodology, its clinical relevance was examined in three studies comprising the second part of the thesis. In the first of these, reported in Chapter 5, it was found that the durations of STS sub-phases have stronger associations with health status (as determined with the European Quality of Life questionnaire), functional status (as determined with the RAND-36) and daily physical activity (as determined with an activity monitor) in 63 older adults than manually recorded test durations. Whereas the manually recorded STS times were neither significantly associated with health status nor with functional status (although almost), the instrumented STS times were significantly associated with both. Furthermore, the manually recorded STS durations only showed a significant association with daily physical activity for mean sitting durations, not for mean standing durations and mean number of locomotion periods. Finally, the durations of the dynamic sit-to-stand phase of the instrumented STS showed more significant associations with health status, functional status and daily physical activity than the static phases standing and sitting.

These findings suggest that the instrumented STS provides a more sensitive, more valid and more informative method than the manually recorded STS; more sensitive and valid because its scores proved to be more strongly associated with health status, functional status and physical activity, and more informative because it allowed assessment of the dynamic phases of the STS test, which turned out to be more strongly associated with health status, functional status and physical activity than the static phases of sitting and standing. It is therefore fair to conclude that the instrumented STS has greater clinical value than the manually recorded STS. This conclusion is consistent with the conclusion of a limited number of previous studies addressing the clinical value of instrumented STS. Notably, Millor et al. concluded that instrumented STS might allow early frailty detection in the clinic, which in turn would allow prescription of subsequent interventions to correct for observed disabilities and limitations before further degradation occurs [4]. In a similar spirit, Regterschot et al. demonstrated that sensor-based measurements of peak power, maximal velocity and duration of the STS movement showed a higher sensitivity to the effects of training leg strength, leg power and balance than standard clinical measures [5]. However, longitudinal studies examining the added value of sensor-based measurements with regard to clinically important outcomes, such as mortality, hospitalization, functional decline, including increasing lower limb dysfunction, are still lacking. Such studies are essential to conduct since they will lead to a broader perspective on the added clinical value of sensor-based movement assessments, i.e. also in terms of the prediction of interventions and long-term predictions, than (could be) provided in the current work and previous studies.

The study reported in Chapter 6 showed that kinematic features of repeated STS are associated with handgrip strength in older adults, suggesting that trunk use becomes more dynamic as muscle strength declines. Twenty-seven healthy older adults participated in this cross-sectional study. Handgrip strength was assessed using a dynamometer and subjects were asked to stand up from three heights of a height adjustable chair at their preferred speed. Trunk movements were measured using an inertial sensor system fixed with an elastic belt around the waist. Durations, angular range and maximum angular velocity of STS phases, as well as the vertical velocity of the extension phase, were calculated based on the raw signals from this system. Backwards elimination using GEE was used to identify which covariate best predicted the kinematics. Older adults with weaker handgrip strength employed a different strategy to stand up from a sitting position making more dynamic use of the trunk during the extension phase. In a previous study of the relative contributions of the trunk and the lower body to the STS movement, Riley et al. [6] noted that: "As the trunk is more massive than the thigh, the upper body must contribute more than the CoM vertical momentum than the thigh" (p. 84). We found that this effect is stronger for older adults with less muscle force. In the context of the aims of the present thesis, the relevance of this study resides in the demonstration that differences in trunk strategy during the STS movement can be efficiently and objectively measured using instrumented STS with automated data analysis, which makes its application in clinical environments both feasible and meaningful.

Finally, in Chapter 7 a new method was developed for scoring STS performance in older adults – a population at risk of losing the capability to stand up from sitting – using the output signals of a single body-fixed sensor. In this cross-sectional study, 79 participants performed multiple STS movements, which were automatically recorded and analyzed. Sub-phase durations, kinematics and their variances were calculated and submitted to an exploratory factor analysis, which revealed that the 24 variables that were entered in the analysis could be described by seven factors, which could be given a meaningful interpretation in terms of temporal and spatial aspects of the movement. Based on the normalized component scores were calculated and the variance they explained, normalized overall scores characterizing the STS performance of an individual participant on an interval scale ranging from 0 to 100. The thus derived scoring method is deemed to have clinically practical value, because it captures STS performance in a single measure, which can be readily compared with reference data of relevant populations, and because the normalized component scores (at least in principle) provide the possibility of evaluating a given STS performance in its functional details, which might lead to clinically relevant insights.

Although the clinical value of the new STS score still needs to be demonstrated, it holds the promise of culminating into a clinically useful approach. However, for this to occur, several essential steps should be taken in future studies and implementation trajectories. First of all, the results of the present study need to be replicated in a study involving more participants, so as to determine their robustness. Additional outcome variables might be taken into account in this context, which might help to further optimize the extracted components and thus the final overall score. It is also important to examine the factor structure in different populations (e.g., young versus older adults, or populations with movement disorders). Once the scoring method has been optimized, and its robustness and validity have been demonstrated, an attempt can usefully be made to implement it in clinical practice, which requires, amongst others, the participation of clinicians who recognize the (potential) practical value of the instrument and see merit in sharing the new score with their colleagues. In addition, effective implementation will critically depend on the availability of reference data for relevant clinical populations, as well as clear guidelines for interpreting the overall and component scores.

PART III. ASSOCIATION PHYSICAL PERFORMANCE – PHYSICAL ACTIVITY

The study presented in this third part of the thesis focused not so much on the merits of automated assessment of STS performance but rather on the relationship between physical performance, operationalized as (clock-timed) STS performance, and physical activity. It was found that better STS performance is associated with shorter sitting durations and more frequent break-ups between sitting episodes, both of which are prerequisites for an active, independent lifestyle, indicating that a relation exists between physical performance and physical activity (Chapter 8). At the same time, however, the primary hypothesis was corroborated that physical performance and physical activity constitute separate domains of physical function, as was the secondary hypothesis that different classes of physical activity (e.g. walking or sitting) provide more information in this regard than overall physical activity like counts of PAL.

These findings are important for both theoretical and practical reasons, because they reveal that physical performance measures (i.e., “what you can do”) should not be equated with physical activity measures (i.e., “what you actually do”). Theoretically, this implies that the factors underlying physical performance only partly overlap with the factors underlying physical activity, implying that the variation seen in physical activity should be accounted for in part by factors unrelated to the variation seen in physical performance, which raises question what these factors are. This question is theoretically relevant because answering it will provide insight into the factors that play a role in physical activity independent of physical performance. This issue is also practically relevant. After all, the aim of most clinical interventions is to enhance physical performance, like the capacity to transfer from sitting to standing, based on the assumption that this will lead to increased physical activity in daily life. However, it follows from the results presented in this part of the thesis that this assumption might not be justified, at least not in the categorical, unproblematized form in which it usually appears. Recognizing that physical performance and physical activity constitute separate domains of physical function, and gaining insight into why this is so, may help to refine intervention methods in which both aspects are addressed in parallel with the aim to induce beneficial changes in both.

As is already apparent from this discussion, there is a definite need to better understand what people can do and what people actually do, not only at a group level, but also at an individual level because relevant factors are likely to have different weightings in different individuals. Gaining insights into these factors and weightings will help to personalize interventions aimed at improving physical performance and physical activity. One of the factors that may play a prominent role in this context is what people think they are capable of doing and what they do, because such convictions might deviate considerably from what they really can do and do. Such deviations may become particularly prominent in older adults when they are confronted with a decline in physical function and a social context in which this decline may be de- or overemphasized. In light of these considerations, it is also important in future research to develop, and subsequently refine and test, a conceptual framework for physical functioning in which individually reported outcomes and objective outcomes are both taken into account.

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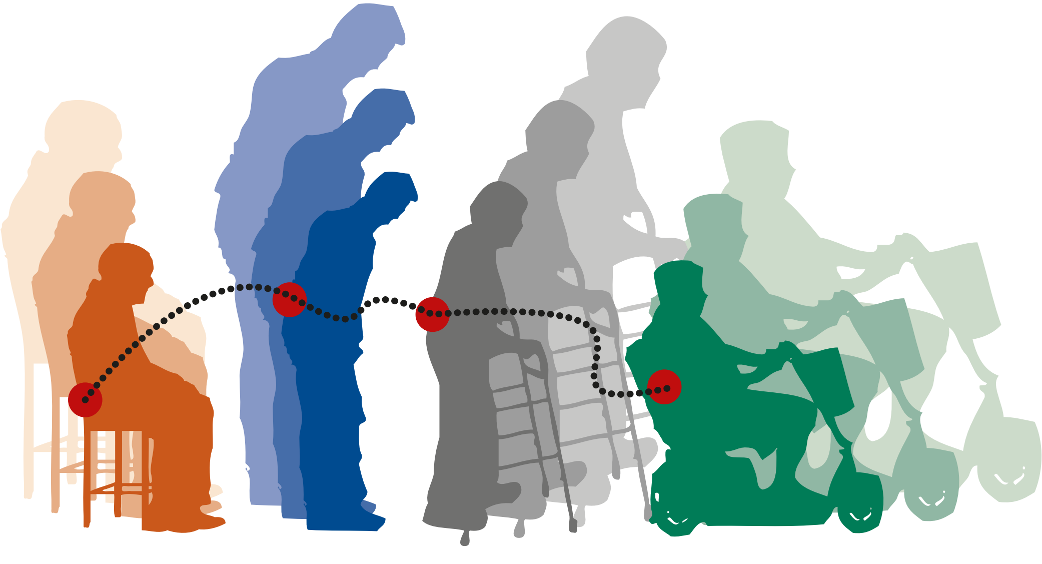

Illustration: *Financieel Dagblad*

4

General discussion and summary

CHAPTER 10

Summary / Samenvatting

SUMMARY

Growing life expectancy is one of the blessings of modern healthcare, but is associated with a gradual loss of mobility, which may lead to a loss of independence in everyday life. As argued in the Introduction (Chapter 1), a prerequisite for independent mobility is the ability to stand up from a seated position, which is therefore used in the clinic as an index of motor functioning. Hence, the Sit-to-Stand (STS) transition formed the main focus of the investigations reported in this thesis. In particular, the main aims of these investigations were threefold: (1) to develop a clinically applicable method to measure and analyze sit-to-stand movements, (2) to demonstrate and explore the clinical relevance of this method, and (3) to analyze associations between physical performance and daily-life physical activity. These main aims were addressed in the three content parts (Part I-III) of the thesis.

The work in Part I started with the introduction of a new automated method for quantifying the repeated STS movements using a single body-fixed sensor located at the waist (Chapter 2), the instrumented STS or iSTS. The validity of this method in quantifying the seat-off and seat-on durations of STS movements was established in young and older adults, using switches underneath the chair for reference (Chapter 3). In a related side project, the intra-rater, inter-rater and test-retest reliability of the instrumented Timed-Up-and-Go (iTUG) were determined in patients with Parkinson's disease (PD) (Chapter 4). Collectively, these results demonstrated the usability, validity and reliability of instrumented (i.e., single sensor-based) and automated assessments of (repeated) STS and TUG.

After having established the feasibility of the developed methodology, its clinical relevance was examined in Part II. In Chapter 5 it was found that the durations of repeated iSTS sub-phases have stronger associations with health status, functional status and daily physical activity in older adults than manually recorded test durations. Subsequently, it was shown in Chapter 6 that kinematic features of repeated iSTS are associated with handgrip strength in older adults, suggesting that trunk use becomes more dynamic with low muscle strength. Finally, in Chapter 7 a new method was developed for scoring STS performance in older adults in a clinical context. These results highlighted the potential of iSTS for clinical use.

The study in Part III focused on the relationship between physical performance (PP) and physical activity (PA). It was found that better STS performance is associated with shorter sitting durations and more frequent break-ups between sitting episodes, both of which are characteristics of an active, independent lifestyle (Chapter 8). Nevertheless, it was found that PP and PA constitute separate domains of physical function, with PA classes providing more information than overall PA. This finding has both theoretical and practical relevance since it underscores that "what you can do" should not be equated with "what you do do".

SAMENVATTING

De stijging van de levensverwachting is één van de zegeningen van de moderne gezondheidszorg. Echter, dit gaat gepaard met een geleidelijk verlies aan mobiliteit; dit kan uiteindelijk leiden tot een verlies aan onafhankelijkheid. Het vermogen om op te staan vanuit een zittende positie is hierin een belangrijke vaardigheid en wordt daarom in de kliniek gebruikt als een index voor motorisch bewegen. In dit proefschrift ligt de focus van het onderzoek op deze 'Sit-to-Stand' (STS) beweging. De belangrijkste doelen van de verschillende onderzoeken in dit proefschrift zijn: (1) het ontwikkelen van een klinisch toepasbare methode om Sit-to-Stand bewegingen te meten en te analyseren, (2) de klinische relevantie van deze methode te laten zien en ontwikkelen, (3) het analyseren van de onderlinge samenhang tussen fysieke vaardigheid testen en fysieke activiteit in het dagelijks leven. Deze drie doelen die uiteengezet worden in de Introductie (Hoofdstuk 1), zijn terug te vinden in de drie delen (Deel I-lll) van dit proefschrift.

Deel I begint met de introductie van een nieuwe, geautomatiseerde methode om met één sensor op de onderrug de herhaalde STS beweging te kwantificeren (Hoofdstuk 2), de geïnstrumenteerde STS of iSTS. De validiteit van deze methode om de 'seat-off' en 'seat-on' tijdsduur van de STS bewegingen te kwantificeren is uitgevoerd bij jonge en oudere volwassenen, met gebruik van schakelaars onder de stoel. (Hoofdstuk 3). In een andere studie werd de intra-rater, inter-rater en test-hertest betrouwbaarheid van de geïnstrumenteerde 'Timed-Up-and-Go' (iTUG) bevestigd. Deze test werd uitgevoerd bij patiënten met de ziekte van Parkinson (Hoofdstuk 4). Gezamenlijk laten deze resultaten de bruikbaarheid, validiteit en betrouwbaarheid zien van een met één enkele sensor geïnstrumenteerde (i) en geautomatiseerde (herhaalde) STS en TUG.

Nadat de haalbaarheid van de ontwikkelde methodologie was vastgesteld, kon in Deel II de klinische relevantie onderzocht worden. In hoofdstuk 5 vonden we dat de duur van sub-fases binnen de herhaalde iSTS sterker samenhangt met de status van gezondheid, status van functioneren en dagelijkse fysieke activiteit van oudere volwassenen dan alleen de handmatig geklokte duur van de tests. Bovendien blijkt dat de kinematica van de herhaalde iSTS samenhangt met handknijpkracht van oudere volwassenen.(Hoofdstuk 6). Dit kan een aanwijzing zijn dat bij vermindering van spierkracht de romp meer dynamisch ingezet wordt. In hoofdstuk 7 wordt een nieuwe methode ontwikkeld om de STS beweging van ouderen een score te geven. Deze score kan mogelijk bruikbaar zijn voor toekomstig klinisch onderzoek. Bovendien brengen de beschreven resultaten de potentiële relevantie van de iSTS in de dagelijkse klinische praktijk onder de aandacht.

Deel III beschrijft de relatie tussen fysieke capaciteit (Physical Performance, PP) en fysieke activiteit (Physical Activity, PA). We vonden dat fysieke capaciteit samenhangt met kortere zit periodes en het vaker onderbreken van zitten, beiden voorwaarden voor een actieve en onafhankelijke leefstijl (Hoofdstuk 8). Desondanks blijkt dat PP en PA bestaan uit verschillende domeinen van fysieke functie. Deze ontdekking heeft zowel theoretische als praktische relevantie omdat het de stelling onderstreept: “wat je kan” staat niet zonder meer gelijk aan “wat je doet”.

Appendices

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CHAPTER 12
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ACKNOWLEDGEMENTS

In this acknowledgment I would like to chronicle the development of this thesis and in so doing thank all the people who helped me with it.

In the autumn of 2010 Professor Peter Beek called me to ask if I would be interested in pursuing a doctorate. My answer was: "Yes I surely would, but it would be impossible to combine this with leading McRoberts'. However, a year later Corinne and I nevertheless decided to go and see Peter and Professor Jaap van Dieën. We agreed that we would await the publication of two articles. I wanted to avoid disruption in the McRoberts team and also to make sure that the doctorate would be in the interest of the company.

SensAction-AAL

The development of an instrumented version of the sit-to-stand started with a "Sit-to-Stand (STS) analysis plan that I presented during a SensAction-AAL meeting in Tel Aviv early 2009. This was an EU supported FP6 project in the programme Ambient Assisted Living (AAL) in the Ageing Society[1] . For this reason I would like to thank Dr. Wiebren Zijlstra, Dr. Uli Lindemann, Dr. Lorenzo Chiari and Professor Jeff Hausdorff as the last author; they were involved in this project and helped me with the 1st publication. I also would like to mention here Bas Pijls who was working at McRoberts at that time; he is the architect of the MoveTest concept of which the STS is a part. He came up with the idea of developing a software shell for the different tests, using a remote control. This idea was very innovative and it has proved to be very practical. At the same time, I thank Erik Ainsworth for the development of the then unique analysis software that laid the foundation for the signal analysis of the STS.

Duinhage Moves!

My thanks go to my friend Paul van Campen, who at the time worked as a physical therapist at the nursing home Duinhage in The Hague. With him we started 'Duinhage Moves!'[2] . It was here that the data was collected for the first study. All the names mentioned above can be found alongside the co-authors of the first article about the instrumented STS (Part 1: chapter 2).

Tubingen CIN

In 2009 Professor Walter Maetzler invited us to participate in an application to the Centre for Integrative Neuroscience (CIN) in Tübingen. The goal was to further develop the instrumented Timed Up and Go (TUG) test for patients with Parkinson's disease. Central to this was the investigation of the reproducibility of the TUG test results. I would like to thank Dr. Caroline Terwee (EMGO) for her support and the design of the protocol. This has led to the third article (Part 1: chapter 4). I thank Walter for his friendship, patience and consistently positive attitude.

Fall Risk Assessment in Older Adults (FARAO)

Late 2009 the grant for the TOP project 'New Instruments Healthcare' was approved:

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[1] http://cordis.europa.eu/project/rcn/80559_en.html

[2] http://www.duinhagebeweegt.nl/Welkom.html

"Fall risk prediction based on accelerometry obtained during daily life activities[3]". To improve the method our measuring instruments were added to analyze the stability of the walking during their daily lives. Due to this project the collaboration with the faculty of human movement sciences intensified. We are very grateful to Professor Mirjam Pijnappels who led the project, Professor Jaap van Dieën as the PI responsible, Dr. Petra Elders involved as a physician researcher and the two PhD graduates Dr. Kim van Schooten and Dr. Sietse Rispens for this inspiring joint project. In FARAO was shown for the first time that measurements of physical activity in daily life resulted in improvement of the prediction of fall risk.

Torendael Moves!

At the same time McRoberts successfully applied for a subsidy from the innovation fund of health insurer Agis. This project was designed to support FARAO. We developed a motion intervention aimed at the residents of a nursing home and the surrounding neighbourhood. In 'Torendael Moves'[4] both the 'physical performance' (what are you able to do) and 'physical activity' (what do you do) were measured for seven successive intervention groups (2010-2012). I thank the staff of Torendael, especially Janneke Tiebie, Swantien Dijkstra and Clemens Beenakker. During this study Martijn Niessen, who had just completed a PhD in human movement sciences joined McRoberts. He has played an important role in the data collection in Torendael and supported the doctoral research within the company.

International Congress on Ambulatory Monitoring of Physical Activity and Movement

The second article (Part 1: chapter 3) was preceded by an abstract which was submitted to the ICAMPAM in Glasgow (2011), the World Congress on ambulatory monitoring of physical activity and movement. The journal Physiological Measurement was dedicating a 'special' to this conference and I was selected to participate. From that moment Jaap van Dieën supported my publications and he became my ongoing help and support.

Factor analysis

The data we collected led to an article in which we examined the relationship between physical function and physical activity (Part III: chapter 8). This was the first time that on the advice of Jaap van Dieën we used factor analysis. Stefan Walgaard started at McRoberts as a student of movement technology and he stayed with us during and after his subsequent study of human movement sciences. He developed into a highly skilled data analyst and thus made an important contribution to McRoberts as well as to this doctorate. I would also like to thank Dr. Judith Garcia-Aymerich. I discussed this article with her at an early stage in Barcelona; as co-author she has delivered a significant, positive and stimulating contribution.

Florence

In the course of FARAO we also asked a large healthcare institution in The Hague (Florence) to join us. In the second article about the clinical value of the instrumented STS, the data from Torendael and Florence are combined to demonstrate the added value of instrumentation (Part II: HTST 5). I would like to thank Florence for

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[3] https://www.zonmw.nl/nl/onderzoek-resultaten/fundamenteel-onderzoek/programmas/project-detail/top-subsidies/a-novel-instrument-to-support-fall-prevention-in-extramural-care/

[4] http://torendaelbeweegt.nl/

this cooperation. In this article, Professor Andrea Maier also played an important role. She was appointed professor at the VU University Medical Centre and is an important partner for us. I am grateful to her for her friendship as well as for the inspiring cooperation and assistance with the article about the added value of instrumentation to STS.

Duinhage, Torendael and Florence
On the basis of the STS data, collected at the three locations, we have developed a new scoring method . Here we have used factor analysis to identify underlying factors of the large amount of data and convert these into individual scores (Part II chapter 7). In this analysis Stefan Walgaard also played an important role.

Participants
The average age of our participants in the various projects was above 84 years. We look back at them with great fondness and many of them I can remember well. Although they will not read this, I would like it to be known that it was a pleasure to work with them. Their enthusiasm and the sometimes surprisingly fanatical way they joined in, was inspiring. Many elderly people are well aware of the importance of improving their condition, they enjoy it and succeed. A quote during the distribution of the SPPB report: "Yes, another point gained".

Gait Lab VU
In the gait Lab of human movement sciences we have collected data to analyse the stabilisation phase of the STS. This was the sequel to the graduation of Jordi Evers who had come to work at McRoberts in 2010. This study provided a new insight into the relationship between grip strength and STS strategy (Part II: chapter 6). I would like to thank Jordi for his support of the analysis and his interest in scientific research in which he is a very pleasant and competent sparring partner.

Movement Technology
The faculty for movement technology in The Hague was founded in 1990. From the start, every year there have been several students with internships and graduation projects associated with McRoberts and many have found a job with us. I would like to thank the faculty and the students for this cooperation. The faculty movement technology was co-founded by my friend Chris Riezebos. Throughout the PhD period, he was able to follow the process almost on a weekly basis. We found each other in our interest to use objective measurement systems for clinical practice and thus give biomechanics a greater place in practical work. Chris, thank you for listening, your infinite knowledge and your positive support.

Reviewers
The management of the publishing process is an important period of learning. After sending a paper to a journal, one always has to wait and see what reaction you are going to get. Will it be rejected? Will the review process start wherein experts give their critical comments? The feedback can lead to a positive experience, but can sometimes evoke mixed feelings. Jaap recommends putting the text aside for a while and reviewing the comments. That works well and always leads to improvement of the manuscript. I would also like to thank the many reviewers, who are usually anonymous, for their knowledge, energy and time spent on the articles in this thesis.

Thesis committee
Professor Christophe Delecluse, Professor Andrea Maier, Professor Pauline Meurs, Professor Riekie de Vet and Professor Wiebren Zijlstra, all members of the thesis committee, I would like to thank you for your willingness to look critically at the dissertation and to ask questions during the defense of the thesis.

Finally
The doctoral process has many periods of waiting, for example, for comments from co-authors or reviewers, or additional analysis. But Jaap was always fast with his reaction to keep the momentum going. Jaap adjusted, came up with new ideas and was not afraid to help with the analysis. It was also fantastic that Peter with his very busy job, always managed to find time to attend the biannual meetings and to provide expert commentary to every text. Your input to the discussion was of great importance. While we were working on the summary and discussion Peter showed me that I should spend more time on formulating. That has impressed me. Peter and Jaap: I have learned a lot from you!

It is the mission of McRoberts to try to deliver a contribution to healthy and active ageing through the development of measurement systems that support the diagnostics of physical function. I greatly appreciate that the faculty have been willing to respect the importance of our mission. I believe that during the course of this PhD programme you have increasingly seen the benefits of this new method of analysis which opens new avenues to applied research in order to improve clinical practice. Recognised by Peter, supported by Jaap and lovingly and with humour endured by Corinne, my interest in scientific research was confirmed and enforced during the work on this PhD. The combination of entrepreneur and researcher has brought many good things to me personally but also to McRoberts!

Dear supporters
Annie, Diek, Jeanne, John, Ruth and Geertje, thank you for posing for this book! Steven, thanks for your help in the production of the thesis, making the cover and help at the party! Steven and Dominique turned this book into a piece of art! Thanks also to Bart, Dieuwke and Henk who helped me with the English text. Pauline gave advice on the introduction and in doing so she improved the coherence of the book.

Corinne, Janneke and Steven, Steven and Luca, Maarten, Coen, Ties, Ize, all McRoberians, Geeta, family and friends: thanks to all of you for the many years of sympathy for an elderly PhD student.

Corinne, Corinne, what would I do without you!

DANKWOORD

In dit dankwoord wil ik gebaseerd op de chronologie van dit proefschrift alle mensen bedanken die me hebben geholpen.

In het najaar van 2010 belde professor Peter Beek me op met de vraag of ik niet geïnteresseerd was om te promoveren. Mijn antwoord was: "ja dat ben ik zeker, maar ik kan het onmogelijk combineren met het leiden van McRoberts". Een jaar later zijn Corinne en ik toch een keer gaan praten met Peter en professor Jaap van Dieën. We spraken af dat we verder zouden zien na publicatie van twee artikelen. Ik wilde onrust vermijden in het McRoberts team en er zeker van zijn dat de promotie ook in het belang van het bedrijf zou zijn.

SensAction-AAL

De ontwikkeling van een geïnstrumenteerde versie van de sit-to-stand is begonnen met een 'Sit-to-Stand (STS) analyse plan' dat ik presenteerde tijdens een SensAction-AAL bijeenkomst in Tel-Aviv begin 2009. Dit was een Europees ondersteund FP6 project in het programma Ambient Assisted Living (AAL) in the Ageing Society[1]. Mijn dank gaat uit naar professor Wiebren Zijlstra, Dr. Uli Lindemann, Dr. Lorenzo Chiari en professor Jeff Hausdorff als laatste auteur; zij waren betrokken bij dit project en hielpen mij bij de 1e publicatie. Ook wil ik hier Bas Pijls noemen, toen bij McRoberts werkzaam en de architect van het MoveTest concept waar de STS deel van uitmaakt. Hij bedacht dat het handig was om voor de verschillende testen een software schil te ontwikkelen, bestuurd met een afstandsbediening. Zoiets was vernieuwend en is zeer praktisch gebleken. Erik Ainsworth bedank ik voor het ontwikkelen van de toen unieke analyse software die het fundament legde voor de signaalanalyse van de STS.

Duinhage beweegt!

Mijn dank gaat uit naar mijn vriend Paul van Campen die destijds als fysiotherapeut werkte in het verzorgingshuis Duinhage in Den Haag. Met hem zijn we 'Duinhage Beweegt!' gestart[2]. Hier zijn de data voor de eerste studie verzameld. Al de bovenstaande namen vindt u terug bij de coauteurs van het eerste artikel over de geïnstrumenteerde STS (Deel 1: hfst 2).

Tübingen CIN

In 2009 nodigde professor Walter Maetzler ons uit om mee te doen met een aanvraag bij het Centre for Integrative Neuroscience (CIN) in Tübingen. Het doel was om de geïnstrumenteerde Timed Up and Go (TUG) test verder te ontwikkelen voor patiënten met de ziekte van Parkinson. Centraal hierin stond het onderzoek naar de reproduceerbaarheid van de TUG test resultaten. Ik wil Dr. Caroline Terwee (EMGO) bedanken voor haar ondersteuning en het ontwerp van het protocol. Dit heeft geleid tot het derde artikel (Deel 1: hfst 4). Ik bedank Walter voor zijn vriendschap, geduld en altijd positieve instelling.

FAll Risk Assessment in Older Adults (FARAO)

Eind 2009 werd het TOP project Nieuwe Instrumenten Gezondheidszorg subsidie goedgekeurd: "Fall risk prediction based on accelerometry obtained during daily

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[1] http://cordis.europa.eu/project/rcn/80559_en.html

[2] http://www.duinhagebeweegt.nl/Welkom.html

life activities[3]". Om de methode te verbeteren werden onze meetinstrumenten toegevoegd om de stabiliteit van het lopen tijdens het dagelijks leven te meten. Door dit FARAO project intensiveerde de samenwerking met de faculteit bewegingswetenschappen. Ik ben professor Mirjam Pijnappels die het project leidde, professor Jaap van Dieën als verantwoordelijke PI, Dr. Petra Elders verbonden als arts onderzoeker en de twee promovendi Dr. Kim van Schooten en Dr. Sietse Rispens zeer dankbaar voor dit inspirerende gezamenlijke project. In FARAO werd voor het eerst aangetoond dat metingen van fysieke activiteit in het dagelijks leven tot een verbetering leiden van het voorspellen van valrisico.

Torendael Beweegt!

Gelijktijdig vroeg McRoberts met succes een subsidie aan bij het innovatiefonds van zorgverzekeraar Agis. Dit project was opgezet om FARAO te ondersteunen. Er werd door ons een beweeginterventie ontwikkeld gericht op de bewoners van een verzorgingshuis en de omliggende wijk. In 'Torendael Beweegt!'[4] werd zowel de 'physical performance' (wat kan je) als de 'physical activity' (wat doe je) gemeten bij 7 achtereenvolgende interventiegroepen (2010-2012). Ik bedank de medewerkers van Torendael, in het bijzonder Janneke Tiebie, Swantien Dijkstra en Clemens Beenakker. Tijdens deze studie kwam Martijn Niessen, die net was gepromoveerd bij bewegingswetenschappen, bij McRoberts werken. Hij heeft een belangrijke rol gespeeld in de data verzameling in Torendael en is vanaf dat moment het promotie proces gaan ondersteunen.

International Congress on Ambulatory Monitoring of Physical Activity and Movement

Aan het tweede artikel (Deel 1: hfst 3) ging een abstract vooraf dat ingestuurd was naar de ICAMPAM in Glasgow (2011), het wereldcongres over ambulante monitoring van fysieke activiteiten en beweging. Het blad Physiological Measurement ging een 'special' aan dit congres wijden en ik werd geselecteerd om mee te doen. Vanaf dat moment ging Jaap van Dieën mijn publicaties ondersteunen en werd hij mijn steun en toeverlaat.

Factor analyse

De data die we in Torendael verzamelden leidde tot een artikel waarin we de samenhang tussen fysieke functie en fysieke activiteit gingen onderzoeken (deel III: hfst 8). Dit was de eerste keer dat we op advies van Jaap van Dieën factor analyse gebruikten. Stefan Walgaard begon als student bewegingstechnologie bij McRoberts en bleef ook tijdens en na zijn vervolgstudie bewegingswetenschappen bij ons werken. Hij ontwikkelde zich tot een zeer bedreven data analist en heeft daarmee een belangrijke bijdrage geleverd aan McRoberts en aan deze promotie. Ik wil ook graag Dr. Judith Garcia-Aymerich bedanken. Met haar besprak ik in een vroege fase dit artikel in Barcelona; zij heeft als coauteur een belangrijke, positieve en stimulerende bijdrage geleverd.

Florence

In de loop van FARAO hebben we ook een grote zorginstelling in Den Haag (Florence) gevraagd mee te doen. In het tweede artikel over de klinische waarde van

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[3] https://www.zonmw.nl/nl/onderzoek-resultaten/fundamenteel-onderzoek/programmas/project-detail/top-subsidies/a-novel-instrument-to-support-fall-prevention-in-extramural-care/

[4] http://torendaelbeweegt.nl/

de geïnstrumenteerde STS zijn de data van Torendael en Florence samengevoegd om de meerwaarde van instrumentatie aan te tonen (Deel II: htst 5). Ik wil Florence bedanken voor deze samenwerking. In dit artikel speelde ook professor Andrea Maier een belangrijke rol. Zij werd tot hoogleraar ouderengeneeskunde in het VUmc benoemd en is voor ons een belangrijke partner. Ik ben haar, naast de vriendschap, dankbaar voor de inspirerende samenwerking en hulp bij het artikel over de toegevoegde waarde van instrumentatie aan de STS.

Duinhage, Torendael en Florence
Op basis van de STS data, verzameld op de 3 locaties, hebben we een nieuwe methode ontwikkeld om individuele scores uit te rekenen. Hierbij hebben we factor analyse gebruikt om uit de grote hoeveelheid data onderliggende factoren te identificeren en deze om te zetten naar individuele scores (Deel II: hfst 7). Ook bij deze analyse speelde Stefan Walgaard een belangrijke rol.

Deelnemers aan de studies
De gemiddelde leeftijd van onze deelnemers aan de verschillende projecten was ruim 84 jaar. We denken met veel plezier aan hen terug en velen kan ik me goed herinneren. Hoewel zij dit niet zullen lezen wil ik toch laten weten dat het fijn was om met hen te werken. Hun enthousiasme en soms verrassend fanatiek meedoen was hoopgevend. Veel oudere mensen zijn zich bewust van het belang van het verbeteren van hun conditie, hebben er plezier in en slagen daar in. Quote tijdens het uitdelen van de SPPB rapportage: "Yes, punt erbij!".

Loopzaal VU
In de loopzaal van bewegingswetenschappen hebben we data verzameld voor het analyseren van de stabiliseringsfase van de STS. Dit was het vervolg op het afstudeerproject van Jordi Evers die vanaf 2010 bij McRoberts was komen werken. Dit onderzoek leverde een nieuw inzicht op in de samenhang tussen handknijpkracht en STS strategie (Deel II: hfst 6). Ik wil Jordi bedanken voor zijn ondersteuning van de analyses en zijn interesse in wetenschappelijk onderzoek waarbij hij een zeer prettige en deskundige sparringpartner is.

Bewegingstechnologie
De opleiding bewegingstechnologie in Den Haag is opgericht in 1990. Vanaf het begin zijn er elk jaar meerdere studenten door stage en afstudeerprojecten verbonden geweest aan McRoberts en velen vonden een baan bij ons. Ik wil de opleiding en de studenten bedanken voor deze samenwerking. De opleiding bewegingstechnologie werd mede opgericht door mijn vriend Chris Riezebos. Hij heeft tijdens de hele promotieperiode vrijwel wekelijks het proces kunnen volgen en we vonden elkaar in onze interesse om objectieve meetsystemen te gebruiken voor de klinische praktijk en op die manier de biomechanica een grotere plek te geven in het praktische werk. Chris, dank je wel voor je luisterend oor, je oneindige kennis en je positieve ondersteuning.

Reviewers
Het managen van het publicatieproces is een belangrijk leermoment. Na het sturen van een paper naar een tijdschrift is het altijd afwachten hoe er wordt gereageerd. Wordt het afgewezen? Wordt het review proces gestart waarbij deskundigen hun kritisch commentaar geven? De feedback kan leiden tot een positieve ervaring, maar kan soms ook gemengde gevoelens oproepen. Jaap adviseerde om de tekst dan even weg te leggen en opnieuw de commentaren door te nemen. Dat werkte

goed en leidde altijd tot verbetering van het manuscript. Ik wil alle reviewers, die meestal anoniem zijn, dan ook hartelijk danken voor hun kennis, energie en tijd besteed aan de artikelen in dit proefschrift.

Leescommissie
Professor Christophe Delecluse, professor Andrea Maier, professor Pauline Meurs, professor Riekie de Vet en professor Wiebren Zijlstra, ik wil jullie als leden van de leescommissie bedanken voor de bereidheid om kritisch naar het proefschrift te kijken en te opponeren tijdens de promotie.

Tot slot
Het promotieproces kent veel periodes van wachten, bijvoorbeeld op commentaar van coauteurs of van reviewers, of op aanvullende analyses. Maar Jaap was altijd supersnel met zijn reactie en hield zo de vaart erin. Jaap stuurde bij, kwam met nieuwe ideeën en schuwde niet om ook mee te helpen met de analyses. Het was ook fantastisch dat Peter met zijn zeer drukke baan steeds tijd wist te vinden om de halfjaarlijkse besprekingen bij te wonen en alle teksten van deskundig commentaar te voorzien. Zijn inbreng in de discussie was van groot belang. Peter liet me tijdens het werken aan de samenvatting en de discussie zien hoe belangrijk het is de inhoud nauwkeurig onder woorden te brengen. Dat heeft indruk op me gemaakt. Peter en Jaap: ik heb heel veel van jullie geleerd!

Het is de missie van McRoberts om te proberen een bijdrage te leveren aan gezond en vitaal oud worden door meetsystemen te ontwikkelen die de diagnostiek van fysieke functie ondersteunen. Ik heb veel waardering voor het feit dat de faculteit het belang van deze missie heeft willen respecteren. Ik meen dat jullie In de loop van het promotie traject ook steeds meer heil zijn gaan zien in deze analyse methode, die nieuwe wegen opent naar toegepast onderzoek om de klinische praktijk te verbeteren.

Herkend door Peter, ondersteund door Jaap en liefdevol en met humor ondergaan door Corinne is mijn interesse voor wetenschappelijk onderzoek tijdens deze promotie bevestigd en versterkt. De combinatie van ondernemer en onderzoeker heeft voor mij persoonlijk maar ook voor McRoberts heel veel goeds gebracht!

Dierbare achterban
Annie, Diek, Jeanne, John, Geertje en Ruth, bedankt voor het poseren!

Steven, dank voor je hulp bij de productie van het proefschrift, het maken van de omslag en je hulp bij het feest! Steven en Dominique maakten dit boekje tot een kunstwerkje! Dank ook aan Bart, Dieuwke en Henk die me hielpen met de Engelse tekst. Pauline gaf advies bij de inleiding en verbeterde daarmee de samenhang van het boek.

Corinne, Janneke en Steven, Steven en Luca, Maarten, Coen, Ties, Ize, alle McRoberianen, Geeta, familie en vrienden: dank aan allemaal voor het jarenlang meeleven met het studeren van een promovendus op leeftijd.

Corinne, Corinne, wat moet ik zonder jou beginnen!

Appendices

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CHAPTER 11
Acknowledgements / Dankwoord

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CHAPTER 13
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CHAPTER 12

List of publications

PUBLICATIONS

1 Micó-Amigo ME, Kingma I, Faber GS, Kunikoshi A, van Uem JM, van Lummel RC, Maetzler W, van Dieën JH. Is the Assessment of 5 Meters of Gait with a Single Body-Fixed-Sensor Enough to Recognize Idiopathic Parkinson's Disease-Associated Gait? Ann Biomed Eng. 2017 Jan 20. doi: 10.1007/s10439-017-1794-8.

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Appendices

5

CHAPTER 11

Curriculum Vitae

CURRICULUM VITAE

Robert Christiaan van Lummel

Personal data

Address: Raamweg 43
2596 HN Den Haag
The Netherlands
Phone number: +31 (0)6 51 355 745
E-mail: r.vanlummel@mcroberts.nl
Nationality: Dutch
Marital status: Married (1971)
3 children
3 grandchildren
Date of birth 17th March 1948

Education

2012 – to date	PhD fellow Supervisors: Prof.dr. Peter J. Beek, Prof.dr. Jaap H. van Dieen Faculteit Gedrags- en Bewegingswetenschappen Vrije Universiteit Amsterdam
1983	Master's degree philosophical and historical pedagogy University Utrecht
1966 - 1970	Physical education (MO-P) Academie voor Lichamelijke Opvoeding
1966	Hogere Burger School (HBS) - B

Work

1988 – to date	Founder and CEO McRoberts BV
1986	Research Admission Disabled on the CIOS (OCW)
1982	Coordinator Development Group Sport and Exercise Restructuring training curriculum SB CIOS for MDGO
1972 - 1990	Central Institute for Teacher Training of Sport Leaders (CIOS)
1970	Sports coach Leiden University

Sports

Present	Squash
1976	Dutch National Rugby Team
1971 - 1976	Leids Studenten Rugby Gezelschap, ereklasse
1966 - 1970	Storks Baseball, The Hague, hoofdklasse

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