JYU DISSERTATIONS 709

Antti Löppönen

Free-Living Sit-to-Stand Kinematics as an Indicator of Lower Extremity Physical Function

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UNIVERSITY OF JYVÄSKYLÄ
FACULTY OF SPORT AND
HEALTH SCIENCES

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in building Capitolium, auditorium C1, on November 24, 2023, at 12 o'clock noon.

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ABSTRACT

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Strength-demanding daily activities such as sit-to-stand (STS) transitions are essential for independent living among older adults. Measurement of STS transitions using advanced wearables offers a broader picture of physical activity and potentially indicate a future decline in physical functioning. This dissertation had three aims: first, to develop an open and universal algorithm that can detect and quantify the intensity of free-living STS transitions; second, to compare how free-living STS characteristics differ between age and sex groups and how they are associated with laboratory-based measurements; and third, to determine whether free-living STS characteristics could be an indicator of future decline in physical functioning among community-dwelling older adults. Data were drawn from three projects: the Active Ageing–Resilience and External Support as Modifiers of the Disablement Outcome (n = 1 021), which included baseline (n = 479), 1-year intervention (n = 86), and 4-year follow-up measurements (n = 340); the Leuven project (n = 63) and Finnish Retirement and Aging Finnish project (n = 188). The participants in the studies were community-dwelling older adults aged 60 to 90 years. Free-living STS characteristics were measured using an algorithm developed in this study that processes thigh-worn accelerometer data (from 3–7 days of continuous recording). The results showed that free-living STS transitions could be accurately detected, and intensity could be quantified using a single thigh-worn accelerometer. Free-living STS characteristics differed between age and sex groups. Men performed more and higher-velocity STS transitions than women. Free-living STS characteristics were associated with laboratory-based measurements, fear of falling, and stair negotiation problems. Older and low-functioning individuals appeared to perform free-living STS transitions at a higher percentage of their maximal capacity than younger and high-functioning individuals. In addition, free-living STS maximal angular velocity can predict future physical decline over a 4-year follow-up. The study findings suggest that daily strength-demanding activities may indicate the adequacy of lower extremity muscle strength and that STS characteristics may predict physical functioning decline among older adults.

Keywords: accelerometer, laboratory based, older adult, chair rise, daily life

TIIVISTELMÄ (ABSTRACT IN FINNISH)

Löppönen, Antti
Arjen seisomaan nousut alaraajojen toimintakyvyn indikaattorina
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Arjen voimaa vaativat aktiviteetit, kuten seisomaan nousut ovat tärkeitä itsenäisen asumisen kannalta. Seisomaan nousujen mittaaminen kehittyneen päälle puettavan sensoriteknologian avulla laajentaa fyysisen aktiivisuuden ymmärrystä ja voi toimia indikaattorina tuleville toimintakykyrajoituksille. Tällä väitöskirjalla oli kolme tavoitetta: ensinnäkin kehittää avoin algoritmi, joka pystyy tunnistamaan arjen seisomaan nousut ja arvioimaan niiden nopeuden; toiseksi vertailla, kuinka arjen seisomaan nousujen määrä ja nopeus eroavat iän- ja sukupuolten välillä ja miten ne ovat yhteydessä laboratoriossa suoritettuihin toimintakykymittauksiin; ja kolmanneksi määrittää, voisivatko arjen seisomaan nousut ennustaa tulevaa toimintakyvyn heikkenemistä kotona asuvien iäkkäiden ihmisten keskuudessa. Tutkimuksessa hyödynnettiin kolmen isomman tutkimuksen aineistoa: Aktiivisuuden, terveyden ja toimintakyvyn yhteys hyvinvointiin vanhuudessa (AGNES) tutkimusta (n = 1 021), joka sisälsi lähtötilanteen mittaukset (n = 479), 1-vuoden interventiomittaukset (n = 86) ja 4-vuoden seurantamittaukset (n = 340); Leuven-tutkimuksen mittaukset (n = 63); Aktiivisena eläkkeelle. Eläkkeelle siirtyminen, terveys ja hyvinvointi –tutkimuksen mittaukset (n = 188). Tutkittavat olivat kotona asuvia 60-90-vuotiaita henkilöitä. Arjen seisomaan nousuja mitattiin tässä tutkimuksessa kehitetyllä algoritmilla, joka analysoi reiteen kiinnitetyn kiihtyvyysanturin dataa. Tulokset osoittivat, että arjen seisomaan nousut voitiin tunnistaa luotettavasti ja niiden nopeus voitiin määrittää tarkasti käyttäen yhtä reiteen kiinnitettyä kiihtyvyysanturia. Arjen seisomaan nousujen määrä ja nopeus erosivat ikä- ja sukupuolien välillä. Miehet suorittivat enemmän ja nopeampia seisomaan nousuja kuin naiset. Arjen seisomaan nousut olivat positiivisesti yhteydessä laboratorio-olosuhteissa suoritettuihin toimintakykymittauksiin sekä negatiivisesti yhteydessä kaatumisen pelkoon ja portaiden kävelyvaikeuksiin. Lisäksi arjen seisomaan nousujen maksimaalinen nopeus voi ennustaa tulevaa toimintakyvyn laskua 4 vuoden seurannan aikana. Tutkimustulokset viittaavat siihen, että päivittäiset voimaa vaativat aktiviteetit voivat viitata alaraajojen lihasvoiman riittävyyteen ja ennustaa fyysisen toimintakyvyn heikkenemistä kotona asuvien iäkkäiden ihmisten keskuudessa.

Asiasanat: kiihtyvyysanturi, iäkkäät, tuolilta nousu, arki, toimintakyky

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ORIGINAL PUBLICATIONS AND AUTHOR CONTRIBUTION

This thesis is based on the following four original publications, which will be referred to by their Roman numerals.

I. **Löppönen, A.,** Karavirta, L., Portegijs, E., Koivunen, K., Rantanen, T., Finni, T., Delecluse, C., Van Roie, E., & Rantalainen, T. (2021). Day-to-Day Variability and Year-to-Year Reproducibility of Accelerometer-Measured Free-Living Sit-to-Stand Transitions Volume and Intensity among Community-Dwelling Older Adults. Sensors, 21(18), Article 6068. https://doi.org/10.3390/s21186068

II. **Löppönen, A.,** Karavirta, L., Portegijs, E., Koivunen, K., Rantanen, T., Finni, T., Delecluse, C., Van Roie, E., & Rantalainen, T. (2022). Association between free-living sit-to-stand transition characteristics, and lower-extremity performance, fear of falling, and stair negotiation difficulties among community-dwelling 75 to 85-year-old adults. The Journals of Gerontology: Series A. https://doi.org/10.1093/gerona/glac071

III. **Löppönen, A.,** Delecluse, C., Suorsa, K., Karavirta, L., Leskinen, T., Meulemans, L., Portegijs, E., Finni, T., Rantanen, T., Stenholm, S., Rantalainen, T., & Van Roie, E. (2023). Association of sit-to-stand capacity and free-living performance using thigh-worn accelerometers among 60-90-year-old adults. Medicine and Science in Sports and Exercise. https://doi.org/10.1249/MSS.0000000000003178

IV. **Löppönen, A.,** Karavirta, L., Delecluse, C., Portegijs, E., Rantanen, T., Finni, T., Van Roie E., & Rantalainen T. Knee-extension strength and daily sit-to-stand performance predict functional decline among older adults over a 4-year follow-up. (Submitted)

As the first author of the original publications, while also considering the co-authors' comments, I drafted the design and research questions of the manuscripts. In addition, I prepared the data for statistical analyses, performed all statistical analyses, and took the primary responsibility of writing the manuscript. I participated in algorithm coding, testing, and developing algorithm characteristics in collaboration with Timo Rantalainen. In studies I and II, we were privileged to use pre-existing data. I participated in the collection and recording of data in the Active Ageing–Resilience and External Support as Modifiers of the Disablement Outcome (AGNES) Follow-up Study, which were used in studies III and IV.

FIGURES

TABLES

ABBREVIATIONS

aADL	advanced activities of daily living
ADL	activities of daily living
EMG	electromyography
iADL	instrumental activities of daily living
ICF	*International Classification of Functioning, Disability and Health*
ICIDH	*International Classification of Impairments, Disabilities and Handicaps*
iSTS	instrumented sit-to-stand test
LPA	light physical activity
MAD	mean amplitude deviation
MET	metabolic equivalent of task
mg	milligravity
MMSE	Mini-Mental State Examination
MVPA	moderate-to-vigorous physical activity
N	Newton
SD	standard deviation
STS	sit-to-stand
WHO	World Health Organization

CONTENTS

1 INTRODUCTION

Safe and independent living in own home and the community maintains good mental, cognitive, and physical functioning among older adults (Popejoy et al., 2022). Moving to intensive care housing can cause relocation stress, associated with depression, anxiety, and a decline in physical functioning (Costlow & Parmelee, 2020; Lotvonen et al., 2018; Wu et al., 2015). In addition, older adults consider maintaining self-importance when they have the opportunity to live independently (Harrefors et al., 2009). Among Finnish people older than 80 years, 89.3% lived in their homes in 2022. The number has increased since 2000, when 84.9% of Finns lived at home, which means that a significant proportion of older adults live in their own home. The growth logically follows the relative increase in the number of older adults (The Finnish Institute for Health and Welfare, 2023a). According to estimates, 33% of the population in Finland will be older than 65 years in 2070. The trend is significant because in 1990, 13.5% of Finns were older than 65 years (Official Statistics of Finland, 2023). The situation in Finland follows the global trend. The number of people older than 65 years is expected to double and will be more than 1.5 billion in 2050. The proportion of older adults is predicted to increase in all regions from 9.3% in 2020 to more than 16% in 2050 (United Nations, 2020).

Activities of daily living (ADL), such as bathing, eating, dressing, going to the toilet, moving, and controlling urinary and bowel functions, are essential and routine tasks to live independently. According to the most recent Healthy Finland Survey, 8.0% of people older than 65 years' experience limitations in at least one ADL (The Finnish Institute for Health and Welfare, 2023a). However, many of those aged >80 years still have a reasonably good physical functioning, as almost every second person self-reports that they can climb one flight of stairs without problems (Koponen et al., 2018). Sufficient muscle strength is an essential determinant of ADL capability (Hasegawa et al., 2008), and good muscle strength has been shown to protect against the decline of ADL functions (Wang et al., 2020).

To enable ADL functions, various transitions between different types of activity, such as sitting, standing, and walking, are also crucial for independent living (Alexander et al., 2000; Hughes et al., 1996, p. 201; Inkster et al., 2003; K. Kerr et al., 1994; Painter et al., 1999). One of the most common strength-demanding daily activity is the sit-to-stand (STS) transition (Dall & Kerr, 2010; K. Kerr et al., 1994; Ploutz-Snyder et al., 2002). On average, community-dwelling older adults have been reported to perform 45 STS transitions per day (Bohannon, 2015). Previous studies have found that 14.0% to 21.6% of older adults report difficulties with STS transitions (Verghese et al., 2008; Williamson & Fried, 1996), which can lead to decreased mobility (Guralnik et al., 1995). The combination of the relatively high strength-demanding activity and the fact that older adults engage with STS transitions multiple times a day are essential for independent living, making STS transitions a potentially interesting indicator of strength-demanding daily activities, which should be investigated further. Indicators are important because they facilitate the early identification of older adults at risk of functional decline. This enables the timely implementation of personalized preventive strategies, effectively managing healthcare system needs while enhancing the overall quality of life (Koponen et al., 2018).

Measuring STS transitions objectively using advanced wearables would provide more extensive information than questionnaires and allow the opportunity to study the kinematics and intensity of STS transitions in a free-living environment. Previously, STS transitions were detected accurately using three-axial accelerometers and inertial measurement units (Bohannon, 2015; Janssen et al., 2008; Martinez-Hernandez & Dehghani-Sanij, 2019; Pickford et al., 2019; Vissers et al., 2011). Previous free-living STS transition explorations have typically used transition duration to indicate the intensity of the STS transition rather than to evaluate the kinematics directly (Adamowicz et al., 2020; Janssen et al., 2008). However, Pickford et al. (2019) evaluated STS transition kinematics in the free-living environment using a proprietary algorithm to compare peak velocities of STS transitions (Pickford et al., 2019). To the best of our knowledge, no algorithm is publicly available that can detect STS transitions and quantify STS transition intensity based on free-living thigh-worn tri-axial accelerometer records. Therefore, we developed a new algorithm to detect and quantify STS transitions in a free-living environment among older adults in the present study.

Hence, the aims of this dissertation were to determine whether an open and universal algorithm can be developed to detect free-living STS transitions and quantified their intensity from data produced by a single thigh-worn accelerometer and investigate its accuracy and reproducibility; to study how free-living STS characteristics differ between age and sex groups, how they associate with laboratory-based capacity measurements and self-reported fear of falling, and stair negotiation difficulties; and to investigate whether the free-living STS characteristics could be an indicator of future declines in physical functioning during a 4-year follow-up among community-dwelling older adults.

This thesis consists of a literature review where first the physical functioning, its definition, evaluation, and disability process are described using previous literature and the International Classification of functioning (ICF) framework. After this, physical activity, and aging, which also includes sit-to-stand (STS) transitions will be introduced. The introduction will finish with an overview of the current physical activity measurement methods, particularly focusing on technological solutions that are available for measuring multiple-day free-living strength-demanding activities.

2 REVIEW OF THE LITERATURE

2.1 Physical functioning and aging

In 1976, in accordance with the twenty-ninth World Health Assembly Resolution, the *International Classification of Impairments, Disabilities, and Handicaps* (*ICIDH*) was published (World Health Organization [WHO], 1980) to provide a standardized way to classify and describe disabilities. This was later replaced in 2001 by the *International Classification of Functioning, Disability and Health* (*ICF*), published by the WHO (2001). Unlike the *ICIDH* classification, which is a 'classification of the consequences of diseases', the *ICF* is a more comprehensive classification of 'components of health'. In this thesis, ICF is the basis of the definitions and theoretical structures used in this thesis, but not all of its dimensions are appropriate for this thesis. The main component of the *ICF* framework is functioning, which encompasses body function, body structures, activities, and participation. It highlights the positive or neutral aspects of the interaction between a person's health conditions and contextual factors (i.e. environmental and personal factors). Functioning is a multidimensional concept divided into several dimensions: physical, mental, cognitive, and social functioning. Sufficient physical, mental, and social functioning and an environment supporting these help people feel well, find their place in society, cope with working life, and manage independent living (Ahlqvist et al., 2016; Secker et al., 2003; The Finnish Institute for Health and Welfare, 2023b).

Physical functioning refers to people's physical preconditions to cope with the daily tasks that are important to them and is influenced by multiple physical and mental health-related variables (Garber et al., 2010). Physical functioning includes muscular strength and endurance, joint mobility, endurance fitness, control of bodily positions and movements and, finally, the functions of the central nervous system that coordinate these. Physical functioning manifests as people's ability to be physically active and move their bodies. Sense perceptions such as vision and hearing are often included in the domain of physical functioning. Physical functioning is also the ability to perform basic ADL and instrumental ADL (iADL), and the ability of older adults to reside in the community depends mainly on their level of physical functioning (WHO, 2001).

The physical functioning domain can be operationalized into two qualifiers (Figure 1). According to the *ICF*, capacity relates to what an individual can do in a standardized environment (clinical assessment), and performance relates to what the person actually does in their 'current' (usual) environment (WHO, 2001). These qualifiers offer a means to demonstrate how a person's activities and participation are impacted by the environment in which measurements are taken and how living environmental changes can enhance their functioning. This literature review clarified that this definition of terminologies is not consistently used, and in previous studies where both qualifiers have been used, defining the terminology in the introduction sections was deemed necessary (Giannouli et al., 2016; Holsbeeke et al., 2009; Lamb & Keene, 2017; van Lummel et al., 2015).

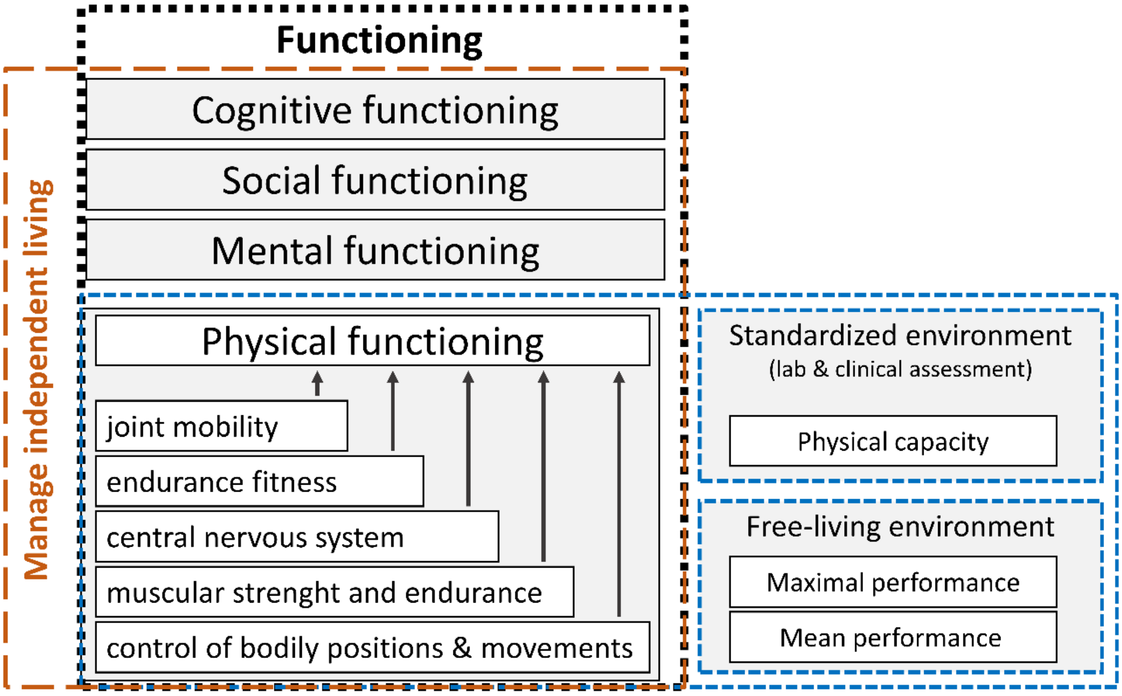

FIGURE 1. Dimensions of functioning and different qualifiers of physical functioning.

2.1.1 Disablement process

In epidemiological and clinical studies that involve older people, it is important to establish a reference framework for the disablement process and identify underlying causes of disability and functional limitations (Kail & Carr, 2017). In addition, a comprehensive understanding of the disablement process is essential for identifying potential points for intervention and developing effective preventive strategies to maintain physical functioning over time.

However, disability has not been defined in a commonly accepted way and has been described from medical, sociological, and political perspectives (Mitra, 2006). As previously mentioned, the *ICIDH* (WHO, 1980) and its updated version, the *ICF* (WHO, 2001), offer a comprehensive synthesis of health from various biological, individual, and social viewpoints. According to the *ICF* model, disability arises from a health condition that results in impairment and subsequently lead to functional and participation limitations in contextual factors (WHO, 2001). The *ICF* model is sometimes termed 'the biopsychosocial model of disability' (Bickenbach et al., 1999).

Other concepts have also been presented. Sociologist Saad Nagi published a scheme in 1965 that includes four central concepts: active pathology, impairment, functional limitation, and disability. Pathology is the starting point of Nagi's model, and for this reason, it can also be called the functional limitation paradigm (Nagi, 1965). Verbrugge and Jette's disablement process published in 1994, combines Nagi's and *ICIDH*/*ICF* schemes as the framework for the disablement process in this study (Verbrugge & Jette, 1994).

Figure 2 shows the process according to the main pathway from pathology to disability. *Pathology* refers to biochemical and physiological abnormalities that are medically diagnosed as diseases, injuries, or developmental conditions. These can include osteoarthritis, cataracts, or cerebral palsy. *Impairments* are dysfunctions and significant consequences for physical, mental, or social functioning in specific body systems. *Functional limitations* are restrictions in performing fundamental physical and mental actions used in daily life, and *disability* is the experienced difficulty in doing activities in any domain of life (the domains typical for one's age-sex group) due to a health or physical problem (Verbrugge & Jette, 1994).

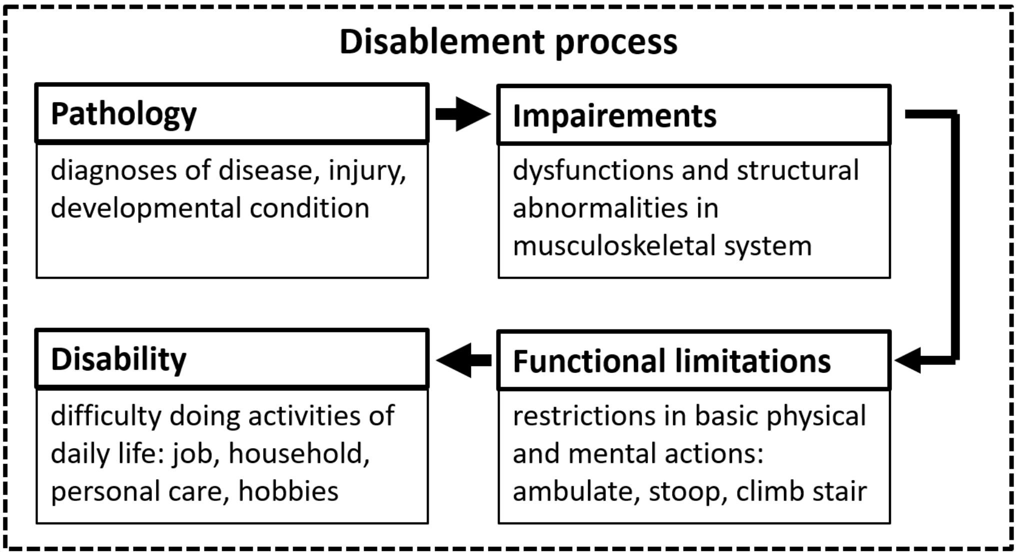

FIGURE 2. The main pathway from pathology to disability: the disablement process (adapted from Verbrugge & Jette, 1994).

When combining the disablement process (Figure 1) with the previously presented *ICF*-based qualifiers (Figure 2), we can consider how the capacity and performance qualifiers appear in the different stages of the process. *Capacity qualifier* reflects the disability process *impairments section* because limitation in the musculoskeletal system strongly affects the maximum capacity. For example, muscle mass determines the maximum gait speed measured in the laboratory environment (Clark et al., 2013; Hayashida et al., 2014; Rantanen et al., 1998). *Performance qualifier* is more suitable for the *functional limitations* section, where the limitations that occur are especially visible in a free-living environment. For example, frailty condition was associated with daily gait speed measured using the Smartphone application (Kawai et al., 2023). The main pathway can also be thought in the opposite direction. Limiting activities at the end of the pathway easily leads to situations where daily life does not challenge individuals enough to maintain their physical functioning level, and inactivity leads to *impairments* and, eventually, *pathologies*. In this case, the *performance qualifier* can act as an early indicator, revealing the features of the free-living activity, as has been found free-living gait complexity is associated with fall risk among community-dwelling older adults (Ihlen et al., 2016).

The disability process can also be viewed from life span perspective (Figure 3) (Kalache & Kickbusch, 1997; WHO, 2001). The disability threshold indicates the individual's level of independent living. When the disability threshold is crossed, it becomes more difficult for individuals to live independently due to their physical functioning (Kalache & Kickbusch, 1997). To promote healthy ageing and reduce disability, training interventions should delay the onset of disability by shifting the ageing trajectory to the right (Cannataro et al., 2022). This goal aligns with Fries' development of the compression of morbidity hypothesis in the 1980s, which aims for ageing to be as healthy and functional as possible and thus postpone morbidity as much as possible until the end of life (Fries, 1980; Fries, 2005). In addition, reaching the peak at an earlier age (i.e. early environmental effects on growth and development) can have long-term effects on human health (Bateson et al., 2004), because the starting level is higher.

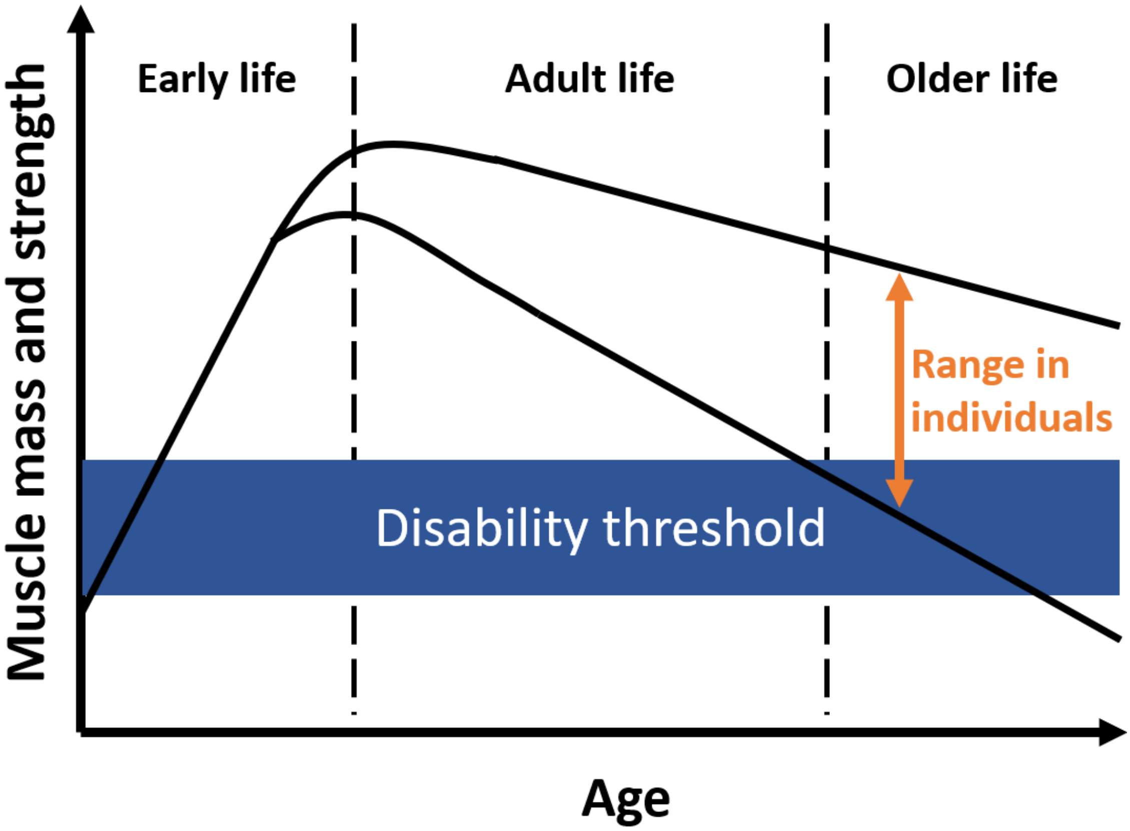

FIGURE 3. Physical functioning across the life span (modified Kalache & Kickbusch 1997).

2.1.2 Laboratory-based assessment of physical functioning

Standardized test batteries or force measurements are typically used to evaluate lower extremity physical functioning, often in a laboratory environment with standardized protocols. One such assessment tool is the Short Physical Performance Battery (SPPB), which was developed in the 1990s and has been shown to be a valid measure of lower extremity physical functioning (Guralnik et al., 1994; Guralnik et al., 1995; Guralnik et al., 2000). The SPPB includes tests that assess standing balance (side-by-side, semi-tandem, tandem), gait speed over a 3- or 4-meter distance, and the five times sit-to-stand test (5 × STS), which assesses lower extremity strength. The total score is calculated on the basis of the results in the three subtests (four points each), with a maximum score of 12 points and higher scores indicating better physical performance (Figure 4).

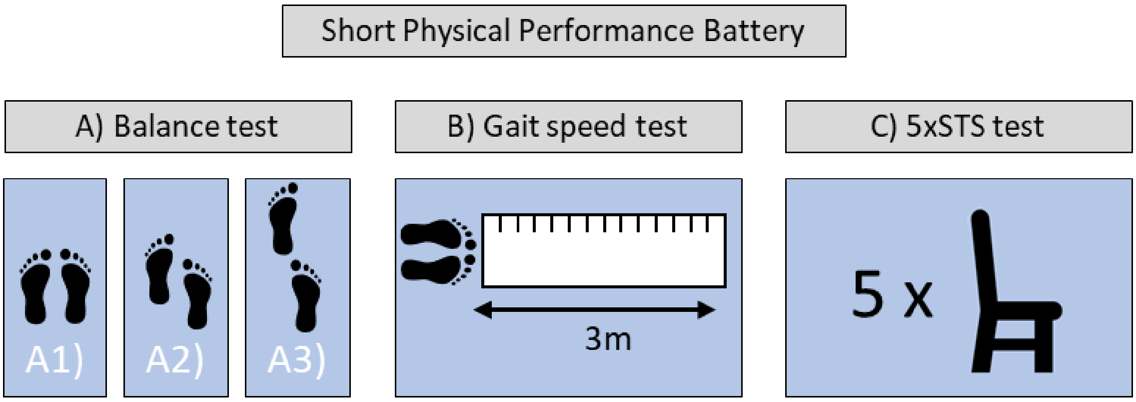

FIGURE 4. Short Physical Performance Battery (SPPB) with subtests.

Cut-off points have been defined for the SPPB to predict future declines or meaningful changes in physical functioning. A score of 8 or lower has been suggested as a favourable screening cut-off point for sarcopenia in clinical settings where lean body mass measurements are unavailable (Phu et al., 2020). In older cardiac inpatients, the cut-off point for determining sarcopenia using SPPB was 9.5 (Ishiyama et al., 2017). Moreover, another study showed that individuals with SPPB scores of 10 or lower at baseline had significantly higher odds of mobility disability, defined as a loss of ability to walk 400 meters at follow-up (Vasunilashorn et al., 2009). Meaningful changes have also been defined for the total SPPB score using the distribution- and anchor-based methods. Perera and colleagues determined that substantial change estimates ranged from 0.99 to 1.34 points (Perera et al., 2006), and Kwon and colleagues determined meaningful changes ranging from 0.40 to 1.50 points (Kwon et al., 2009). These cut-off points provide diagnostic values in addition to the total SPPB scores, which improves the clinical relevance of the test battery. In addition, cut-off points and meaningful changes can be used to define categorical variables for statistical analyses.

The 5 × STS test, which is part of the SPPB, is widely used as a physical measure owing to the simplicity of the assessment and its predictive value for health and functioning in old age (Guralnik et al., 1994; Guralnik et al., 1995). Furthermore, the advantage of STS tests is their versatility in that they can be performed in both clinical and home environments. Typically, the STS test result is the total completion time measured with a stopwatch. Various protocols can be used for STS tests, with the 5-repetition test being the most popular, although 10-repetition (Yanagawa et al., 2016) and 30 s tests are also used. The 30 s test reports the number of repetitions completed in 30 s and has been suggested to correct for floor effects that may occur in the 5 and 10 repetition tests (Jones et al., 1999). The 5 × STS time has been found to be associated with muscle architecture and anthropometric characteristics (Mateos-Angulo et al., 2020), and STS test results have been shown to better represent the physical performance of muscles than muscle strength alone (Yee et al., 2021).

The STS test can be monitored in a laboratory environment in various ways such as performing the test on force plates or with sensors, allowing for the assessment of the power required for STS repetitions (Baltasar-Fernandez et al., 2021; Pai & Rogers, 1990; van Lummel et al., 2016; Zijlstra et al., 2012; Zijlstra et al., 2010). The STS test can be monitored using a commercial McRoberts Dynaport inertial sensor attached to the lower back, which allows the test to be divided into phases. This enables examining the relationships between test phases and health outcomes (Boonstra et al., 2006; van Lummel et al., 2012). Previously, the instrumented STS test (iSTS) has been shown to have better clinical relevance than the manually recorded test, as it allows for a more detailed analysis of the repetitions. The sit-to-stand phase has been found to be strongly associated with health and functional statuses compared with the total completion time measured manually (van Lummel et al., 2016).

Lower extremity functioning can also be evaluated through direct strength measurements. Isometric strength measurements on an adjustable chair have often been used (Rantanen et al., 1997) and higher isometric strength of the lower extremity has been found to be associated with independent living (Hasegawa et al., 2008; Kojima et al., 2014) and can be used to predict future living dependence among older adults (Wang et al., 2020). With age, the isometric knee extensor strength decrease (Skelton et al., 1994). Unilateral knee extension muscle function can be assessed using an isokinetic dynamometer, which is a device that can control the velocity of joint movement during testing. This allows for estimating maximum muscle power, which has been found to decrease in older adults and thus to be a valuable indicator for functional status among older adults (Alcazar et al., 2023; Foldvari et al., 2000). Furthermore, lower extremity muscle power can also be evaluated using the participant's body mass and height, chair height, and the 5 × STS total time. STS muscle power has been found to be a better clinical tool than the traditional STS total time to assess physical functioning among older people (Alcazar et al., 2018). In addition, this power has been found to decrease significantly after the age of 50 years and is negatively associated with mobility limitations (Alcazar et al., 2021).

2.1.3 Physical functioning in a free-living environment

The independent living of older adults includes various activities in a free-living environment. Daily activities can be divided into two levels: ADL and iADL. ADL refer to basic activities such as bathing, eating, dressing, going to the toilet, moving, and controlling urine and faecal movements (Katz et al., 1963). ADL ability can be measured with the widely used Katz index, which includes six basic human functions: bathing, dressing, toileting, transfer, continence, and feeding (Katz et al., 1963; Katz & Akpom, 1976). ADL are essential and routine tasks that most young and healthy individuals without functional limitations can perform without assistance. The inability to perform essential ADL may lead to unsafe conditions, poor quality of life, and inactivity (Edemekong et al., 2022). iADL include using the phone, going to the store, preparing food, doing housework, washing clothes, using transport, handling money, and taking care of medicines (Lawton & Brody, 1969; Spector & Fleishman, 1998).

On the basis of the United States National Health 2000–2015 Interview Survey and the 1999–2002 National Health and Nutrition Examination Survey (NHANES), older adults (at least 75 years of age) were most likely than younger groups to require the help of another person when performing ADL and iADL (Ervin, 2006; NHS, 2016). According to the European SHARE (Survey of Health, Ageing and Retirement in Europe) database, the global prevalence (at least one activity) of iADL limitation was 23.8% and was higher in women than in men (27.1% vs 17.6%) and in people aged ≥ 85 years (51.5%) (Portela et al., 2020). The same findings were indicated in the NHANES data, where women were more likely than men to report difficulty performing ADLs/iADLs (Ervin, 2006).

Muscle strength is a crucial determinant of ADL and iADL ability (Hasegawa et al., 2008), and sufficient muscle strength has been shown to protect against the decline of ADL functioning (Wang et al., 2020). In addition, impaired balance and slow walking speed have been reported to be associated with an increased likelihood of ADL disability (Heiland et al., 2016), and physical activity has been found to have a beneficial effect on the ability to undertake ADL tasks among older adults (Roberts et al., 2017). iADL tasks such as handling money and medications are predominantly more cognitively than physically demanding. Conversely, ADL tasks, moderate physical activities, and climbing stairs are predominantly more physically than cognitively demanding (Fong et al., 2015).

2.2 Physical activity and aging

2.2.1 Physical activity and aging

The traditional definition of physical activity is 'any bodily movement produced by skeletal muscles that results in energy expenditure' (Caspersen et al., 1985). One pioneering study that provided evidence for the significance of physical activity in promoting health is that by Morris and colleagues in 1953. The study concluded that sedentary bus drivers had a higher risk of heart attack than active conductors, who climbed stairs each working day (Morris et al., 1953). Later on, a significant amount of research has consistently shown that physical activity is associated with a progressively lower risk of all-cause mortality (Arem et al., 2015; Paluch et al., 2022) and a reduced risk of various health issues such as breast (Cerhan et al., 1998) and prostate cancers, fractures, recurrent falls, ADL disability, functional limitation, cognitive decline, depression, Alzheimer's disease (Cunningham et al., 2020), and dementia (Vogel et al., 2009). Furthermore, higher cumulative physical activity over the life span has been linked to less decline in physical performance and reduced mobility disability and mortality in older age groups (Stenholm et al., 2016). Physical activity has also been found to attenuate the increased risk of mortality associated with physical disability (Martinez-Gomez et al., 2018) and improve physical function (Hall et al., 2016), to reduce the risk of heart attack (Paffenbarger et al., 1978), and to prevent cardiovascular diseases (CVDs) (Lear et al., 2017).

Physical activity has been repeatedly suggested as "good medicine" in disease prevention and even treatment. Unfortunately, it has not been fully integrated into primary or geriatric medical practice, and its role is minor in training most medical doctors and other healthcare providers (Izquierdo et al., 2021; National Sports Council, 2023). Studies have shown that physical activity-based interventions can effectively increase physical activity levels in community-dwelling older adults (Grande et al., 2020). In addition, a structured physical activity intervention has been found to improve the SPPB score and other measures of physical functioning (Laddu et al., 2020; The LIFE Study Investigators, 2006). Moreover, individualized physical activity counselling sessions have been identified as an important factor for maintaining independence in the community in old age (Mänty et al., 2009).

Global recommendations for physical activity among older adults have been established by the WHO. According to the most recent guidelines published in 2020, older adults should engage in regular multi-component physical activity, which includes aerobic, strength, and balance training, to maintain their health and physical function (Bull et al., 2020). The WHO guidelines recommend that older adults should aim for at least 150–300 minutes of moderate-intensity or 75–150 minutes of vigorous-intensity aerobic physical activity per week and perform strength training at least twice a week (Bull et al., 2020). Older adults with limitations in physical function or chronic diseases should be as physically active as their functioning allows (Bull et al., 2020). Recent evidence using device-based physical activity assessments has demonstrated that physical activity of any duration, without a minimum threshold, is associated with better health and lower all-cause mortality (Ekelund et al., 2019; Jakicic et al., 2019), and this has also been emphasized in the new recommendations pertaining to 'every step counts'. However, evidence suggests that meeting the recommended level of moderate-to-vigorous physical activity (MVPA) is associated with reduced mortality risk, whereas increasing light physical activity (LPA) or reducing sedentary behaviour may not have the same impact (Lee et al., 2018). In addition, recently it has also been found that even small amounts of vigorous physical activity are associated with substantially lower mortality (Stamatakis et al., 2022).

Physical activity decreases with age (DiPietro, 2001; Schrack et al., 2016), and consistent evidence from longitudinal observational studies indicates that physical activity is positively associated with healthy aging (Daskalopoulou et al., 2017; Moreno-Agostino et al., 2020). Recent studies have even estimated that adding 10 minutes of MVPA per day could potentially prevent up to 110,000 deaths in Americans between the ages of 40 and 85 years (Saint-Maurice et al., 2022). Physical activity levels in older adults are influenced by their environments. Safe, walkable, and aesthetically pleasing neighbourhoods with access to various destinations and services positively impact older adults' participation in physical activity (Barnett et al., 2017). Conversely, neighbourhood barriers to outdoor mobility close to home were associated with lower physical activity levels in older adults, while barriers further away did not have the same effect (Portegijs et al., 2020).

Research interest in sedentary and stationary behaviours has been increasing in recent years. Physical activity intensities and sedentary behaviour are defined using energy consumption where the base unit is MET (Metabolic Equivalent of Task). One MET is the energy cost of sitting at rest, equal to approximately 3.5 mL of oxygen uptake per kilogram of body weight per minute (Jetté et al., 1990; Tremblay et al., 2017). Sedentary time refers to activities in which the recommended physical activity levels are not met (Bames et al., 2012), typically involving < 1.5 MET and a lying down or sitting position (Tremblay et al., 2017). The term *stationary behaviour* (or *stationary time*) refers to any waking behaviour performed while lying down, reclining, sitting, or standing, without ambulation (walking or moving about on foot), regardless of energy expenditure (Tremblay et al., 2017). High objectively estimated sedentary time is associated with higher mortality in less active individuals (Ekelund et al., 2020). Meta-analyses revealed that prolonged sedentary time was independently associated with deleterious health outcomes regardless of physical activity (Biswas et al., 2015; Patterson et al., 2018). However, engaging in high levels of moderate-intensity physical activity (approximately 60-75 minutes per day) has been reported to mitigate the increased risk of death associated with high sedentary time (Ekelund et al., 2016), so it can be inferred that the worst combination is high sedentary time and low physical activity.

2.2.2 Characteristics of free-living physical activity and activities

Behind these activity minutes, physical activity consists of many types of activities. As previously mentioned, ADL and iADL are central issues regarding independent living among older adults. In addition, advanced ADL (aADL) are specified (Reuben et al., 1990), which include hobbies and work (Briede-Westermeyer et al., 2023). Most studies have focused on leisure-time physical activity, although the retirement age in Europe varies and many older adults work part-time (Baumann et al., 2022) or as volunteers in various organizations such as sports clubs, charities, and positions of trust (Morrow-Howell & Gonzales, 2020), which has been found to be associated with increased mental, social, and physical well-being (Filges et al., 2020).

Moving from one place to another is a central part of physical activity, and the primary type of locomotion for older adults is walking (Armstrong & Morgan, 1998; Cunningham & Michael, 2004). Among older adults, the built environment is a significant place where walking is done for recreational purposes or to move from one place to another (Eyler et al., 2003). For older adults, gardening is a popular summer hobby that offers diverse physical activities that promote positive aspects among older adults and provide social and physical benefits (Scott et al., 2020). Moreover, for older adults, cycling is suitable for longer journeys. Although cycling-related accidents involving older adults are a concern (Garrard et al., 2012; Gladwin & Duncan, 2022; Ikpeze et al., 2018), cycling has been found to increase life span (Oja et al., 2011) and self-assessed health (Huy et al., 2008; Oja et al., 2011), and reduce the incidence of CVDs (Nordengen et al., 2019). Water sports are also popular among older adults. Swimming has been found to be especially good for them because it reduces weight bearing, thus reducing stress in conditions such as osteoarthritis knee and hip (Cooper et al., 2007). In addition, aqua aerobic therapy has been found to be an effective exercise method for training older adults to reduce their risk of falling (Kim & O'Sullivan, 2013).

Among older adults, daily routines, which involve the duration, order, and placement of activities throughout the day, have been studied using the workflow method (Chung et al., 2017), iVO smart homes (Shahid et al., 2022), and Markov model-based method (Chifu et al., 2022). These studies have identified different daily activities, including their order. Activity types, regularity, frequency, duration, and timing of performance have high variability across individuals (Chung et al., 2017). Overall, studies on the daily activity routines of older adults have highlighted the importance of regular physical and social activities in promoting their well-being, cognitive performance, and quality of life (Smagula et al., 2022). In addition, it has been reported that MVPA timing may have the potential to improve health, although MVPA is associated with lower risks of all-cause mortality regardless of the time of day (Feng et al., 2023).

2.2.3 Strength-demanding free-living activities

Older adults' daily lives include many physical activities that require sufficient lower extremity strength, such as stair walking, especially in the upstairs direction, which requires much higher muscle activity levels than brisk (moderate-intensity) walking (Tikkanen et al., 2013). Moreover, older adults exhibit almost twice the relative electromyographic (EMG) measurement of muscle activities during upstairs stair walking compared with young adults (Hortobagyi et al., 2003). According to a study by Verghesen and colleagues, 45% of older adults report problems walking upstairs, making it a reasonably common activity where older adults experience difficulties (Verghese et al., 2008). Impaired stair walking is associated not only with reduced lower extremity strength but also with impaired sensation, balance, lower vitality, presence of pain, and increased fear of falling (Ploutz-Snyder et al., 2002; Salem et al., 2000; Tiedemann et al., 2007). Stair-walking difficulties often arise from problems with balance control, which can increase the risk of injury, and falls are a potential risk (Jacobs, 2016; Nevitt et al., 1991; Svanström, 1974), but this can be minimized by designing and building stairs with longer 'going' (stair depth) and preparing to go up the stairs by stopping (Di Giulio et al., 2020). Older adults have been observed to employ several alternative strategies to compensate for their reduced musculoskeletal capabilities, such as optimizing positional stability during stair ascent by maintaining a minor separation between the centre of mass and the centre of pressure in the frontal plane (Reeves et al., 2009). As a strength-demanding physical activity and MVPA, stair walking has been found to protect against metabolic syndrome (Whittaker et al., 2021) and declines in IADL functions (Tomioka et al., 2018) among older adults. In addition, stair walking can be used as a test protocol and appears to be more sensitive in detecting age-related changes than leg-extensor power (Van Roie et al., 2019). It has been found to be a simple, quick, and valid clinical tool for estimating the risk of functional decline in community-dwelling older adults, including high-functioning individuals (Oh-Park et al., 2011). Thus, adding a stair walking test to research protocols for older adults is justified.

Another common strength-demanding daily activity is STS transition (Dall & Kerr, 2010; Kerr et al., 1994; Kumar et al., 2022; Ploutz-Snyder et al., 2002), which refers to the period between two activities (Figure 5). In a review, Bohannon found that older adults had an average of 45 STS transitions in a free-living environment (Bohannon, 2015). STS transitions play a crucial role in older adults' daily activity routines, and the STS ability is essential for independent living (Hughes et al., 1996; Painter et al., 1999). Limitations in the ability to perform STS transitions among older adults can lead to decreased mobility (Guralnik et al., 1995), which in turn increases the risks of dependence and mortality (Hirvensalo et al., 2000). Previous studies have found that between 14.0% and 21.6% of older adults report experiencing difficulties with STS transitions (Verghese et al., 2008; Williamson & Fried, 1996). In addition, these difficulties are more prevalent among women than among men (28% vs. 20%), and the prevalence increases with age (Jette & Branch, 1984).

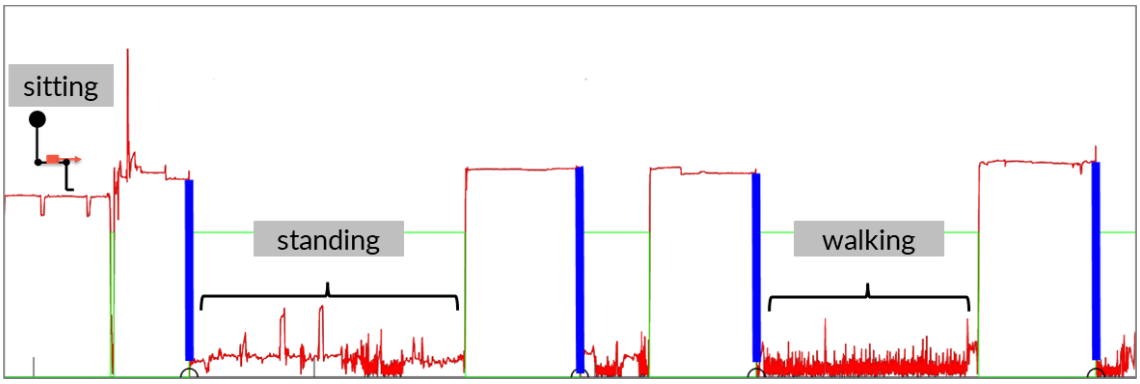

FIGURE 5. Example of placement of STS transitions between daily activities (represented by blue bars).

Older adults perform STS transitions close to their maximum strength capabilities. This is supported by findings indicating that the relative muscle activity required to execute STS transitions is almost twice as high in older adults as in younger adults (Hortobagyi et al., 2003). Moreover, older adults use significantly more of their available strength to rise from any chair height than younger adults do (Hughes et al., 1996). Weak muscle strength affects the success of STS transitions because it hinders generating a sufficiently large torque in the joints that would enable a successful STS transition (Riley et al., 1997). Older adults with lower muscle strength stand up with more dynamic use of the trunk (van Lummel et al., 2018). Peak trunk flexion during the STS transition may be a clinically observable biomechanical measure that could be used to identify different STS transition strategies (Scarborough et al., 2007).

Previous findings suggest that the height of the chair is a significant factor in the success of STS transitions, and a higher chair makes it easier to stand up owing to reduced hip and knee biomechanical demands and muscle activity

(Arborelius et al., 1992; Hurley et al., 2016). In addition to chair height, the STS transition is significantly influenced by the utilization of armrests and foot positioning (Janssen et al., 2002). Placing the feet in a posterior position during STS transitions shortens the movement duration, which reduces the hip flexion level and speed, whereas placing the feet in an anterior position increases the pre-extension phase in muscles (Kawagoe et al., 2000; Shepherd & Koh, 1996). This can also be referred to as a 'stabilization strategy' during STS transitions (Hughes et al., 1994). Furthermore, the synchrony of body segment maximal extension angular velocities was altered for the older adults at the lowest chair heights, which suggests that they change their movement as the activity becomes more strength demanding (Schenkman et al., 1996).

Although sufficient lower extremity strength plays an important role in STS transitions, research has shown that the ability to perform this transfer is a complex skill influenced by various physiological and psychological factors rather than just a measure of lower extremity strength (Lord et al., 2002). STS transitions require good balance, which is why they involve the risk of falling (Najafi et al., 2002; Tiedemann et al., 2008; Tinetti et al., 1988), as imbalance during the rising phase of the STS transfer can lead to falls (Hill et al., 2013). According to a systematic review, training interventions containing STS transitions can improve STS and motor functioning. However, owing to the poor quality of the studies, generalisations about the effectiveness of the intervention cannot be made, and further research is needed to confirm its potential benefits (Duarte Wisnesky et al., 2020). On the other hand, STS transitions are usually part of lower extremity function training, which also includes balance training or progressive marching in place (Kato et al., 2018), and STS transition training alone would not be the most effective option for maintaining physical functioning.

2.3 Assessment of physical function and activity in a free-living environment

2.3.1 Device-based physical activity assessment

Traditionally, physical activity has been assessed using structured questionnaires such as the International Physical Activity Questionnaire and the Yale Physical Activity Survey (Craig et al., 2003; Dipietro et al., 1993). However, these have been found to measure different physical activity behaviours, and their results do not necessarily correspond to each other (Ferrari et al., 2020; Garriguet et al., 2015; Sylvia et al., 2014). Physical activity can also be assessed objectively using wearable devices such as pedometers and accelerometers (Schrack et al., 2016) and this literature review focuses on measuring physical activity in a free-living environment. Wearables are mainly worn in four different locations (the chest, hip, wrist, or thigh) and are often attached with a wristband, waterproof film, or elastic straps (Allahbakhshi et al., 2019). Accelerometers measure the acceleration experienced by the device, which is then processed to provide an estimation of physical activity intensity. A significant part of processing includes determining different physical activity levels using acceleration cut-off points. The most frequently used categories are sedentary, light, moderate, and vigorous (Norton et al., 2010). In addition, a MVPA combination category can be formed.

Previously mentioned sedentary activity has an energy expenditure level of < 1.5 MET and involves lying, quiet sitting, watching TV, and driving a car. Light activity is defined for the 1.6- to 3.0-MET level. Light activity is an aerobic activity that does not cause a change in breathing rate and, in practice, includes household walking and playing darts. Moderate activities are aerobic activities that may cause a change in breathing rate but enable speaking, such as walking and cycling. Moderate activity is defined for the 3.0- to 6.0-MET level. Vigorous intensity is defined as a level where the energy expenditure is > 6.0 MET and can be achieved through running or swimming. During vigorous activities, speaking more than two words at a time is challenging (Norton et al., 2010).

Before defining the cut-off points for physical activity levels, the data must be processed. One way to do this is to calculate the resultant acceleration magnitudes of all accelerometer axes (x, y, z) for sampling instants and calculate the mean amplitude deviation (MAD; in g) for non-overlapping 5 s epochs using the method published by Vähä-Ypyä and colleagues in 2015 (Vähä-Ypyä et al., 2015). In addition, the ActiGraph (AG, Pensacola, FL) activity meter 'counts' are widely utilized. These 'counts' are derived from the summation of post-filtered accelerometer values into epochs, accompanied by the utilization of specific cut-off points for distinguishing various levels of physical activity intensities (Freedson et al., 1998; Hart et al., 2011).

The location of the device has been found to have significant effects on the assessment of physical activity (Cleland et al., 2013; Kerr et al., 2017; Schall et al., 2016; Watson et al., 2014) and cut-off points are often defined separately according to the location of the devices (Arif & Kattan, 2015). However, there are no commonly accepted values for cut-off points, and how the durations of different activity levels are separated from each other after pre-processing (Gorman et al., 2014). Furthermore, this has been recognized, and recently, efforts have also been made to unify the cut-off points (Clevenger et al., 2022), but this work is just beginning. This will enable the comparability of studies because variations in researcher-driven decisions about processing methods have made it difficult to compare study findings (Brady et al., 2022). Figure 6 shows by way of illustration the physical activity levels of four randomly selected older adults from the AGNES dataset (Rantanen, 2022) during the 24-hour period using the following cut-off points: light, 0.0420; moderate, 0.2375; and vigorous, 0.6285 (White et al., 2019).

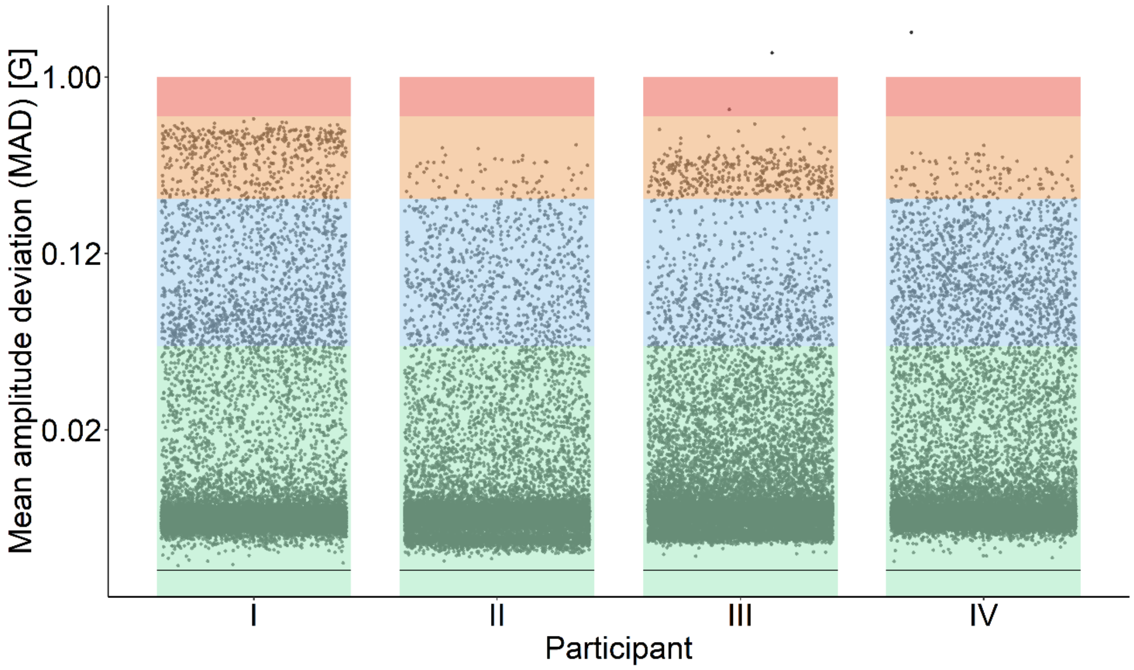

FIGURE 6. Example data of physical activity over a 24-hour period. Divided into 5 s bouts (1 point is 1 bout) and cut-off points for sedentary (green), light (blue), moderate (orange), and vigorous (red) intensities. Noise of 0.003 g marked with a cross line for the UKK RM42 device.

Traditionally, fixed cut-off points have been employed for differentiating physical activity intensities and have been recommended for objective assessment of compliance with physical activity recommendations (Vähä-Ypyä et al., 2022). However, individually defined relative thresholds may benefit individualised physical activity prescriptions in physical activity counselling (Vähä-Ypyä et al., 2022). Relative physical activity cut-off points can eliminate the dependency of physical activity on age and gait speed (Karavirta et al., 2020). Moreover, it can be used to measure intensity relative to maximal capacity (Siddique et al., 2020).

As previously mentioned, physical activity intensity levels such as MVPA time (in minutes) have been used against a single-response variable such as quality of life or perceived health. In addition, compositional analysis, which has become popular in recent years, can be used to study interactions between different activity levels and sedentary time and their effects on health and functional capacity variables (Amagasa et al., 2022; Collings et al., 2023; Farrahi et al., 2021). By using composition analysis, replacing sedentary time with MVPA has been found to be associated with cardiometabolic risk factors and light physical activity assigns additional and unique metabolic benefits (Collings et al., 2023).

As previously mentioned, behind the activity minutes are always more specific activities such as walking, standing, transitions, running, swimming, cycling, housework, and upper body movements (Allahbakhshi et al., 2019). When detecting these activities, one approach is first detecting the person's posture position in the accelerometer signal (Vähä-Ypyä et al., 2018), after which, more specifically, detecting types of activities is easier. In 1996, the distinction between the cyclical dynamic activities of walking, stair ascent, stair descent, and cycling was detected using two uniaxial thigh and sternum-worn accelerometers (Veltink et al., 1996). After that, recent studies have concluded that accelerometers can be used to reliably detect different positions and physical activity types in a free-living environment (Arif & Kattan, 2015; Bach et al., 2021; Crowley et al., 2019; Skotte et al., 2014; Stemland et al., 2015).

The sensitivity and specificity of the assessments have been at a high level. In 2014, a study by Skotte and colleagues (2014) found that the sensitivity for discriminating between the physical activity types, namely sitting, standing, walking, running, and cycling, in the standardized trials were 99–100% and 95% for walking stairs using ActiGraph GT3X+ (Skotte et al., 2014). With similar hardware and software, in the following year, Stemland and colleagues (2015) found reasonable estimates (sensitivity, 75–99% and specificity, > 90%) of time spent on different activity types (i.e. lying, sitting, standing, walking and running) in semi-standard environments and for sitting, standing, and walking in a non-standard environment with typical movement complexity (Stemland et al., 2015). With an advanced machine learning classifier (XGBoost) and two thigh- and low back-worn Axivity AX3 accelerometers, daily physical activity types (lying down, sitting, standing, walking, running, or cycling) in a free-living environment could be identified with an accuracy of 96% for the dual accelerometer setup and 93% and 84% for the single thigh and back accelerometer setups, respectively, when the results were compared with the activities assessed from the GoPro camera video (Bach et al., 2021).

At the moment, several accelerometers from different manufacturers in active research are used to assess physical activity and its types. ActiGraph, activPAL (PAL Technologies Ltd. Glasgow, United Kingdom), and Fibion (Fibion Inc, Jyväskylä, Finland) are currently more common in addition to a few universal devices. Although accelerometers of different brands differ in hardware components and analysis methods, their physical behaviours can be classified with negligible differences (Clark et al., 2021; Crowley et al., 2019). On the other hand, more research is needed. For example, for Fibion, a large cohort is necessary to confirm its usability, especially for detecting low-intensity PAs (Yang et al., 2018). In addition, compatibility is especially important in follow-up studies, it is important to use a device of the same brand on the same leg to optimise reliability (Montoye et al., 2022).

Once the type of activity has been detected, the intensity of these activities can now be quantified, offering detailed information about daily activities. The most commonly studied submaximal activity in a free-living environment is gait. Gait speed has been quantified using a mobile phone (Kawai et al., 2020; Nomura et al., 2021), a trunk-worn inertial sensor with a tri-axial accelerometer (Van Ancum et al., 2019), a wrist-worn device (Soltani et al., 2021), and a waist-worn accelerometer (Takayanagi et al., 2019), in which case, gait speed in daily life can be compared with gait speed in the laboratory or health problems. However, measuring gait speed in a free-living environment is challenging, and standard protocols still need to be established.

2.3.2 Assessment of strength-demanding activities in a free-living environment

Analysing strength-demanding activities in a free-living environment such as stair walking and STS transitions requires more complex data analysis, than just identifying the type of activity. In these analyses, the aim is often to find all these activities in free-living recordings rather than just trying to find selected and successful repetitions. Recently, stair walking has been monitored especially in the laboratory, but methods have also been implemented for free-living environments. The common method used is the identification of walking upstairs using a shank-worn miniature gyroscope, a device used for measuring or maintaining orientation and angular velocity and therefore detecting the rhythm of stair walking (Coley et al., 2005; Formento et al., 2014). In addition, stair walking has been detected by a combination of a machine learning algorithm and a lower back-worn accelerometer or an accelerometer and gyroscope combination (Psaltos et al., 2022), thus detecting periods of stair ascent with >89% accuracy. Analyses aimed at detecting stair walking are still preliminary, and to the best of our knowledge, no epidemiology studies have been conducted among community-dwelling older adults.

Another strength-demanding activity whose method development is much further in free-living environment is STS transitions. Previously, STS transitions were detected using three-axis accelerometers and inertial measurement units relatively accurately. Various sensor locations, such as wrist, lower back, sternum and thigh, have been used to monitor free-living STS transitions (Klenk et al., 2022).The widely used commercial thigh-worn activPAL sensor with a closed algorithm for detecting STS transitions in a free-living environment and especially the number of daily STS transitions have been extensively studied (Bohannon, 2015; Mitchell et al., 2017; Pickford et al., 2019) and the number of STS transitions it detects has been found to correlate with video observation in studies conducted on children (Aminian et al., 2012). Rodríguez-Martín achieved a sensitivity of 88.2% and a specificity of 98.6% using a single waist-worn inertial sensor and a novel postural transition detection algorithm (Rodríguez-Martín et al., 2012). Atrsaei and colleagues achieved a mean positive predictive value of 98% and a mean sensitivity of 95% for healthy individuals, also with a single waist-worn inertial sensor (Atrsaei et al., 2020). Pham et al. (2018) introduced an algorithm that uses data from a single inertial sensor on the lower back and yielded a detection accuracy of 82%. In addition to these methods, the scikit-digital-health (Python) open-source software package (Adamowicz et al., 2020, 2022) was recently published. It implements algorithms from STS detection from lumbar inertial data. However, no publications are currently available.

When the STS transition has been detected, its intensity or velocity can be assessed in a free-living environment. In general, the intensity or velocity of STS transitions have been measured by detecting the start and end point of the transition and, therefore, the time spent on the transition (Janssen et al., 2008; Vissers et al., 2011). In this case, the accurate detection of the beginning and end of the movement also plays a central role, which can be challenging. This can be avoided by placing the sensor on the thigh and calculating the thigh angular velocity during STS transitions. However, this method has been used to a very limited extent in free living environment. Pickford and colleagues compared the peak thigh angular velocity between stroke and healthy patients using the activPAL proprietary software algorithm (Pickford et al., 2019) precisely by focusing on evaluating thigh angular velocity and peak angular velocity has been found to be in good agreement with a gold-standard in study where participants where mainly middle-aged adults (Vicon MX+, Vicon Motion Systems, Oxford, UK) (Klenk et al., 2022).

To sum up, studying STS transitions in a free-living environment using present technology appears to be reliable. However, they have yet to be studied extensively among older adults, even though STS transitions are central to ADL functions and independent living. In addition, more information is needed regarding the intensity (i.e., duration or velocity) of STS transitions in free-living conditions.

2.4 Summary of the literature

Functioning can be determined using the ICF framework published by the WHO. Functioning is a multidimensional concept divided into several dimensions: physical, mental, cognitive, and social functioning, of which this thesis focused especially on physical functioning. Physical functioning is often measured in laboratory-environment using standardized test protocols where a short physical performance battery (SPPB) is a widely used tool to assess lower-extremity functioning. In a free-living environment physical functioning is often approached via ADL/IADL activities which have been studied with questionnaires, but there are limited studies focused on the objective assessment of physical functioning in the free-living environment. According to the ICF, the physical functioning domain can be operationalized into two qualifiers: laboratory-based capacity and free-living performance. Recent studies have found that the capacity measured in the laboratory and the performance measured in a free-living environment are different constructs, and capacity does not necessarily determine daily performance for everyone. Future studies should aim to improve the understanding of the associations between these qualifiers and investigate whether the performance measured in the free-living environment can provide additional information for predicting the decline in physical functioning. This literature review clarified that this definition of terminologies is not consistently used, and in the future, it will be important to clarify current terminology as the monitoring of free-living environment develops.

The literature review revealed that physical activity is also a multi-dimensional phenomenon and positively associated with health and good life. Physical activity research has developed strongly in recent decades in the direction of objective measurement. Although physical activity has been studied using objective methods for a long time and different types of physical activity can be identified reliably, limited studies have focused on strength-demanding daily activities among older adults especially using open and universal methods. In addition, there has been a limited attempt to quantify the variables describing the intensities of strength-demanding daily activities from the data measured in a free-living environment. Nowadays, this is possible through advanced sensor technology, owing to not only advanced sensors (accelerometers, gyroscopes, etc.) but also advanced computing capacity (supercomputers) that makes it possible to analyse raw signals in a feasible time. Furthermore, constantly developing artificial intelligence and extensive open data enable new ways to analyse physical activity even more precisely. The possibilities are significant because current technology enables the measurement of kinematic variables in the individual's living environment, whereas previously they could only be done in standardized laboratory environment. However, many methods are still in the development phase, and when reviewing the results, it is important to consider the accuracy of the estimates.

Advanced sensor technology has enabled completely new types of physical activity research targets. One of these is activities and movements which require sufficient lower extremity strength among older adults include various transitions such as getting up from a chair, bed, or toilet seat which are essential in performing ADL and iADL. Since these strength-demanding activities are central to independent living, studying them objectively in a free-living environment using novel methods can provide a new indicator for the decline in physical functioning. In addition, studying these activities a free-living environment can touch a different phase in the four-step disablement process. Thus, it can complete information in the early identification of physical functioning decline in addition to traditional laboratory-based capacity and strength tests for example by adding information about lifestyles, physical activity, hobbies and living environment requirements. This study focused on the STS transitions, which are one of the most common strength-demanding daily activities among older adults and which have been studied relatively limited, especially in free living environment.

Currently, many technical solutions aimed to measure free-living kinematics are multi-sensor systems or inertial measurement units that consume a lot of current. The limitation of these solutions is the short monitoring period due the battery life, which does not allow an adequate assessment of physical behaviour. For this reason, multi-day monitoring should use solutions that pay attention to a simple solution. Based on the literature review, the most practical way to identify STS transitions is to attach the sensor to the thigh, where the body segment makes a clear change of position during the STS transition, and thus the use of a low-current tri-axial accelerometer is also possible. Based on the literature review, the commercial thigh worn ActivPal device is capable of measuring STS transitions and their peak angular velocity, but since it is a proprietary closed algorithm and measure only peak angular velocity, we developed an open algorithm whose accuracy can be evaluated, the data recorded by universal sensors can be analysed and whose data can be combined with other physical activity measures.

3 AIM OF THE STUDY

The primary aim of this study was to determine whether STS characteristics can predict a prospective decline in physical functioning among community-dwelling older adults. To address the primary aim, we first developed an algorithm to detect STS transitions in free-living environments and examined the association between laboratory-based measurement and STS characteristics produced by algorithm. The specific aims of the present thesis are outlined as follows:

> 1) Methodological development: The first part of the thesis was aimed at developing an open and universal algorithm that can be used to detect STS from data produced by a single thigh-worn accelerometer and investigate its accuracy and reproducibility (Study I). The specific aims were as follows:
>
> (a) to develop an accurate and open algorithm that can detect STS transitions and quantify their angular velocity in a free-living environment using a one thigh-worn accelerometer;
>
> (b) to evaluate the day-to-day variability and year-to-year reproducibility of the algorithm in a free-living environment among community-dwelling older adults;
>
> 2) Understanding the association between the different constructs: The second part of the thesis compared how free-living STS characteristics differed between age and sex groups, how they associated with laboratory-based capacity measurements and self-reported fear of falling, and stair negotiation difficulties (studies II and III). The specific aims were as follows:
>
> (a) to compare the number of STS transitions and their angular velocity in free-living between age and sex groups;

(b) to evaluate the associations between free-living STS characteristics and laboratory-based lower extremity capacity measurements; and

(c) to evaluate the associations between free-living STS characteristics, self-reported fear of falling, and stair negotiation difficulties.

3) Predictive value for future physical functioning declines: The third part of the thesis investigated whether the free-living STS characteristics could be an indicator of future declines in physical functioning during a 4-year follow-up period among community-dwelling older adults and added value of combining laboratory-assessed strength and free-living STS characteristics into one prediction model (study IV).

4 METHODS

4.1 Datasets and study designs

This study utilized data from three study projects: the AGNES project, Leuven project, and Finnish Retirement and Aging (FIREA) project. All persons who participated in these projects were community-dwelling individuals aged 60–90 years.

TABLE 1. Datasets, study designs, and participants in the different studies (I–IV).

Study	Dataset	Design	n (% women)	Age (years)
I, II	AGNES Baseline	Cross-sectional	479	75–85
I	AGNES Intervention	Longitudinal	86	75–85
III, IV	AGNES 4-year follow-up	III: Cross-sectional IV: Longitudinal	III: 23 IV: 340	79–89
III	Leuven	Cross-sectional	63	60–90
III	FIREA	Cross-sectional	188 (83%)	60–64

The AGNES dataset included three data collection waves. The AGNES baseline data were collected from 75-, 80-, and 85-year-old people in Jyväskylä between 2017 and 2018, and the AGNES intervention measurements were obtained between October 2018 and August 2019. Data from the AGNES 4-year follow-up, which is the 4-year follow-up phase of the AGNES baseline dataset, were collected in 2021–2022 (Table 1 and Figure 7). The Leuven dataset measurements were performed between 2020 and 2022 in Flanders, Belgium, among 60- to 90-

year-olds. The FIREA dataset was collected from 60- to 64-year-old people in Turku, Finland, in the period 2017–2018.

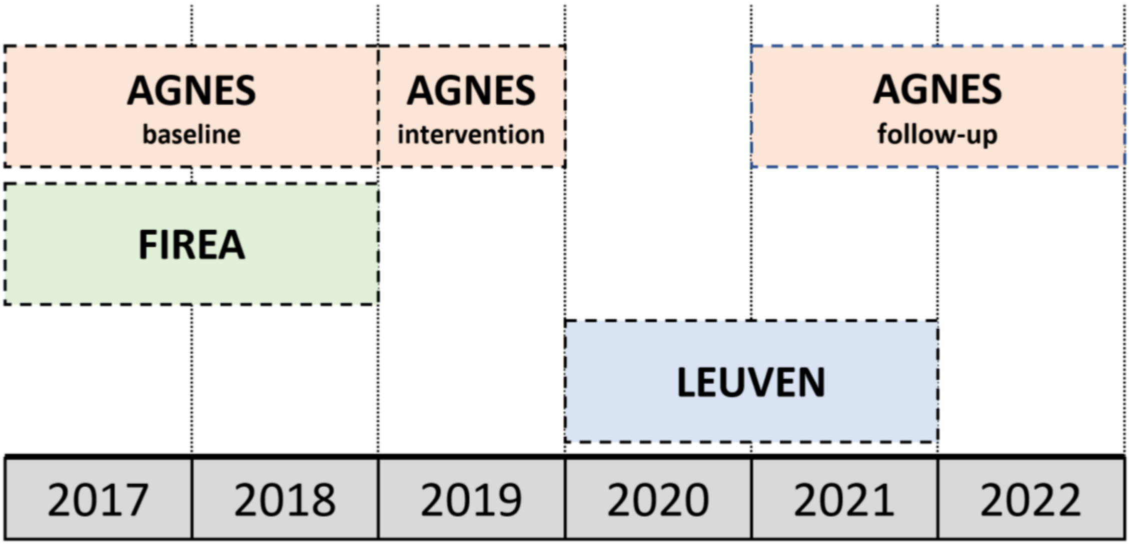

FIGURE 7. Timeline for data collection across different projects.

4.1.1 Active ageing (AGNES, studies I–IV)

AGNES cohort (studies I and II)

The first dataset consisted of data from the AGNES study. This study investigated the determinants and modifiers of active ageing by collecting data on activity, health, and physical and cognitive functioning (Rantanen et al., 2018). We invited participants for a home interview, clinical assessment, and physical and cognitive performance tests in our laboratory at the Faculty of Sport and Health Sciences, University of Jyväskylä. All participants were living independently in the municipality of Jyväskylä, Finland. For the baseline data, a total sample of 2791 participants was drawn from the Finnish population register, and 2348 individuals were asked by telephone if they would be willing to participate. The inclusion criteria were age and residence in the study area, willingness to participate in the study, and the ability to communicate (Rantanen et al., 2018). After exclusions, 1021 individuals participated in the study, of whom 479 wore a triaxial accelerometer for 3 to 7 consecutive days.

AGNES intervention (study I)

In study I, which examined the year-to-year reproducibility and day-to-day variability of the STS detection and quantification algorithm, data from the participants of the AGNES counselling intervention measurements were used (75 and 80 years of age). The counselling intervention did not affect the participants' physical activities, so the intervention and control group data were pooled. This resulted in 86 (3–7 days continuously) recordings repeated at 1-year intervals.

AGNES 4-year follow-up measurement in the cross-sectional setting (study III)
Data from the 4-year follow-up of the AGNES project were used as the dataset for study III. This dataset consisted of participants aged 79, 84, or 89 years (n = 679). The measurements were performed in 2021–2022. The 4-year follow-up cross-sectional setting included participants with at least 3 days of free-living accelerometer data and valid instrumented STS test, resulting in a total of 236 participants (women 53%). This cross-sectional dataset was combined with the FIREA and Leuven datasets, thus forming a pooled research data of 497 participants. Visual inspection did not show conspicuous differences (similarity of associations and overlap between values) between the cohorts in the free-living STS variables, so we concluded that it was reasonable to pool the datasets.

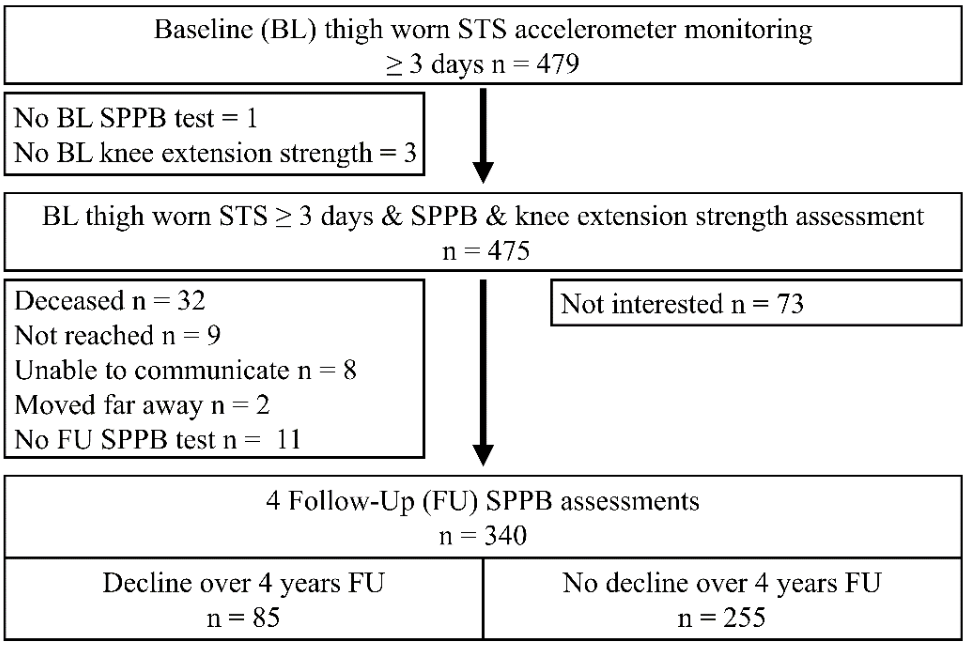

FIGURE 8. Flowchart of the AGNES 4-year follow-up measurements in the longitudinal setting (study IV). Decline over 4 years of FU = decline in total SPPB score was at least two points (≥ 2) over the 4-year follow- up (from BL to FU). No decline over 4 years of FU = decline in total SPPB score was < 1 point (≤ 1) over the 4-year follow-up (from BL to FU). STS = sit-to-stand, BL = baseline, FU = follow-up, SPPB = Short Physical Performance Battery.

AGNES 4-year follow-up measurements in the longitudinal setting (study IV)
In study IV, the AGNES baseline and 4-year follow-up measurements were combined into the longitudinal setting. Of the 479 potentially eligible older adults, 73 were not interested, 32 were deceased, and 34 were excluded (not reached, missing data). Hence, the final sample consisted of 340 participants (Figure 8) who had at least 3 days of successful accelerometer recordings at baseline, isometric knee extension isometric force data, and total SPPB score and participated in a follow-up complete set of SPPB measurements. The participants whose decline in total SPPB score was more than 2 points (substantial, meaningful change)

(Kwon et al., 2009; Perera et al., 2006) were classified into the group with a 'decline in lower extremity functioning' over 4 years of follow-up, and those with a decline of 1 or 0 points or improvement were classified into the group with 'no decline in lower extremity functioning'. This was determined as the dependent variable in study IV.

4.1.2 Leuven study (study III)

The second dataset consisted of data from the Leuven cross-sectional study. This study was aimed at testing the reliability of a sensor-based technology to assess physical functioning (i.e., stair climbing and STS transitions) in the laboratory and examine age-related trajectories. Men and women living independently in Flanders, Belgium, who belonged to the following age categories were recruited for the study: 20–39, 40–54, 55–64, and ≥ 65 years. The target sample was n = 50 per group (men, n = 25 and women, n = 25) for the youngest two age groups and n = 100 per group (men, n = 50 and women, n = 50) for the oldest two age groups. The participants were asked to wear an accelerometer in the free-living environment, although this was not obligatory. In study III, we only included participants older than 60 years with at least 3 days of free-living accelerometer data, which included a total of 62 (women 45%) independently living participants aged 60–90 years.

4.1.3 FIREA (study III)

The third dataset was from the FIREA, an ongoing longitudinal cohort study of older public sector workers (Leskinen et al., 2018). This study was aimed at examining health behavioural and clinical risk marker changes during retirement transition by following older workers from work to full-time retirement and included 773 participants. The FIREA was established at the University of Turku in 2013. In study III, we included participants from the clinical sub-study. We used their baseline measurements when the participants were still working and had at least 3 days of free-living accelerometer data and valid instrumented STS test, resulting in a total of 188 participants (women 83%) aged 60–64 years (Stenholm et al., 2021).

4.2 Ethical considerations

All participants in the AGNES, LEUVEN, and FIREA studies signed an informed consent form when they entered the study, and the research ethical principles required at the time were followed. All participants of the FIREA, LEUVEN, and AGNES studies were informed about the nature of the study and how data would be used and managed.

The Central Finland Hospital's ethical committee approved the AGNES baseline research plan (23 August 2017) and follow-up study (8 September 2021).

Ethical Committee Research UZ/KU Leuven (S62540) approved the research plan of the LEUVEN study, and the Ethical Committee of the Hospital District of Southwest Finland approved the research plan of the FIREA study (84/1801/2014).

The digital data gathered for both studies were stored and treated confidentially on the University of Jyväskylä, University of Turku, and KU Leuven servers. The pseudonymized data were accessible to the researchers behind university passwords and only members of the research group had access to the data.

4.3 Measurements

All descriptives, laboratory-based, and free-living STS measurements are presented in Table 2.

TABLE 2. Summary of outcomes and independent variables.

Variable/Measurement	Study	Methods and Reference
Descriptives variables		
Age	I-IV	DVV (AGNES and FIREA) and self-reported (LEUVEN)
Sex	I-IV	
Education	I, IV	(Rantanen et al., 2018)
Number of chronic conditions	I, IV	(Rantanen et al., 2018)
Mini-Mental State Examination (MMSE)	I-IV	(Folstein et al., 1975)
Moderate-vigorous physical activity (MVPA)	I	(Vähä-Ypyä et al., 2015)
Mean amplitude deviation (MAD)	I	(Vähä-Ypyä et al., 2015)
Laboratory-based variables		
Short Physical Performance Battery (SPPB)	I-IV	(Guralnik et al., 1994)
Isometric knee extension force	II, IV	(Rantanen et al., 1997)
Instrumented 5×STS	III	
Free-living STS variables		
No of STS transitions	I-IV	STS detection and quantification algorithm (Rantalainen, 2021b)
Maximal STS angular velocity	I-IV	
Mean STS angular velocity	I-IV	

DVV = Digital and Population Data Services Agency.

4.3.1 Accelerometer-based free-living measurements

For the AGNES and LEUVEN datasets, we used the UKK RM42 activity monitor, which is a compact (size, 35 × 27 × 9 mm and weight, 9.3 g) and universal tri-axial accelerometer with a long battery life (7–9 days), manufactured by the Finnish company UKK Terveyspalvelut Oy (Tampere). UKK RM42 measures sampling continuously at 100 Hz using 13-bit analogue-to-digital conversion and has an acceleration range of ±16 g.

In the FIREA dataset, we used Axivity AX3, a compact (size, 23 × 32.5 × 7.6 mm and weight, 11.0 g) tri-axial accelerometer manufactured by Axivity Ltd. (York, United Kingdom). AX3 measures sampling continuously at 100 Hz and uses 13-bit analogue-to-digital conversion, with an acceleration range of ±8 g.

UKK RM42 and Axivity AX3 were attached by a research assistant to the anterior aspect of the mid-thigh of the dominant leg (defined primarily as the take-off leg, secondarily as the kicking leg, and thirdly as the leg on the side of the dominant hand). In practice, the attachment was made by placing the acceleration sensor against the skin and attaching it with a transparent adhesive film for covering to make it water resistant and to minimize non-wear.

4.3.1.1 Accelerometer-based STS transitions

The first part of this thesis was conducted to develop an algorithm for detecting STS transitions in a free-living environment and quantify their intensity. The algorithm uses data produced by a single thigh-worn triaxial universal accelerometer. The algorithm is open to the public and has been published as a complete GitLab environment by the University of Jyväskylä 2021 (Rantalainen, 2021b). The algorithm was developed using MATLAB R2018a (MathWorks Inc., MA), but analyses have also been done with the newer versions R2021b and R2022b.

In the first phase of the algorithm, the magnitude (Euclidian norm) of the resultant acceleration for each sampling instant was calculated from raw accelerometer data. The MAD was calculated in non-overlapping 5 s epochs based on the magnitude of the resultant acceleration (resultant magnitude = $\sqrt{x^2 + y^2 + z^2}$) (Vähä-Ypyä et al., 2015).

To detect the direct orientation of the thigh, we calculated an angle for postural estimation (APE) from resultant acceleration values using the method described by Vähä-Ypyä et al. (2018). The calculation requires knowing the direction of the gravitational pull when the participant is in the upright position (reference vector). This was defined as the median of the mean X, Y, and Z accelerations of each continuous bout of ≥ 20 s with the MAD between 0.035 g (g is the acceleration of Earth's gravity) and 1.2 g. These MAD cut-off points were determined from the AGNES baseline dataset laboratory session 6 minute walking test. The data included all participants; hence, bouts with such characteristics comprised walking. During walking, the mean orientation of the thigh is upright, and the median acceleration is equivalent to that caused by the pull of gravity. The instantaneous acceleration in each recorded direction was low-pass filtered with a 1 Hz zero-lag Butterworth filter, and the APE signal was subsequently calculated for each time instant as the vector angle between the instantaneous filtered acceleration and reference vectors. After that, the APE signal was smoothed with a 4th order Butterworth zero-lag low-pass filter with a 10 Hz cut-off frequency. The filtered APE signal was transferred into a rectangular signal with a value of 1 when the APE signal was < pi (≈3.14)/4 and, otherwise, a value of 0. That is, upright and horizontal thigh postures were assigned 1 and 0 points, respectively. This rectangular signal was then smoothed with a sliding median filter of 23 samples to produce the final posture estimation signal. The 23 sample length for the median filter and the two (1 and 10 Hz) Butterworth filter cut-off point frequencies were selected on the basis of experimentation.

The STS transitions were detected as follows: all posture estimation signal transitions from 0 (horizontal) to 1 (upright) were considered candidate STS transitions. A candidate was accepted as an STS transition when the following three criteria were met (Figure 9):

(a) The variance of the magnitude of the resultant acceleration between 2.5 and 0.5 s before the candidate transition was < 0.02 *g* (i.e., the participant had been stationary for at least 2 s before the transition).
(b) The starting angle of the STS transition (APE signal) was > 65 degrees (1.14 radians).
(c) The movement of the STS transition ended at an angle of < 35 degrees (0.61 radians).

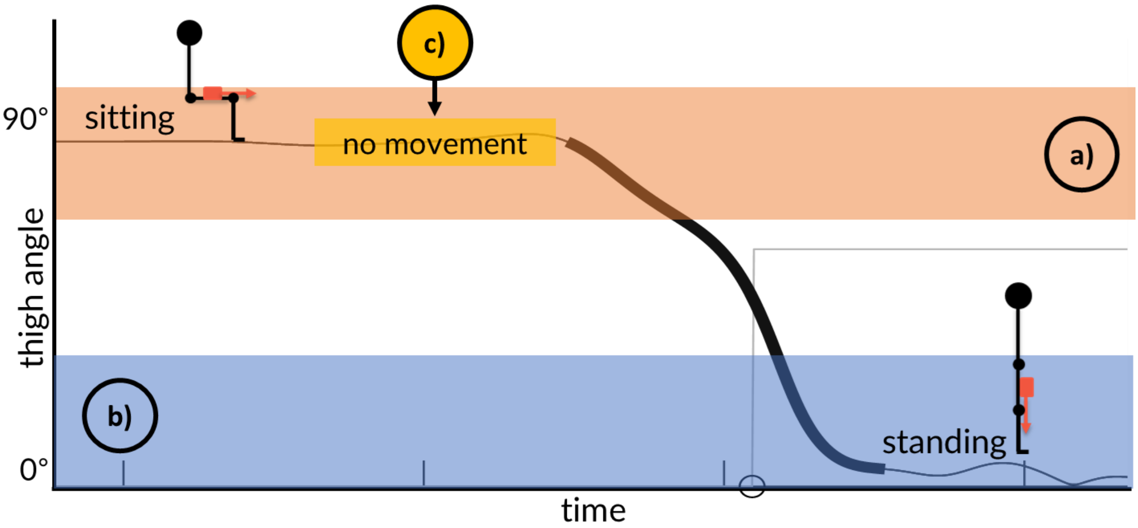

FIGURE 9. Placement of the STS transitions between daily activities (represented by blue bars).

The selections of the criteria for the beginning and end of the STS transitions were based on the previous kinematic variables of STS transitions in the older adults and the basis of experimentation (Dehail et al., 2007; Fotoohabadi et al., 2010). Owing to the variance criterion, the algorithm will only detect the first of a set of STS movements (e.g., if an individual performed continuous seat-based squatting starting from a seated posture, only the first STS would be included).

The intensity of a detected STS transition was estimated on the basis of the APE signal time derivative (i.e., angular velocity) as follows: the baseline APE signal (corresponds to the thigh angle prior to the STS transitions) was established as the mean between 2.5 s and 1.5 s to the detected transition instant. The last sample at the baseline value prior to the transition instant was after that set as the initiation of the angular velocity determination. Linear fits were applied to each data set from the initiation sample until the transition instant to transition instant + 0.15 s with one sample length increment. The longest fit where the square of the last instant of the fit and the APE signal differed by less than the experimentally determined 0.005 degrees was chosen and the slope of the chosen fit is reported as the STS transition intensity.

The angular velocity quantification accuracy of the STS detection and quantification algorithm was checked using a two-dimensional (2D) motion analysis. Three people participated in the pilot measurement and performed STS transitions at different velocities. A camera was placed on a tripod 4 meters from the participant so that the camera was facing the lateral side of the participant's body. Two markers were placed on the knee (lateral epicondyle of the femur) and the midpoint of the thigh. The knee joint angles were determined around these points. Markers were digitized using an open-source Java-based digitization tool (Rantalainen, 2021a). The results of this study are presented partly in section 5.2, and the entire measurement data, all videos, MATLAB code, and all results are available online (https://cmj.sport.jyu.fi/sittostand/).

Accelerometer-based STS variables. The participants needed at least 3 days (complete 24-h measurement days) to be included in the analyses. The volume of the free-living STS transitions was determined as the mean number of transitions per complete 24-h monitoring day. In determining the mean free-living STS angular velocity (mean performance), the median angular velocities [degrees/seconds] of the STS transitions were first calculated for each complete monitoring day, and the mean was calculated from these daily medians. The maximal free-living STS angular velocity (maximum performance) of the STS transitions was determined as the median of the 10 fastest STS transitions over the monitoring period. In studies III and IV, this was done using complete 24-h monitoring days, and in studies I and II, the start and end days were included for maximal free-living STS angular velocity determination.

In study III, where the 5 × STS test was instrumented, none of the participants exceeded 4 radians/seconds; therefore, we filtered out any STS transitions > 4 radians/seconds from the data prior to the estimation of the maximum free-living angular velocity. In study II, 79 transitions were removed because of this, which was 0.04% of the 182,103 transitions detected in this dataset. In study III, 73 transitions were removed because of this, which was 0.036% of the 97,401 transitions detected in this dataset.

4.3.1.2 Laboratory-based and instrumented STS tests

When determining the STS capacity from an STS test (study III), the above-mentioned free-living STS detection algorithm was modified to enable detecting multiple consecutive STS transitions. To determine the median angular velocity of the STS test repetitions, the algorithm's stationarity criterion (criteria a) was disabled so that repeated transitions could be detected. The stationarity criterion was re-enabled for the free-living analyses.

The STS capacity was determined by manually extracting the tests from the first day of the recording and calculated as the median of the thigh angular velocity of five test repetitions. The data that included those from the STS test were collected before the first midnight of the recording and were therefore disregarded in the free-living STS analyses.

4.3.2 Isometric knee force measurement

In AGNES baseline dataset maximal knee extension strength of the dominant lower extremity with the knee at 60 degrees was measured in a sitting position using an adjustable dynamometer chair (Metitur LTD, Jyväskylä, Finland) in the laboratory. At least three attempts were required, and the highest force was chosen for the analyses (Rantanen et al., 1997). The device reported the result in newtons and normalized it for body mass (Corrigan & Bohannon, 2001).

4.3.3 Short Physical Performance Battery

In all the datasets, the most important assessment measure of the physical functioning of the lower extremity was the Short Physical Performance Battery (SPPB). The SPPB is comprised of sub-tests on standing balance, gait speed over a 3-m distance, and the 5 × STS. Each sub-test is rated from 0 to 4 points according to established cut-off points (Guralnik et al., 1994; Guralnik et al., 1995; Guralnik et al., 2000). In this study, we used the total SPPB score (maximum of 12 points, higher scores mean better performance) and the time of the 5 × STS test as outcomes (lower time means better performance).

In accordance with the standard protocol, the participants held their legs in a side-by-side, semi-tandem, and tandem position in the standing balance subtest for 10 s. In the walking test, the time in the 3-m usual-pace walk was used as the official result. The STS test started with the participant seated and ended at the fifth standing position. The participants were asked to stand up as fast as possible to full (hips and knees) extension and to sit down with their back touching the back of the chair for five (or ten) consecutive repetitions. The height of the chair was 45–46 cm.

In the AGNES datasets, the SPPB was conducted under the guidance of a research assistant at the participant's home using a standardized procedure and in the FIREA and LEUVEN datasets in a research laboratory.

4.3.4 Descriptive characteristics and cognitive function test

In the AGNES and FIREA datasets, age and sex were extracted from the population register. In the LEUVEN dataset, age and sex were self-reported. In all datasets, body height (stadiometer) and body mass (digital scale) were assessed using standardized procedures (Rantanen et al., 2018). Cognitive function was assessed using the Mini-Mental State Examination (MMSE) (Folstein et al., 1975).

In the AGNES dataset (study II), fear of falling was assessed with the question, 'Are you afraid of falling?' with four response options: never, occasionally, often, and constantly (Rantanen et al., 2012). In this study, 'never' was categorized as 'No fear,' and the rest of the response options were compounded into 'Yes fear'. Difficulties in negotiating stairs were assessed with the question, 'Have you noticed any of the following changes in your ability to ascend a flight of stairs?' The responses were categorized as 'No difficulties', 'I can ascend a flight of stairs, but I have some difficulties', 'I can ascend a flight of stairs, but I have a lot of difficulties', 'I cannot ascend a flight of stairs without help of another person', or 'I cannot ascend a flight of stairs even with help'. In the present study, 'no difficulties' was categorized as 'No difficulties', and the rest of the response options were compounded into 'Yes difficulties'. None of the participant reported, 'I cannot ascend a flight of stairs even with help'.

In the descriptive data from the AGNES dataset (studies I and II), self-reported habitual physical activity was assessed using the 8-item Yale Physical Activity Survey for older adults. The total score ranged from 0 to 137, and higher scores indicated higher physical activity (Dipietro et al., 1993). Device-based physical activity was evaluated from the multiple-day accelerometery records as the daily MAD analysed in 5 s epochs (Rowlands, 2018). In addition, MVPA minutes were estimated as the daily sum of minutes > 0.24 *g* MAD. We previously used 0.24 *g* as the cut-off point for high-pass-filtered vector magnitude (HPFVM) (Karavirta et al., 2020). The MAD and HPFVM calculations resulted in nearly identical numerical values; therefore, we deemed it appropriate to apply the HPFVM-based cut-off point for the MADs for the MVPA analysis.

4.4 Statistical analysis

In all studies, statistical significance was set at $p < 0.05$, and analyses were performed in the 'R' statistical environment (version 4.2.1) (R Core Team, 2021) using the SPSS statistical software package (IBM SPSS Statistics Version 28.0.1.1, SPSS Inc., Chicago, IL) (SPSS, 2021). No significant amount of missing data were found in any of the studies, so no imputation was performed on any dataset. The power calculations of the AGNES study are presented elsewhere (Rantanen et al., 2018). In addition, power calculations were made using the G*POWER software (version 3.1.9.2) (Erdfelder et al., 2009), with an alpha (a) value of 0.05, two tails, a power ($1-\beta$) of 0.80, and a minimum correlation assumption (ρ H1) of 0.3 based on previous research (Giannouli et al., 2016; Ryan et al., 2008). On the basis of these assumptions, the required sample size was 84. All the data in this study also exceeded this in the age and sex sensitivity analyses.

4.4.1 Descriptive statistics and group comparisons

The results of the STS and descriptive characteristics are reported as means and standard deviations (SD). The results of the Shapiro-Wilk normality tests and visual inspection of distributions indicated that some variables were not normally distributed, and consequently, non-parametric statistical tests were chosen.

Sex- and age-group differences were analysed with the independent-samples Mann–Whitney *U* (Wilcoxon rank-sum) and Kruskal–Wallis test. Tertile comparisons in study II and physical functioning comparisons in study III were performed using the Kruskal–Wallis multiple comparison tests and the Dunn's test (Holm-Bonferroni method) using the kruskal.test and pairwise.wilcox.test functions (Holm-adjusted) stats library (version 3.6.2) in the R program. In study I, where the day-to-day variability was analysed, the variation between the five measurement days was examined using the Friedman test (non-parametric repeated-measures analysis of variance).

In studies II and III, the participants were divided into groups according to physical functioning based on data distribution and previous literature (Bergland & Strand, 2019; Bindawas et al., 2015; Vasunilashorn et al., 2009). In study II, good lower extremity function was defined as 11-12 total SPPB points and limited lower extremity function as 10-3 total SPPB points. In study III, individuals were identified as low (SPPB = 0-9), moderate (SPPB = 10-11), or high functioning (SPPB = 12) based on their overall physical functioning level.

4.4.2 Confusion matrix

In study I, the detection accuracy of the algorithm was examined using the AGNES baseline study participants' laboratory sessions. Prior to the 6 minutes walk test, the protocol included two known STS transitions that were defined as the ground truth. Detection accuracy was analysed using the confusion matrix (Ting, 2010). Ground-truth STS transitions detected by the algorithm were defined as true positives (TP). Ground-truth STS transitions that could not be detected were false negatives (FN). False positives and true negatives were not defined, so overall accuracy was used as the main outcome variable, calculated by dividing false negatives (FN) by the number of known STS transitions (total STS). In practice, this was performed by visualizing a 45 minutes period from the laboratory session, and the two STS transitions were manually identified from the data. The manual detection was used as the ground truth and compared with the detection algorithm. The results were also reported by age and sex groups to examine the differences in detection accuracy between these groups (Bassett et al., 2012).

4.4.3 Correlations

All studies tested the associations between the variables with Spearman rank correlation coefficients. Spearman rank correlation coefficients > 0.70 were interpreted to indicate a strong association. A moderate association was defined as < 0.70 but > 0.40, and a weak association was described as a correlation coefficient of < 0.40 (Schober & Schwarte, 2018).

In study I, the correspondence between the two-time points was evaluated with two-way random intraclass correlation coefficients (ICCs; absolute agreement and single measures). In addition, agreement between baseline and 1-year follow-up was analysed using the Bland-Altman analysis (Bland & Altman, 1986), where the limits of the agreement were presented with a 95% confidence interval (CI).

4.4.4 Regression analyses

In study IV, logistic regression analysis was the main statistical method. The likelihood of lower extremity physical functioning decline over a 4-year follow-up period was examined using odds ratios (ORs) with 95% CIs. For comparison between the variables, standardized values were calculated using the formula $z = (x - \mu)/\sigma$, where z is the Z-score, x is the value evaluated, μ is the mean, and σ is the SD. The outcome variable was the dichotomous variable on a decline in lower extremity functioning (0 = ≤ 1 points, 1 = ≥ 2 points), and the predictor variables were lab-based isometric knee extension strength, free-living STS maximal angular velocity, free-living STS mean angular velocity, and the number of free-living STS transitions. The decline in lower extremity functioning was defined on the basis of the decline in total SPPB score of at least 2 points (substantial meaningful change) (Kwon et al., 2009; Olsen & Bergland, 2017; Perera et al., 2006).

In addition to the crude model, the adjusted model was adjusted for age, sex (Bohannon, 2015; Löppönen et al., 2022; Pickford et al., 2019), lower extremity functioning at baseline (baseline total SPPB score), and the self-reported number of diseases. In addition, significant predictor variables (lab-based isometric knee-extension strength and free-living STS maximal angular velocity) were combined into a model to investigate their interactions.

5 RESULTS

5.1 Participants' characteristics

The participant characteristics in the AGNES baseline, AGNES follow-up, LEUVEN, and FIREA datasets included in the present analyses are summarized in Table 3.

TABLE 3. Characteristics of participants in the datasets used in this study.

	AGNES BL (n = 479)	AGNES FU (n = 236)	FIREA (n = 198)	LEUVEN (n = 63)
Women	60.0%	52.5%	82.3%	44.0%
Age (years)	78.3 (3.4)	81.7 (3.0)	62.8 (1.0)	70.1 (5.3)
Education (years)	11.6 (4.3)	-	-	-
Number of chronic conditions	3.1 (1.9)	-	-	-
Knee extension force (N/kg)	4.7 (1.5)	-	-	-
MMSE (points)	27.4 (2.4)	27.5 (2.5)	28.8 (1.3)	28.5 (1.7)
SPPB (points)	10.3 (1.9)	10.3 (1.7)	11.6 (0.7)	11.8 (0.6)
5 × STS (s)	12.6 (3.8)	12.6 (3.1)	10.1 (2.2)	9.2 (1.5)

The data are presented as mean (SD). SD = standard deviation, MMSE = Mini-Mental State Examination, SPPB = Short Physical Performance Battery; 5 × STS = five times sit-to-stand test.

5.2 Accuracy and reproducibility of the STS transition detection algorithm

5.2.1 STS transition detection and angular velocity quantification accuracy (study I)

Table 4 shows the detection accuracy of the algorithm divided by age and sex groups. Overall, 782 participants and 1564 known STS transitions before the 6 minutes walk test were included in the analysis, which was carried out as part of the laboratory protocol of the AGNES baseline measurements. True positives and false negatives were used to calculate the STS transition detection accuracy, which ranged from 82.7% to 97.5%, depending on the age (better accuracy among younger age groups than among older age groups) and sex groups (better accuracy among men than among women), with an overall accuracy of 93.3%.

TABLE 4. Sub-group analysis of the STS transition detection algorithm.

Age (years)	Number of Participants	Total STS	True Positives	False Negatives	Overall Accuracy (%)
Men					
75	158	316	308	8	97.5
80	116	232	217	15	93.5
85	65	130	125	5	96.2
all	**339**	**678**	**650**	**28**	**95.9**
Women					
75	226	452	428	24	94.7
80	136	272	247	25	90.8
85	81	162	134	28	82.7
All	**443**	**886**	**809**	**77**	**91.3**
Total all	**782**	**1564**	**1459**	**105**	**93.3**

In addition, the quantification accuracy of the thigh angular velocity was compared with the thigh angle estimated using a 2D motion analysis. Figure 10 presents the data from a single participant who performed the 5 × STS test at different velocities. The figure shows that the thigh angle quantified by the STS detection and quantification algorithm corresponds to the thigh angle estimated by the 2D motion analysis. The complete analysis with videos and codes is published with open access online (https://cmj.sport.jyu.fi/sittostand/).

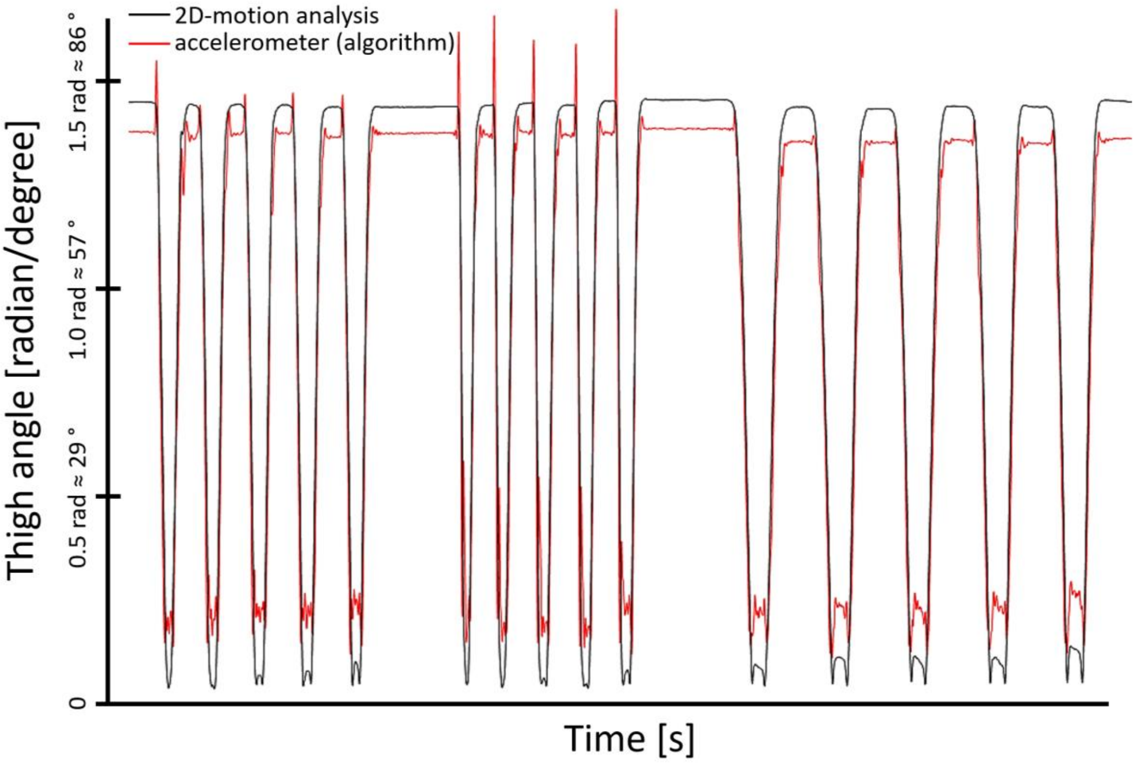

FIGURE 10. Thigh angle as a function of time estimated with STS detection and quantification algorithm and 2D motion analysis.

5.2.2 Year-to-year reproducibility and day-to-day variability of free-living STS characteristics (study I)

Table 5 shows the results of the algorithm for the year-to-year reproducibility of the STS characteristics. The mean number of STS transitions at baseline and 1-year follow-up were similar ($p = 0.931$; Table 5). Likewise, the baseline and 1-year follow-up mean angular velocities did not differ ($p = 0.587$). The maximal angular velocity decreased over the 1-year follow-up ($p = 0.017$). The physical activity indicated by the 24-h mean MAD ($p = 0.835$) or MVPA ($p = 0.567$) did not differ between the baseline and follow-up measurements.

The year-to-year ICCs for the number of STS transitions and mean and maximal angular velocities were good to excellent, as indicated by the following ICC values: 0.79 (95% CI, 0.70–0.86; $p < 0.001$), 0.81 (95% CI, 0.72–0.87; $p < 0.001$); and 0.73 (95% CI, 0.61–0.82; $p < 0.001$), respectively. The ICCs for the MAD (ICC = 0.89; 95% CI, 0.84–0.93; $p < 0.001$) and MVPA (ICC = 0.85; 95% CI, 0.79–0.90; $p < 0.001$) were excellent.

TABLE 5. STS assessment from the free-living recordings at baseline and 1-year follow-up and the reproducibility of the STS characteristics (n = 86).

	Baseline Mean (SD)	Follow-up Mean (SD)	p Value[a]	ICC (95% CI)
Number of STS (no./day)	44.2 (15.9)	44.5 (15.2)	0.931	0.79 (0.70–0.86)***
Mean angular velocity (degrees/s)	56.9 (8.0)	56.6 (8.0)	0.587	0.81 (0.72–0.87)***
Max angular velocity (degrees/s)	111.6 (22.0)	107.3 (19.7)	0.017	0.73 (0.61–0.82)***
MAD 24 h (mg)	25.1 (8.1)	24.8 (8.8)	0.835	0.89 (0.84–0.93)***
MVPA (minutes/day)	34.4 (24.7)	33.7 (25.8)	0.567	0.85 (0.79–0.90)***

STS = sit-to-stand, SD = standard deviation, ICC = intraclass correlation coefficient, mg = milligravity, CI = confidence interval of ICC, [a] Wilcoxon signed-rank test, ***p < 0.001.

The day-to-day ICCs ranged from 0.63 to 0.72 (95% CI, 0.49–0.81; p < 0.001) in a number of STS transitions and from 0.75 to 0.80 (95% CI, 0.64–0.87; p < 0.001) in mean angular velocity (Table 6). In addition, no statistically significant differences were found between the days in the number of STS transitions [$\chi^2(4) = 7.521$, p = 0.111] and mean angular velocity [$\chi^2(4) = 6.760$, p = 0.149].

TABLE 6. Mean values (SD) of the free-living STS variables for the five follow-up recording days (upper part of the table) and ICC (95% CI) between the 4-day pairs (lower part of the table; n = 86).

Days	Number of STS transitions [no/day]	Mean angular velocity [degrees/s]
1 (n = 85)	45.5 (17.7)	56.2 (8.1)
2 (n = 86)	44.4 (16.1)	55.5 (8.3)
3 (n = 86)	44.4 (20.0)	57.2 (7.9)
4 (n = 83)	43.4 (17.4)	56.4 (9.2)
5 (n = 81)	45.9 (18.2)	56.8 (8.6)
1–2 (n = 85)	0.63 (0.49–0.74)	0.79 (0.69–0.86)
2–3 (n = 86)	0.72 (0.60–0.81)	0.78 (0.68–0.86)
3–4 (n = 83)	0.64 (0.50–0.75)	0.75 (0.64–0.83)
4–5 (n = 81)	0.71 (0.58–0.80)	0.80 (0.71–0.87)

STS = sit-to-stand, SD = standard deviation, ICC = intraclass correlation coefficient, CI = confidence interval of ICC, ***All *p* < .001.

5.3 Free-living STS characteristic differences between the age and sex groups and association with laboratory-based measurements of self-reported fear of falling and stair negotiation difficulties

5.3.1 Differences in free-living STS characteristics and instrumented 5×STS test results between the age and sex groups (studies II and III)

The number of STS transitions and mean and maximal angular velocities differed between the age and sex groups (all $p < .001$). The 85-year-old women showed 19.6% fewer STS transitions ($p = 0.005$) and 9.2% lower mean ($p < 0.001$) and 14.6% lower maximal angular velocity ($p < 0.001$) in the free-living environment than the 75-year-old women. The 85-year-old men showed 18.3% fewer STS transitions ($p = 0.015$) and 8.9% lower mean ($p = 0.012$) and 9.4% lower STS maximal angular velocity ($p = 0.042$) than the 75-year-old men (Table 7).

TABLE 7. Free-living STS characteristics in each age group.

Age (years)		n	Number of STS transitions (no/day)	Mean angular velocity (degrees/s)	Max angular velocity (degrees/s)
75 (n = 244)	Women	149	42.8 (16.3)	57.6 (8.5)	109.0 (18.8)
	Men	95	50.4 (16.8)	60.6 (8.8)	115.9 (20.0)
80 (n = 153)	Women	87	41.4 (15.4)	56.1 (8.4)	106.5 (22.9)
	Men	66	47.3 (18.8)	59.8 (9.5)	112.3 (18.6)
85 (n = 82)	Women	51	34.4 (15.2)	52.3 (7.5)	93.1 (14.8)
	Men	31	41.2 (14.1)	55.2 (9.0)	105.0 (20.9)
p-value age groups[a]		Women	0.005	<0.001	<0.001
		Men	0.015	0.012	0.042
p-value sexes[b]			<0.001	<0.001	<0.001

The data are presented as mean (SD). [a]Independent-samples Kruskal-Wallis test. [b]Independent-samples Mann-Whitney *U* test.

The results were similar in the study that included participants with a more extensive age range (study III). Free-living mean and maximal angular velocities were statistically different between the age groups ($p < 0.05$). In study III, an instrumented 5 × STS test was also used. A significant difference in angular velocity was observed between the age groups in the laboratory-based STS capacity, where the difference between the 60- to 70- and 81- to 90-year age groups was 45% for women and 43% for men ($p < 0.05$). When the intensity of the STS test could be measured, the difference (reserve) between laboratory-based STS capacity and maximal free-living performance was calculated. This was 39.1 degrees/s for women and 39.0 degrees/s for men aged 60–70 years and was smaller in the older age groups (i.e., 24.0 degrees/s women and 25.7 degrees/s men aged 71–80 years, and 22.6 degrees/s for women and 24.9 degrees/s for men aged 81–90 years; Figure 11).

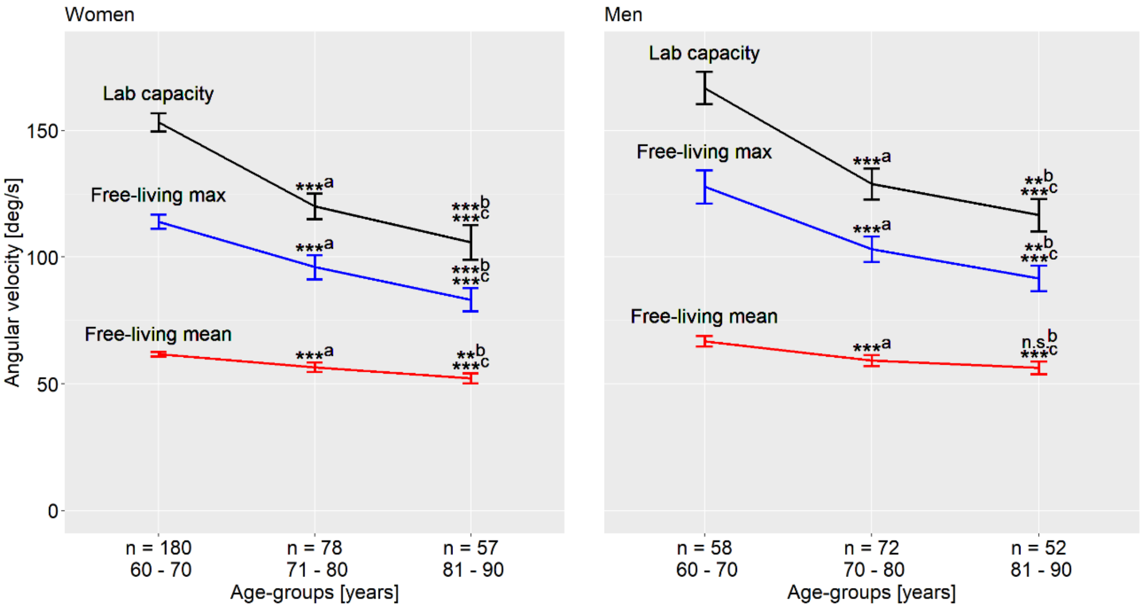

FIGURE 11. Angular velocity in laboratory-based STS (lab capacity), free-living mean STS performance (free-living mean), and free-living maximal STS performance (free-living max) across age groups in women and men (mean, 95% confidence intervals). The Mann-Whitney *U* test (Holm adjusted) was used to compare the results with those from the previous age groups: n.s. = not significant, *p < 0.05, **p < 0.01, ***p < 0.001. a 60–70 vs. 71–80, b 71–80 vs. 81–90, c 60–70 vs. 81–90.

5.3.2 Associations between the free-living STS characteristics and laboratory-based measurements (studies II and III)

The Spearman rank correlation coefficients between the free-living STS and laboratory-based measurements are presented in Table 8. The number of STS transitions and mean and maximal angular velocity were positively associated with the total SPPB points and maximal isometric knee extension force (*r* = 0.18–0.39, all p < 0.001) and negatively associated with the 5 × STS test (*r* = −0.13 to −0.45, p < 0.05). The angular velocity of laboratory-based STS capacity was moderately associated with the free-living mean and maximal STS angular velocity (*r* = 0.52–0.65, p < 0.01) and weakly associated with a number of STS transitions (*r* = 0.35, p < 0.01).

TABLE 8. Spearman's correlation coefficients between the free-living STS characteristics and laboratory and home-based physical measurements.

Laboratory Assessment	Number of STS transitions (no./day)	Mean Angular Velocity (degrees/s)	Max Angular Velocity (degrees/s)
Study II (75-80-85 years old) (n = 479)			
5 × STS test time (s)	−0.13**	−0.18**	−0.24*
SPPB score (points)	0.18**	0.24**	0.33**
Knee extension force (N/kg)	0.25**	0.28**	0.39**
Study III (60–90 years old) (n = 428)			
Instrumented 5 × STS (degrees/s)	0.35**	0.52**	0.65**
5 × STS test time (s)	−0.24**	−0.35**	−0.45*

*p < 0.05, **p < 0.01, ***p < 0.001.

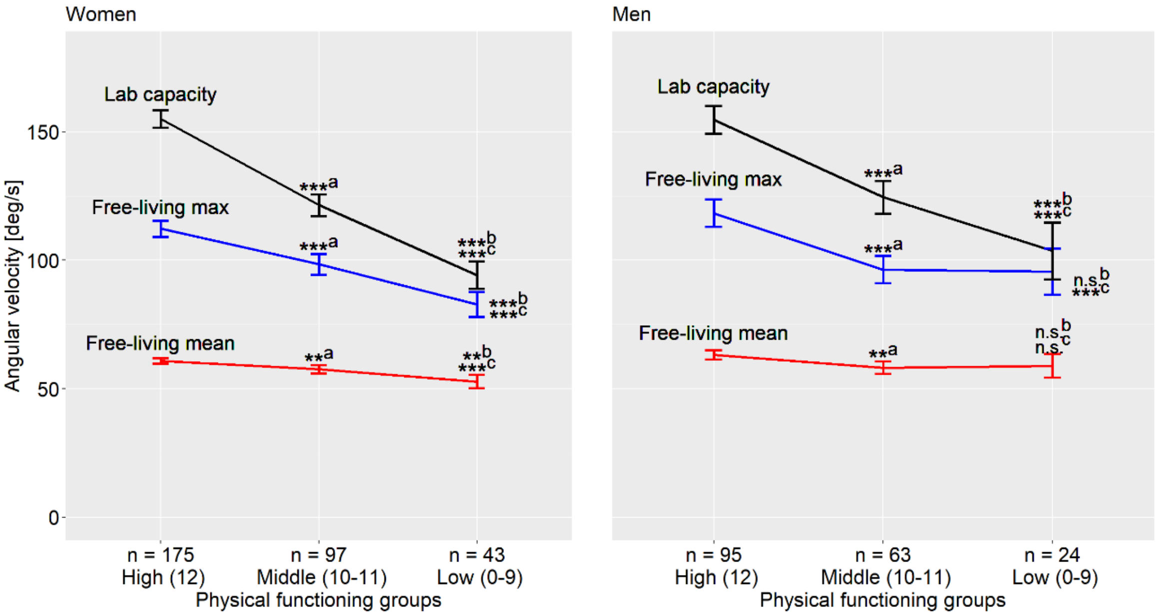

FIGURE 12. Angular velocity in laboratory-based STS (capacity), free-living mean STS performance (free-living mean), and free-living maximal STS performance (free-living maximal) across the SPPB groups in women and men (mean, 95% confidence intervals). The Mann-Whitney *U* test (Holm adjusted) for comparison of results with those from the previous age groups: n.s. = not significant, *p < 0.05, **p < 0.01, ***p < 0.001. ^{a}high versus middle, ^{b}middle versus low, and ^{c}high versus low.

Figure 12 shows differences between the physical functioning groups in the angular velocity of laboratory-based instrumented STS capacity and free-living mean and maximal STS performance. Angular velocity was lower in the low- and middle-functioning groups than in the high-functioning group for each of the STS conditions (p < 0.05), except for free-living mean and maximal performance in men. The difference (i.e., reserve) between the STS test capacity and maximal free-living performance was higher in the high-functioning group (in women 42.8 degrees/s and in men 36.2 degrees/s) than in the low-functioning group (in women 11.4 degrees/s and in men 8.0 degrees/s; p < 0.05).

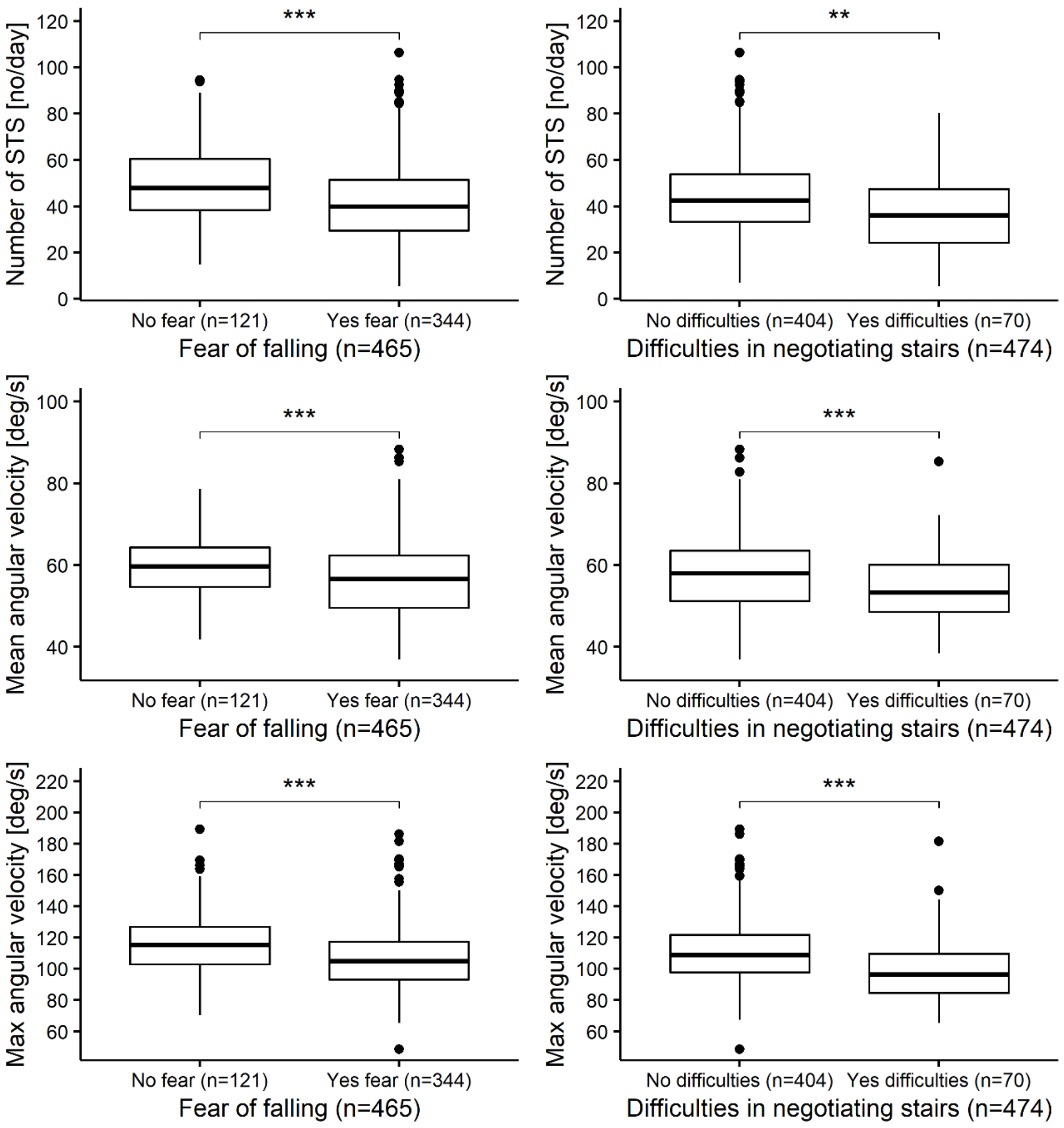

FIGURE 13. Number of STS transitions and mean and maximal angular velocity group comparisons between self-reported fear of falling, difficulties in negotiating stairs, and lower extremity functional limitations in free-living environment. Independent-samples (unpaired) Mann–Whitney *U* test (Wilcoxon rank-sum test). ***p < 0.001, **p < 0.01 (two-sided). STS = sit-to-stand.

5.3.3 Associations between free-living STS characteristics, self-reported fear of falling, and stair negotiation difficulties

Individuals who feared falling showed 15.8% fewer STS transitions (p < 0.001) and had 5.5% lower STS mean angular velocity (p < 0.001) and 8.9% lower maximal angular velocity (p < 0.001) in the free-living environment than individuals who reported no fear of falling. In addition, individuals who reported difficulties with stair walking had 16.8% fewer STS transitions ($p < 0.01$) and 6.9% lower mean STS angular velocity ($p < 0.001$) and 10.0% lower maximal STS angular velocity ($p < 0.001$) than individuals who reported no difficulties with stair walking (Figure 13).

5.4 Free-living STS characteristics as a predictor of future functional decline among older adults (study IV)

In study IV, the participants not available for follow-up (dropouts, n = 139) were older, had lower SPPB scores and isometric knee-extension strength, and took longer to complete the 5 × STS test ($p < 0.05$) at baseline than the final sample. A total of 85 participants in the final sample (25%; of which 75% were women) experienced a decline of at least 2 points in lower extremity function from baseline to 4-year follow-up. At baseline, several diseases, isometric knee-extension strength, and free-living STS maximal angular velocity statistically differed between the groups that had or had no decline in lower extremity function over the 4-year follow-up ($p < 0.05$; Table 9).

TABLE 9. Baseline characteristics of the AGNES dataset at 4-year follow-up according to decline in physical functioning.

	All (N = 340)	No, change over 4-y FU (n = 255)	Yes, change over 4-y FU (n = 85)	p[a]
Female, n (%)	59.6 %	54.8 %	74.4 %	
Age (y)	78.0 (3.2)	77.9 (3.1)	78.6 (3.4)	0.147
Short Physical Performance Battery (points)	10.5 (1.7)	10.6 (1.6)	10.4 (1.9)	0.534
Lab-based 5 × STS total time (s)	12.3 (3.7)	12.2 (3.6)	12.4 (4.1)	0.857
Laboratory-based isometric knee force/body mass (N/kg)	4.8 (1.4)	5.0 (1.4)	4.1 (1.3)	**<0.001**
Free-living STS maximum angular velocity (degrees/s)	102.7 (21.3)	105.0 (20.3)	95.9 (22.8)	**<0.001**
Free-living STS mean angular velocity (degrees/s)	57.8 (8.8)	58.2 (8.4)	56.3 (9.9)	0.091
Free-living no. of STS (no/d)	44.7 (17.0)	45.4 (16.6)	42.6 (18.1)	0.251

U = follow-up, STS = sit-to-stand. [a]Independent-samples Mann-Whitney *U* test. The bold font indicates statistical significance ($p < 0.05$).

After adjusting for age, sex, baseline SPPB points, and number of diseases, the higher knee-extension strength (OR, 0.64; 95% CI, 0.50–0.81; per 1 N/kg increase) and higher maximal angular STS velocity (OR, 0.84; 95% CI, 0.73–0.9; per 10 degrees/s increase) lowered the odds for future decline in lower extremity function in the separate models (Figure 14). When comparing the odds of the standardized values, the higher isometric knee-extension strength lowered the odds of decline in lower extremity functioning over the follow-up (OR, 0.53; 95% CI, 0.37–0.75) more than free-living maximal angular STS velocity did (OR, 0.70; 95% CI, 0.51–0.94; Figure 14). Neither the number of STS transitions nor the mean angular velocity showed significant odds ratios for a future decline.

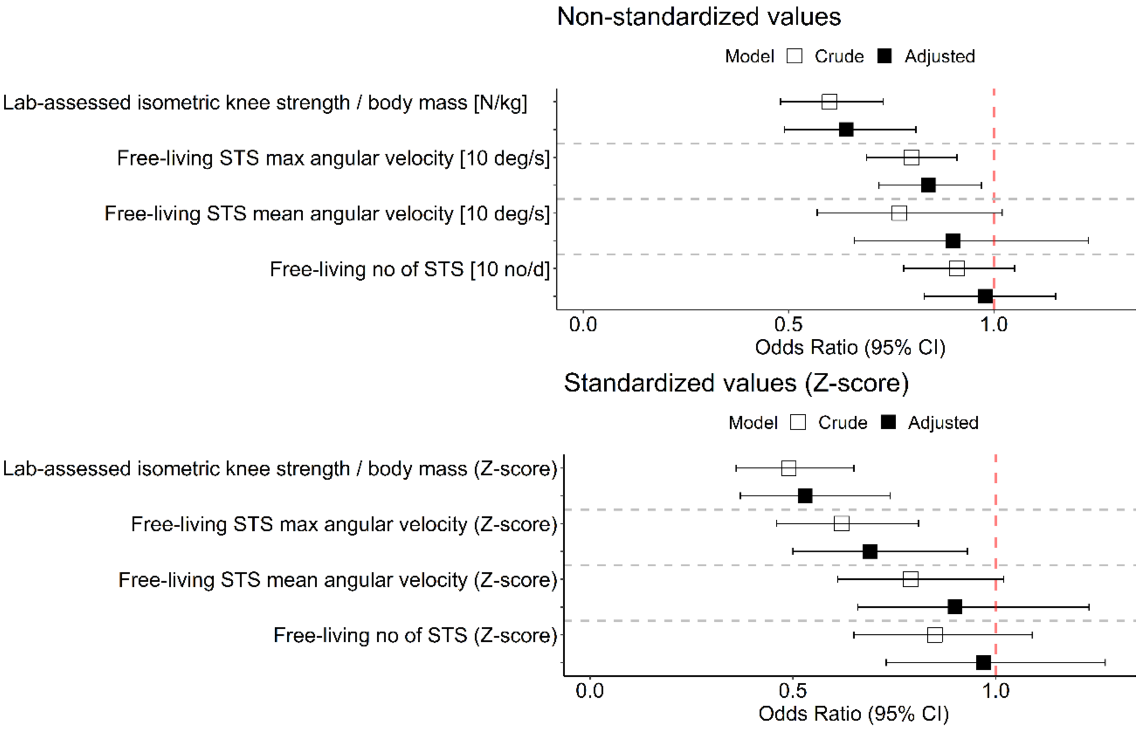

FIGURE 14. Predictors of at least a 2-point decline in the 4-year-follow-up non- and standardized Short Physical Performance Battery scores (Z-score). Crude model: unadjusted model. Adjusted model: adjusted for baseline age, sex, baseline total SPPB score, and number of diseases. The bold font indicates statistical significance (p < .05). STS = sit-to-stand, CI = confidence interval.

When both statistically significant predictors (i.e. isometric knee extension strength and maximal angular STS velocity) and their interaction were in the same model (standardized values), only isometric knee extension strength was a significant predictor (OR, 0.54 [95% CI, 0.39–0.73]; OR, 0.76 [95% CI, 0.57–1.03]; and OR, 1.05 [95% CI, 0.77–1.44], respectively) of future decline in lower extremity functioning.

6 DISCUSSION

The present study investigated whether it is possible to detect STS transitions and quantify their intensity in a free-living environment using a single thigh-worn accelerometer. Its further aim was to investigate whether free-living STS characteristics are associated with laboratory-based lower extremity measurements, self-reported fear of falling, and stair negotiation difficulties, and whether they can predict physical functional decline among community-dwelling older adults.

The results of the present study show that free-living STS transitions can be reliably detected with more than 90% accuracy using a single thigh-worn three-axis accelerometer. In addition, the angular velocity of the thigh during the transition can be quantified. The detected STS volume and quantified intensity are associated with laboratory-based lower extremity measurements, self-reported fear of falling, and stair negotiation difficulties among community-dwelling older people. Finally, free-living maximal STS angular velocity can predict future declines in lower extremity functioning among older adults, but the number of STS transitions or their mean angular velocities showed no significant odds ratios for a future decline.

Free-living STS transition characteristics may provide an indicator of the adequacy of lower extremity muscle strength among older individuals. The assessment of STS characteristics in a free-living environment allows for frequent remote assessments, enabling early-stage changes to be detected so that preventive strategies can be initiated in time.

6.1 Methodological development considerations

The first part of this thesis was to develop an open and universal algorithm that can be used to detect STS transitions and quantify their intensity in a free-living environment using a single thigh-worn accelerometer. The goal was to develop an open method that can be applied to universal, generally available accelerometers. The critical issues in this study were the evaluation of the reliability and usability of the method and finding out how the method can be developed for future wearable sensor solutions.

When we designed the algorithm, attention was first focused on the sensor location. When transitioning from STS, the angle of the thigh changes significantly (Figure 13). The angle change is 90 degrees, but often, when older adults sit on raised chairs (Hurley et al., 2016), the difference may be more negligible, according to our criteria, STS transitions should start at > 65 degrees from the angle of the thigh. Placing the sensor in the thigh also enables angular velocity quantification, which can be used as an intensity variable for STS transitions while lacing the sensor on the hip or sternum will lead to a situation where the intensity variable of the STS transitions is the movement duration, for example. This can be challenging to implement accurately because detection of the beginning and end of the movement can be challenging from a signal that does not contain information about orientation.

The accuracy of the STS detection algorithm was evaluated using the laboratory protocol of the AGNES baseline. Here, the two previously known STS transitions were detected using an algorithm. The weakness of this evaluation was the inability to estimate the number of false positives, that is, how often the algorithm detected a STS transition even though it did not actually occur. However, no additional transitions were visually observed within the 45 minutes laboratory session, which could be counted as false positives. There was variation in detection accuracy between age and sex groups, so that detection accuracy was weaker in older age groups. In addition, the detection accuracy was weaker for women, which can be explained by the fact that in the AGNES baseline dataset, women's physical functioning was relatively weaker compared to men. The physical functioning can therefore affect the technique of STS transitions so that the detection of STS transitions is more difficult. The greatest inaccuracy of the STS detection algorithm relates to occasions where the participant's thigh is not stationary prior to the STS transition. Movement can be caused by wiggling or trembling of the foot. In addition, the accelerometer can only indicate the postural angle of the thigh. Consequently, incorrect interpretations may arise in situations where the thigh is extended in the absence of STS. Finally, the thigh must be positioned close to horizontal (i.e., a postural angle of > 65) at the initiation of the STS transition. For this reason, detection is likely to fail when the participant is standing up from, for example, a saddle chair, medicine ball, or other relatively high seats. In addition, the weakness of the detection accuracy can be affected by the unreliability of the recognition of walking periods, which means that the reference values may become slightly inaccuracy, which in turn can affect the fact that the STS transition is not performed within the criteria of the algorithm.

Real-life validation has been demonstrated in a few studies where activities have been determined using wearable video recording; thus, the ability of wearable sensors and their algorithms to detect these activities could be studied (Bourke et al., 2016; Giurgiu et al., 2023; Stamatakis et al., 2022; Stemland et al., 2015). In the future, the accuracy and reliability of our STS algorithm should also be evaluated with a similar approach in a free-living environment to understand the weaknesses of the method better and develop it more for future applications.

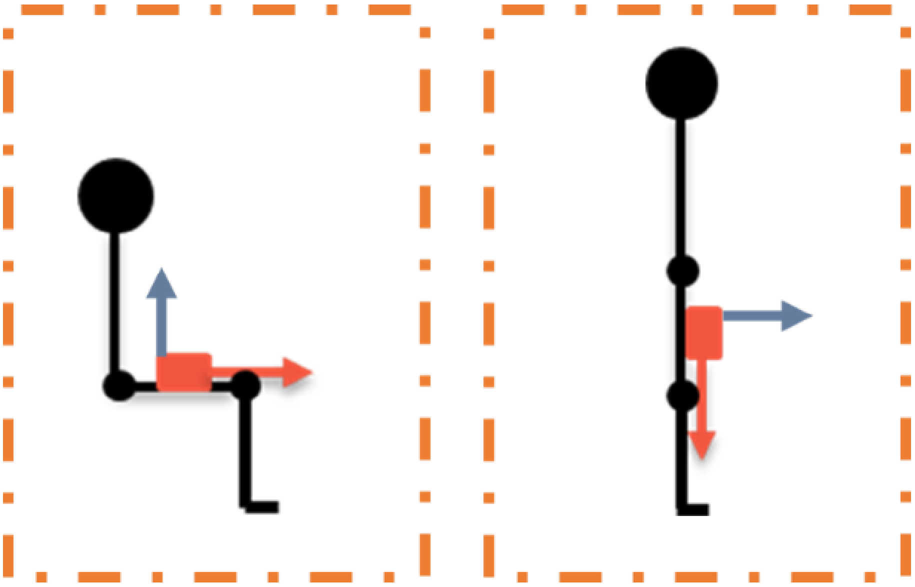

FIGURE 15. Position of the accelerometer on the thigh and the effect of the position on the axis of the sensor during the STS movement.

The algorithm produces three different STS variables that were used to describe free-living STS characteristics in this study. First, the number of detected transitions was calculated as the mean of the complete 24-h measurement days. According to study I, the daily variation was minimal in the number of STS transitions. Hence, the mean is the best way to describe the average of the entire measurement period, and the median should not be used. The first STS intensity variable was the mean thigh angular velocity, which was determined by calculating the median of the angular velocities for each complete monitoring day, and the final variable (mean) was calculated from these daily medians. Using the median delimited blatant outliers, which were also delimited by filtering all transitions with angular velocity over 4 radians/seconds based on the finding that no participants exceeded 4 radians/seconds on the instrumented 5 × STS test. Often these excluded STS transitions were very high overshoots, probably due to interference or device detachment such as 6-8 radians/seconds, and their amount in all datasets was low (< 0.05%). The second STS intensity variable was maximal angular velocity, which was determined as the median of the ten fastest STS transitions over the monitoring period. This was chosen because we wanted to obtain a variable that describes the daily maximal STS angular velocity but is unrelated to the number of transitions (compared on the basis of confidence intervals) and, on the other hand, that does not just pick up the fastest STS transition. The weakness of this estimation is that it is not possible to know with certainty whether this free-living STS transition is fastest that the individual is capable of. The main concern pertains to the monitoring duration. The required monitoring period to identify the highest level of performance in the free-living environment is unclear.

It has previously been concluded that the monitoring duration used in this study (3–7 days continuously) is sufficient for assessing physical activity patterns (Pedersen et al., 2016). In addition, although a minimum of 3 days was required, the mean was often closer to 7 days. In study II, the mean was 6.2 days; and in study III, the mean in this thesis was 6.3 days. However, no similar insight was obtained into identifying the highest level of free-living STS transitions velocity, and the length of adequate monitoring should be evaluated in future studies, especially as methods of objective physical activity are developing rapidly.

Some limitations must be kept in mind when interpreting the STS transition angular velocity findings of this study. In this thesis, we checked the angular velocity of free-living STS transitions against a small-sample 2D motion analysis (https://cmj.sport.jyu.fi/sittostand/). An actual larger validation study of STS transition intensity quantification with a wide age distribution and different physical functioning levels should be conducted in the future. Another limitation is that the use of the arms during STS transitions cannot be controlled in the free-living environment. This can lead to misinterpretations, especially in determining angular velocity, because STS transitions have been found to have a slightly stronger association with STS performance when using the arms is not allowed than when it is allowed (Eriksrud & Bohannon, 2003).

In this study, an open and universal algorithm for detecting STS transitions and quantifying their angular velocity was developed. This means that the algorithm's code and properties are freely available (Rantalainen, 2021b). In addition, the algorithm can be used to analyse the data recorded by any three-axis accelerometer, as long as the frequency is 100 Hz, and the sensor is attached to the middle of the thigh. This is a significant strength in this research, especially in method development. The aim of this thesis was to develop a method based on one accelerometer instead of multi-sensor systems (i.e., inertial measurement units or several sensors placed in many different body locations). This was especially decided because the goal was to collect as long recordings as possible to estimate activity patterns reliably (Pedersen et al., 2016) and to chase maximal performance in daily life (Cleland et al., 2013). For this, the size and usability of the device should be considered small enough so that the participants will be motivated to use the device for a week. In addition, the battery life must be sufficient. At the moment, the battery life of inertial measurement units does not last up to 7 days, even if more information could be obtained owing to a wider range of sensors.

6.2 Associations between free-living STS characteristics and laboratory-based measurements

This study showed that free-living STS characteristics were associated with laboratory-based lower extremity measurements. This association has been rarely reported. Ryan and colleagues reported no significant association ($r = -0.12$, p =

0.47) between 5 × STS test time and the number of STS events in leisure time (number of STS) in people with chronic low back pain (Ryan et al., 2008). In study II, we found that the free-living STS maximal angular velocity was most strongly associated with laboratory-based measurements, especially with the isometric knee extension strength, which can indicate that maximal angular velocity might be a better representation of the capacity of the lower extremities than mean STS angular velocity and number of STS transitions. However, in the present thesis, the associations between 5 × STS test time and free-living mean and maximal angular velocity of the STS transitions were relatively weak. Furthermore, this can be explained by the fact that the 5 × STS test result is a total time that includes the static standing and sitting phases. However, when the 5 × STS test was instrumented and thus different phases could be distinguished from each other, it was found that the dynamic phases of the test are the more informative part of the test (van Lummel et al., 2016) than the static phases. Our algorithm in a free-living environment quantified angular velocity only in the STS phase, so it is evident that there are also methodological differences between total time and daily angular velocity. However, in study III, we used the instrumented thigh angular velocity during the STS test, and the result showed that this led to a higher correlation between the instrumented 5 × STS test and the free-living maximal and mean STS transition angular velocity compared to 5 × STS total test time. In addition, the association can be affected by the fact that people with good lower extremity capacity may not necessarily use their full capacity in a free-living environment, at least not whenever they get up from a chair. This is supported by the fact that the maximal angular velocity of free-living STS transitions showed a stronger association with the SPPB score and its 5 × STS test than the mean angular velocity of free-living STS transitions. We believe that the recorded free-living STS transitions describe how people use their lower extremity strength or power daily, clearly different from their maximum strength or power capacity, unless an individual is very weak. For individuals with high strength reserve, that is, whose strength is much higher than the minimum strength required for an STS, their free-living STS transition angular velocities may not be closely linked to their maximum strength. On the other end of the lower extremity strength distribution, people whose maximum strength is at or above the minimum required strength for STS transition use all or most of their force production capacity for free-living STS transitions. This study defined no cut-off points for STS characteristics to identify threshold values for functional limitations. For instance, it can be assumed that the number of STS transitions is very low once an individual crosses the disablement threshold, indicating that the transitions are limited to only essential tasks such as getting out of bed or toilet seat.

In study III, we also found that the difference between the STS capacity determined in the test and the maximum STS angular velocity measured in daily life, a kind of *reserve*, decreases according to age and physical functioning categories. This finding is supported by muscle EMG activity evidence that STS transitions and stair walking require more relative activity to be successful in older adults than younger ones (Hortobagyi et al., 2003). A high reserve not only allows better adaptation to the challenges of daily environmental factors but also provides a margin of safety in situations of injury or illness so that the disability threshold is not exceeded when faced with adversity (Goldspink, 2005), so it is recommended for older adults to maintain an adequate physical reserve.

The association between the number of STS transitions and laboratory-based measurements was weak. This may suggest that the number of STS transitions is more related to individual and environmental factors than laboratory-based measurements, as noted for physical activity (Rai et al., 2020), especially when capacity does not limit STS transition in a free-living environment. It should also be noted that methodological reasons can affect especially the association between the number of STS transitions and other laboratory-based measurements. Even though the detection accuracy was found to be > 90%, it should still be noted that there was a variation between the age groups (82.7–97.5%), which can also contribute to the weak associations between the number of STS transitions in a free-living environment and laboratory-based assessments.

Individuals who reported fear of falling showed fewer daily STS transitions, and their mean and maximal angular velocities were lower than those of individuals who did not report fear of falling. These results are in line with previously published results. Parvaneh and colleagues (2017) reported that the number of STS transitions measured by the accelerometer was weakly ($r = -0.11$, $p = 0.009$) associated with fear of falling (Fall Efficacy Scale-International) in a free-living environment (Parvaneh et al., 2017). Concerns about falling have been found to be associated with a low number of STS transitions among community-dwelling older men and women (Yu Shiu et al., 2022). In addition, the results of another daily activity that requires strength, stair walking (Tikkanen et al., 2016), led to similar conclusions regarding the number of daily STS transitions, and their velocities differed between individuals who reported stair walking problems and those who did not report fear of falling.

6.3 Free-living STS characteristics as a predictor of future decline in physical functioning

Ageing studies have long sought to find indicators of physical function decline so that preventive strategies can be initiated promptly. Weak muscle strength is a good predictor of future functional limitations (García-Hermoso et al., 2018), and maintaining high levels of muscle strength also protects against a decline in physical functioning (Ikezoe et al., 2021). Clinically useful indicators are often easy and straightforward methods in which hand-grip force measurements have been specially considered (Rantanen et al., 1999; Rantanen et al., 2000). In this study, this issue was approached through a hypothesis that intensive STS behaviour performed in a free-living environment could lead to a situation where the principles of transient overload and subsequent supercompensation are appropriately fulfilled and maintaining muscle strength is possible (Shen et al., 2023).

As we found in study III, older adults are not challenged to their full capacity, especially when they do not have any functional limitations. However, previous studies have reported that even with moderate-intensity resistance training, positive responses in terms of physical functioning in older adults have been achieved (Balachandran et al., 2023; Kamiya et al., 2023), and similar patterns could also be realized in a free-living environment in strength-demanding movements such as STS transitions.

The results of this study clearly show that isometric knee extension strength is a stronger indicator of future physical functional declines or limitations than free-living STS characteristics. The ability of isometric knee extension to predict functional decline has also been previously reported (García-Hermoso et al., 2018; Ikezoe et al., 2021). In addition, free-living STS maximal angular velocity can also predict a future decline in physical functioning, which is the novel finding of our study. Mean angular velocity and the number of STS transitions did not predict the decrease in physical functioning, which is in line with the cross-sectional findings of study III, where maximal angular velocity was most strongly associated with laboratory-based measurements compared with the number of STS transitions and STS mean angular velocity.

This study also examined the 'use it or lose it' hypothesis, which means that laboratory-based physical capacity (isometric knee extension strength) is not used in a daily activities in which case it could be assumed to lead to a decrease in physical functioning compared to individual who are using the capacity in daily activities (Maula et al., 2019). The hypothesis was tested using logistic regression, adding significant predictive variables (laboratory-based isometric knee-extension strength and free-living STS maximal angular velocity) in the same model. The results were clear. Isometric knee-extension strength was the only statistically significant predictor in this model. This finding is also in line with other results in this study that although the correlation between laboratory-based measurements and daily STS characteristics is not high, it is probable that laboratory-based capacity determines free-living STS performance. However, the 'use it or lose it' hypothesis should be investigated further.

A previous study indicated that laboratory-based measurements and the intensity of free-living activities are different constructs (Van Ancum et al., 2019). The results of this study also support this observation; for example, the correlation between isometric knee extension force and maximal STS angular velocity was low (0.37, $p < 0.01$; Study IV, Supplementary table 2), even though they both predicted physical functional decline over a 4-year follow-up. Therefore, the results of laboratory-based measurements and the intensity of STS transitions performed in a free-living environment may be determined by different individual environmental and individual factors that have already been highlighted in the *ICF* classification (WHO, 2001). STS performance has also been found to be affected by various factors such as visual contrast sensitivity and lower extremity proprioception (Lord et al., 2002). These factors can affect free-living angular velocity more than laboratory-based measurements because the lighting is often better in the laboratory, the chair is more stable, and the circumstances may be perceived to be safer when the researcher has secured the test. In addition, the activity in the free-living environment can be influenced by mood (Hirvensalo et al., 2007), self-efficacy (Feltz & Payment, 2005), and cognition (Kaspar et al., 2015). On the other hand, over- or under-performance can also be observed in laboratory measurements. The Hawthorne effect (Berthelot et al., 2011), which could have a capacity-enhancing impact on laboratory performance compared with daily performance, may also influence the behaviour between the laboratory and free-living environments (Rojer et al., 2021).

6.4 Theoretical aspects

This study relied on the *ICF* classification published by the WHO in 2001 (WHO, 2001). The qualifiers, capacity, and performance, which are defined in the *ICF*, were highlighted in this study. A capacity qualifier, which represents an individual's ability to execute tasks or actions in a standardized environment, was determined using laboratory-based measurements, and the novelty was an instrumented 5 × STS test, which allowed direct comparison of STS intensity with a free-living environment. A performance qualifier represents the intensity of the actual living environment. Examining STS transitions in a free-living environment also brought in different intensities within this qualifier when we found that the distribution of STS transitions varied between participants and was thus an exciting thing to investigate further. So we decided to define two variables, maximal and mean STS angular velocity, which we also called free-living *maximal and mean performance.*

Capacity and performance qualifiers have not been used consistently in the literature. For example, the widely used SPPB battery already contains the word 'performance' in its name (Guralnik et al., 1994). However, the term 'capacity' has also been used in studies when measuring force, walking speed, or 5 × STS time (Qazi et al., 2021; Tiihonen et al., 2018; Westerståhl et al., 2018). Many other authors have highlighted the clarity of terminology when studying their topics in two different environments, for example, when studying mobility capacity and performance (Giannouli et al., 2016) and when studying motor activities of young children with cerebral palsy (Holsbeeke et al., 2009). In addition, the importance of these two different concepts encountered in health care practice with older people has been highlighted (Lamb & Keene, 2017). The differentiation between these terms, according to the *ICF*, is justified, especially now when advanced sensor technology and improved computing capabilities enable more complex analysis, which allows for identifying intensities in detail in a free-living environment. However, this study found that the total SPPB score could be used to determine physical functioning level, as it contains many subtests, which form a value that describes lower extremity functioning as a whole. For example, in study IV, using the total SPPB scores and the previously reported meaningful change, participants who experienced a decline in physical functioning during follow-up were identified.

6.5 Implications and future directions

With the growth of telerehabilitation, daily monitoring (Baroni et al., 2023; Schütz et al., 2022) and advanced wearable sensor technology daily activities can be easily identified, and how the ability to perform these progresses during life span can be investigated. Our new finding is that the maximal intensity of activities that take place in a free-living environment can be evaluated. Continuous monitoring allows for the evaluation of how free-living performance changes and target early interventions without frequent laboratory visits. In this study, we determined maximal STS performance as the median of the ten fastest STS transitions of the entire monitoring period, which is considered an indicator of strength-demanding activity. As the methods continue to develop, it could be interesting to study gait speed in the same approach, which is essential for independent living (Graham et al., 2010). Walking could reveal early indicators of future functional limitations and thus can be a new novel measure for detecting physical functioning limitations. However, accurate free-living gait speed monitoring method is still under development. Furthermore, quantification of the free-living maximal gait speed requires that almost all and even shorter walking periods should be reliably detected. Sensor fusion also enables completely new approaches, and combining continuous EMG monitoring with accelerometer devices may also allow for determining how much of the maximal capacity of muscle activity older adults use when performing daily activities, how much the activity levels differ between activities, and the ageing changes.

Owing to the micro electro-mechanical system technology, wearables technology continues developing toward smaller and more inconspicuous devices (Passaro et al., 2017). This opens up new possibilities for monitoring physical functioning, fall risks (Bagalà et al., 2012), walking kinematics and another strength-demanding activity, stair walking. In addition, adding global positioning systems (GPS) to device can enable the positioning of people with the risk of disappearing. This requires not only an even more advanced battery technology, which is taking a new technological leap due to the increased number of electric cars, but also more advanced calculation algorithms, machine learning, and better calculation power to produce usable and scientifically proven indicators from people's daily lives.

This study found that monitoring various functional tests using wearable sensors is meaningful. When planning research protocols, it is important to attach the devices intended for monitoring physical activity before the test protocol so that the kinematics and kinetics of the tests can also be measured. The advantage of this arrangement is that comparing these variables from the laboratory with those from a free-living environment is also possible from a technical point of view when the device is the same and attached in the same way and positions.

The technology would still need to be developed significantly. Sensors should be placed in clothes because attaching sensors with film to the skin or belts to the limbs is not a long-term solution. In this study, maximal free-living performance could be the most exciting indicator, and a meaningful examination of this should lead to almost continuous monitoring. Integrated wearable textile electronic solutions and manufacturers of Smart Clothes would make this possible in the future and for use by older adults to support their independent living.

7 MAIN FINDINGS AND CONCLUSIONS

The main findings of this study are as follows:

1. Free-living STS transitions could be accurately detected. Their intensity was reliably quantified among older adults using a single thigh-worn accelerometer, and characteristics of STS transitions were reproducible from day to day and from year to year.

2. Free-living STS characteristics differed between age and sex groups. Older age groups had fewer and slower STS transitions than younger age groups. Men performed more STS transitions in a free-living environment than women, and their angular velocities were higher.

3. The number of free-living STS transitions and their angular velocities were associated with laboratory-based measurements, fear of falling, and stair negotiation problems. Older and low-functioning individuals appeared to perform free-living STS transitions at a higher percentage of their maximal capacity than younger and high-functioning individuals.

4. Free-living STS maximal angular velocity can predict future physical decline over a 4-year follow-up period. STS angular velocity can be self-assessed more frequently in a free-living environment than in on-site clinical examinations, which may enable initiating preventive strategies in a personalized and timely manner.

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ORIGINAL PAPERS

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DAY-TO-DAY VARIABILITY AND YEAR-TO-YEAR REPRODUCIBILITY OF ACCELEROMETER-MEASURED FREE-LIVING SIT-TO-STAND TRANSITIONS VOLUME AND INTENSITY AMONG COMMUNITY-DWELLING OLDER ADULTS

by

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Communication

Day-to-Day Variability and Year-to-Year Reproducibility of Accelerometer-Measured Free-Living Sit-to-Stand Transitions Volume and Intensity among Community-Dwelling Older Adults

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Abstract: (1) Background: The purpose of this study was to evaluate the day-to-day variability and year-to-year reproducibility of an accelerometer-based algorithm for sit-to-stand (STS) transitions in a free-living environment among community-dwelling older adults. (2) Methods: Free-living thigh-worn accelerometry was recorded for three to seven days in 86 (women $n = 55$) community-dwelling older adults, on two occasions separated by one year, to evaluate the long-term consistency of free-living behavior. (3) Results: Year-to-year intraclass correlation coefficients (ICC) for the number of STS transitions were 0.79 (95% confidence interval, 0.70–0.86, $p < 0.001$), for mean angular velocity—0.81 (95% ci, 0.72–0.87, $p < 0.001$), and maximal angular velocity—0.73 (95% ci, 0.61–0.82, $p < 0.001$), respectively. Day-to-day ICCs were 0.63–0.72 for number of STS transitions (95% ci, 0.49–0.81, $p < 0.001$) and for mean angular velocity—0.75–0.80 (95% ci, 0.64–0.87, $p < 0.001$). Minimum detectable change (MDC) was 20.1 transitions/day for volume, 9.7°/s for mean intensity, and 31.7°/s for maximal intensity. (4) Conclusions: The volume and intensity of STS transitions monitored by a thigh-worn accelerometer and a sit-to-stand transitions algorithm are reproducible from day to day and year to year. The accelerometer can be used to reliably study STS transitions in free-living environments, which could add value to identifying individuals at increased risk for functional disability.

Keywords: test–retest; mobility limitation; chair rise

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1. Introduction

Sit-to-stand (STS) transitions are necessary in daily living [1] and a good STS ability is an important factor in maintaining functional independence [2]. Accordingly, the sit-to-stand test is part of the short physical performance battery (SPPB), widely utilized for capacity assessments among older adults [2]. However, performance technique used and measured in the laboratory may differ from free-living [3,4] and, accordingly, it has been noted that maximal physical performance does not necessarily equate with functioning in daily activities [5]. One of the reasons for this discrepancy is that laboratory measurements cannot take into account the effect of the environment and individual factors on mobility in free-living environments [5]. Therefore, identifying sit-to-stand transitions (STS) in a free-living environment may provide added value to an otherwise laboratory-bound comprehensive performance assessment.

The kinematics of the STS transitions have been measured in many, typically laboratory-bound, studies [6–12]. For example, a smartphone acceleration sensor has been used to quantify STS transition and was found to be valid [6,7]. The widely used 5x STS test [8–10], 10x STS test [11] and sit-to-walk [12] movement kinematics of the different phases have also been interpreted successfully with body-fixed gyroscope and/or accelerometer sensors. In addition, previous studies have measured the power of the STS transitions using force platforms [9] and magnetic-field sensors [13].

Many of the approaches utilized in the laboratory are not feasible in free-living environments due to not being portable or energy requirements being too high for multiple-day recordings. Accelerometers, on the other hand, may provide a feasible alternative for free-living STS assessments. Accelerometers are routinely used to monitor physical activity and functioning in free-living environments over multiple days [14,15]. Body postures and types of physical activity have been reliably identified using wearable triaxial accelerometers [16,17] and STS transitions have been identified in free-living environments using wearable sensors [16,18,19]. Both the number of STS transitions (volume) as well as the intensity of the transitions have been studied previously [20]. However, the reproducibility of STS transition detection and quantification remains to be established.

Reproducibility is the minimum requirement for any assessment to be useful and, therefore, it needs to be determined for identifying and quantifying sit-to-stand transitions (STS) as well. Low reproducibility (low ICC) indicates a random measurement error [21]. The reproducibility of free-living accelerometry-based physical behavior has been estimated for a number of metrics, both in the time scale of day to day and year to year. The reproducibility of accelerometer-assessed physical activity and sedentary behavior has been assessed in older adults [22], children [23,24], and working-age individuals [25]. In addition, reproducibility of accelerometers to detect standing and sitting postural changes [26] and test–retest reliability of the number of STS transitions among type 2 diabetics (64.9 (6.0) years) using the ActivPal [27] and a multiple sensor system [28] among older adults with dementia have been examined. However, the reproducibility of free-living STS transition intensity remains unevaluated among older individuals. This is of practical importance because STS transitions could be monitored in prolonged follow-up studies as an indicator of functional deficits.

The purpose of the present study was to evaluate the day-to-day variability and year-to-year reproducibility of a novel STS volume detection and intensity quantification algorithm in a free-living environment among community-dwelling older adults.

2. Materials and Methods

2.1. Study Design and Participants

To test the reproducibility of the STS detection and quantification algorithm, data from participants of the AGNES (Active Ageing—Resilience and external support as modifiers of the disablement outcome) counselling intervention study were used (75 and 80 years of age). The study protocol has been published by Rantanen et al. [29,30] and the study was approved by the ethical committee of the Central Finland Health Care District.

The counselling intervention did not affect physical activity and therefore the data from the intervention and control group were pooled for the present study [31]. This resulted in 86 multiple-day (3–7 days) recordings that were repeated with a one-year interval. The baseline records were obtained between October 2017 and August 2018 (baseline), while the one-year follow-up records were obtained between October 2018 and August 2019.

2.2. Measurements

Age and sex were extracted from the Digital and Population Data Services Agency register, while height (stadiometer), weight (digital scale Seca, Hamburg, Germany), life-space mobility and cognitive function test (mini-mental state examination, MMSE) were assessed using standardized procedures [30]. Self-reported habitual physical activity was assessed using the Yale Physical Activity Survey for older adults (eight-item, YPAS). The total score range was 0 to 137 and higher scores indicate a higher level of physical activity [32].

Lower-extremity physical performance was assessed in the participants' homes by the Short Physical Performance Battery (SPPB) [33,34]. The battery comprised tests on standing balance, walking speed over a 3 m distance, and the 5x STS test. In this study, we used the SPPB total score and the time of the 5x STS test as outcomes. Maximal isometric handgrip force was measured on the dominant side during the home interview using a hand-held adjustable dynamometer (Jamar Plus digital hand dynamometer, Patterson Medical, Cedarburg, WI, USA), and expressed in kg [35].

2.3. Accelerometry Outcomes

Accelerometry was conducted with a thigh-worn accelerometer (tri-axial accelerometer, which sampled continuously at 100 Hz, 13-bit analog-to-digital conversion, acceleration range ±16 g, UKK RM42, UKK Terveyspalvelut Oy, Tampere, Finland) attached on the anterior aspect of the dominant thigh.

The STS transition algorithm (Supplementary Material) was developed using Matlab (R2019a, The MathWorks Inc., Natick, MA, USA). The raw accelerometer data were used to calculate the resultant acceleration for each sampling instant and then the mean amplitude deviation (MAD) was calculated in non-overlapping 5 s epochs [36]. After this, an upright position that serves as a reference vector was determined by searching the data for a walking period that allowed the calculation of the reference posture. Next, the angle for posture estimation (APE) [37] was calculated for each time instant as the vector angle between the reference vector and instantaneous acceleration vector, which had been low-pass filtered at 1 Hz cut-off (4th order zero-lag digital Butterworth filter). The APE signal was further smoothed with a 4th-order Butterworth zero-lag low-pass filter with a 10 Hz cut-off frequency. STS transitions were identified according to the following conditions: (1) movement begins at an APE of at least 65 degrees and ends at an APE of at least 35 degrees; (2) the participant had been stationary for at least 2 s prior to the transition); (3) movement begins at a femoral angle of at least 65 degrees and ends at a femoral angle of at least 35 degrees (Figure 1). The intensity of an identified STS transition was estimated based on the APE signal time derivative (i.e., angular velocity). The STS transition's mean intensity (mean median angular velocity) was the mean of daily median transitions and the maximal intensity (maximal angular velocity) was defined as the median of the ten fastest STS transitions over the entire monitoring period. The volume of the STS transitions was determined as the number of transitions per monitoring day (Figures 2 and S1).

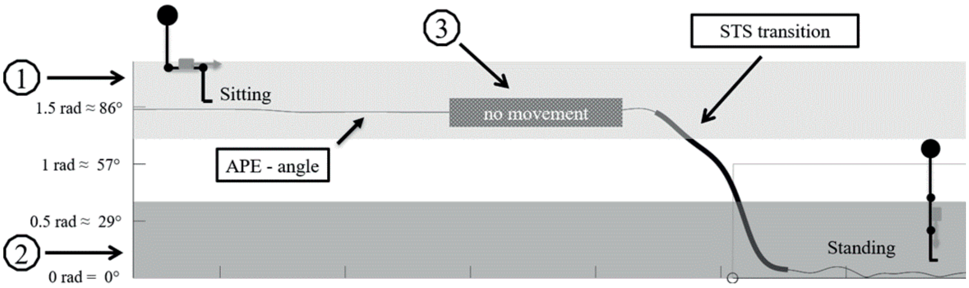


Figure 1. STS transition detection conditions: (1) STS start position > 65 degrees; (2) STS start position > 35 degrees; (3) no motion before STS transition (results of MAD variation < 0.02).

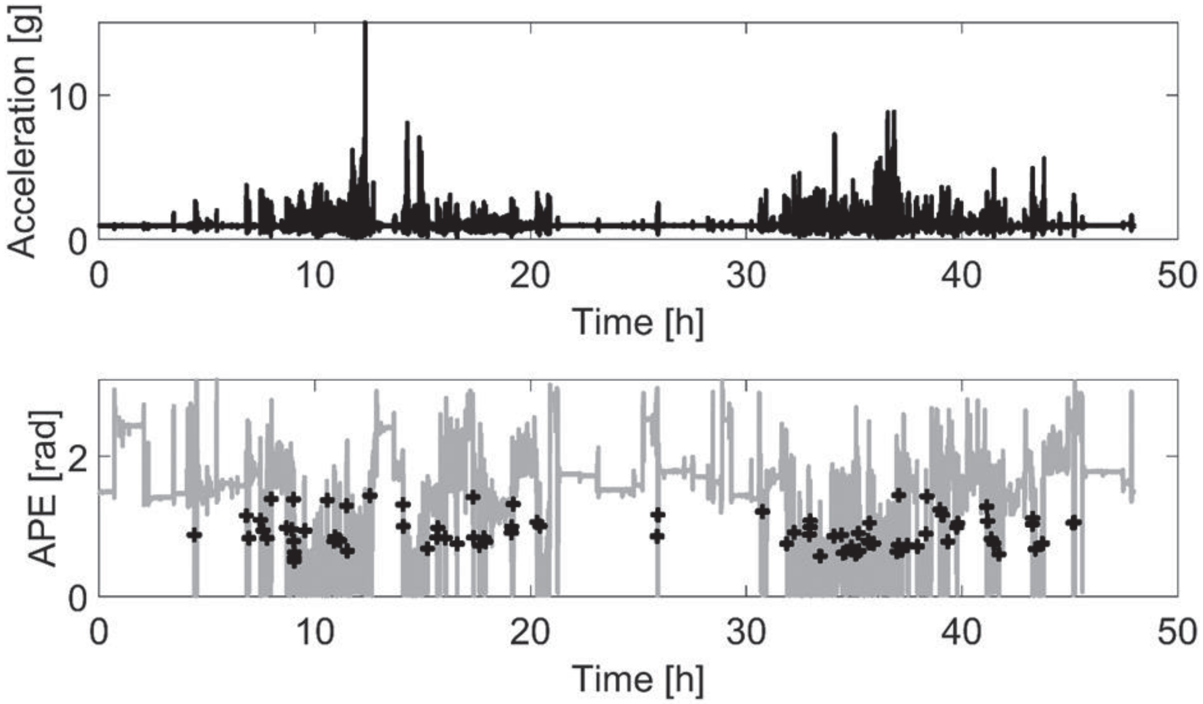


Figure 2. A visualization of the signals used to detect and quantify sit-to-stand (STS) transitions in a free-living environment. The two-day sample starts at midnight and shows the expected diurnal pattern in STS transitions, with very few occurring over the night-time. Top pane: resultant magnitude acceleration. Bottom pane: angle for postural estimation (APE, grey) and the identified STS transitions (black "+").

Physical activity was evaluated from the multiple-day accelerometry records as the daily average mean amplitude deviation (MAD) analyzed in 5 s epochs [38]. In addition, moderate-to-vigorous physical activity (MVPA) minutes were estimated as the daily sum of minutes above 0.24 g MAD. We have previously used the 0.24 g cut-point for high-pass filtered vector magnitude (HPFVM) [39]. MAD and HPFVM calculations resulted in nearly identical numerical values and we therefore deemed it appropriate to apply the HPFVM-based cut-point to MADs for the MVPA analysis.

2.4. Statistical Analyses

Results of STS transitions are reported as mean and standard deviation (SD). Shapiro–Wilk normality test was used to check the normality of the data, which indicated that some of the variables were not normally distributed and non-parametric tests were therefore chosen for all variables. The change from baseline to follow-up measurements was analyzed using Wilcoxon signed-rank test and correspondence between the two time points was evaluated with two-way random intraclass correlation coefficients (ICC, absolute agreement, single measures). Agreement between test and retest was analyzed by Bland–Altman analysis [40], where the limits of the agreement were presented with a 95% confidence interval (dotted line).

In the day-to-day variability analysis, the variation between the five measurement days was examined using the Friedman test (non-parametric Repeated Measures ANOVA). The day-to-day agreement was estimated by calculating intraclass correlation coefficients for four day-pairs (day 1–day 2, day 2–day 3, day 3–day 4 and day 4–day 5) in follow-up measurements. ICC was used to characterize the correspondence as poor (<0.40), fair (0.40 to <0.60), good (0.60 to <0.75) or excellent ($\geq$0.75) [41]. Statistical significance was set at $p \leq 0.05$ and analyses were performed in the "R" statistical environment (version 4.0.3, R Core Team (2020) [42].

The smallest amount of change for STS variables was estimated by calculating the Minimum Detectable Change (MDC) over a 95% confidence interval. This was calculated using the following equations [43]. First, the Standard Error of Measurement (SEM) was calculated:

$$\mathrm{SEM} = \mathrm{SD}_{\mathrm{1st\ test}} \times \sqrt{1 - \mathrm{ICC}}$$

The Minimal Detectable Change (MDC) was then calculated for a 95% confidence interval:

$$\mathrm{MDC}_{95} = 1.96 \times \mathrm{SEM} \times \sqrt{2}$$

3. Results

Time taken to complete the 5x STS tests improved from 11.9 (±2.9) seconds at the baseline to 10.3 (±3.0) at the follow-up (p = 0.001), with a concomitant improvement in the SPPB total score (10.7 ± 1.4 versus 11.3 ± 1.0, $p < 0.001$) at follow-up (Table 1). No statistically significant changes were observed in hand grip force (p = 0.570) or life-space mobility score (p = 0.515). In addition, no difference was observed in 24 h mean MAD (p = 0.835) nor in MVPA (p = 0.567), but self-reported habitual physical activity scores were higher at follow-up (p = 0.001).

Table 1. Descriptive statistics of the study (n = 86, female 64%) (mean (SD)).

	Baseline	**Follow-Up**	***p*-Value** [1]
Age [year]	76.5 (±1.9)		
Weight [kg]	73.7 (±14.0)		
Height [m]	164.6 (±9.8)		
MMSE [points]	28.2 (±1.3)		
YPAS [points]	57.7 (±21.0)	66.6 (±24.6)	0.001
Life-space mobility [points]	74.2 (±10.3)	75.3 (±14.1)	0.515
Hand grip force [kg]	35.3 (±11.3)	36.7 (±12.7)	0.570
5x STS test time [s]	11.9 (±2.9)	10.3 (±3.0)	<0.001
SPPB overall points [points]	10.7 (±1.4)	11.3 (±1.0)	<0.001
MAD 24 h [mG]	25.1 (±8.1)	24.8 (±8.8)	0.835
MVPA [min/d]	34.4 (±24.7)	33.7 (±25.8)	0.567

SD = standard deviation; MMSE = Mini-Mental State Examination; YPAS = self-reported habitual physical activity scores from the Yale Physical Activity Survey for older adults; STS = sit-to-stand; SPPB = Short Physical Performance Battery; MAD = mean amplitude deviation; MVPA = moderate-to-vigorous physical activity; [1] Wilcoxon signed-rank test.

The mean number of STS transitions at baseline and at follow-up were similar (44.2 ± 15.9 versus 44.5 ± 15.2, p = 0.931) (Table 2). Likewise, baseline and follow-up mean angular velocities did not differ (56.9 ± 8.0°/s versus 56.6 ± 8.0°/s, p = 0.587). Maximal angular velocity decreased over the follow-up (111.6 ± 22.0°/s versus 107.3 ± 19.7°/s, p = 0.017). Physical activity indicated by the 24 h mean MAD (25.1 ± 8.1°/s versus 24.8 ± 8.8°/s, p = 0.835) or minutes accumulated in MVPA (34.4 ± 24.7°/s versus 33.7 ± 25.8°/s, p = 0.567) did not differ between baseline and follow-up measurements.

The year-to-year ICC's for the number of STS transitions, mean and maximal angular velocities were good to excellent, i.e., ICC = 0.79 (95% ci 0.70–0.86, $p < 0.001$), ICC = 0.81 (95% ci 0.72–0.87, $p < 0.001$) and ICC = 0.73 (95% ci 0.61–0.82, $p < 0.001$), respectively. The ICCs for MAD (ICC = 0.89, 95% ci 0.84–0.93, $p < 0.001$) and MVPA (ICC = 0.85, 95% ci 0.79–0.90, $p < 0.001$) were excellent. Minimum detectable change (MDC) based on a 95% confidence interval was 20.1 transitions/day for volume, 9.7°/s for mean intensity, and 31.7°/s for maximal intensity.

Table 2. Sit-to-stand assessment from the free-living recordings at baseline and the one-year follow-up and reproducibility of the sit-to-stand transition outcomes ($n = 86$).

	Baseline Mean (SD)	Follow-Up Mean (SD)	*p*-Value [1]	ICC	ICC 95% ci
Number of STS [no/d]	44.2 (±15.9)	44.5 (±15.2)	0.931	0.79 ***	0.70–0.86
Mean angular velocity [deg/s]	56.9 (±8.0)	56.6 (±8.0)	0.587	0.81 ***	0.72–0.87
Maximal angular velocity [deg/s]	111.6 (±22.0)	107.3 (±19.7)	0.017	0.73 ***	0.61–0.82
MAD 24 h [mg]	25.1 (±8.1)	24.8 (±8.8)	0.835	0.89 ***	0.84–0.93
MVPA [min/d]	34.4 (±24.7)	33.7 (±25.8)	0.567	0.85 ***	0.79–0.90

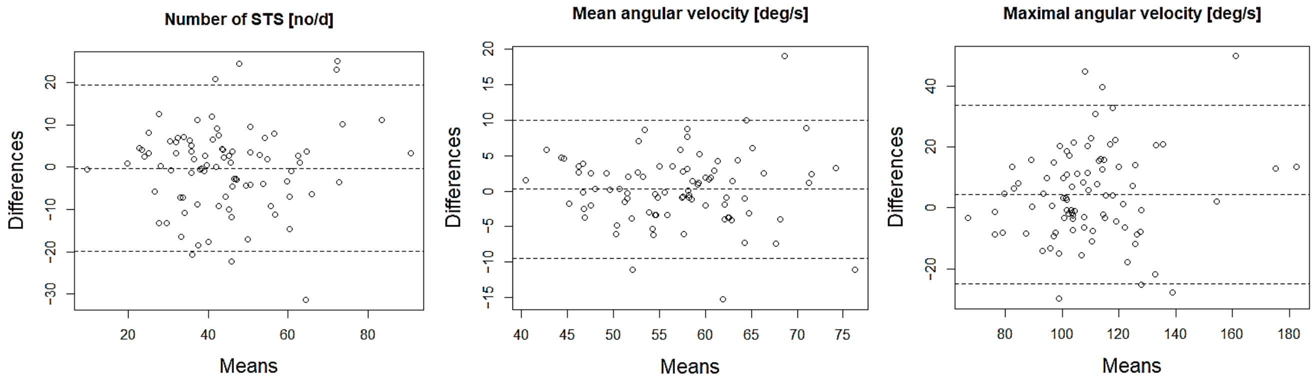
STS = sit-to-stand; SD = standard deviation; ICC = intraclass correlation coefficients; Ci = confidence interval of ICC; [1] Wilcoxon signed-rank test; *** $p < 0.001$.

Day-to-day ICC varied in number of STS transitions between 0.63and 0.72 (95% ci, 0.49–0.81, $p < 0.001$) and in mean angular velocity between 0.75 and 0.80 (95% ci, 0.64–0.87, $p < 0.001$) (Table 3). In addition, there were no statistically significant differences between days in the number of STS transitions ($\chi^2(4) = 7.521$, $p = 0.111$) and in mean angular velocity ($\chi^2(4) = 6.760$, $p = 0.149$). Bland–Altman's analysis (Figure 3) shows that there were only a few cases outside the limits of the agreement (95%, dotted line) and there was no systematic difference between the two measurements.

Table 3. Mean values of free-living STS variables for five follow-up recording days and intraclass correlation coefficients between four day-pairs ($n = 86$).

Mean (SD)	Number of STS (no/day)	Mean Angular Velocity (deg/s)
day 1 ($n = 85$)	45.5 (±17.7)	56.2 (±8.1)
day 2 ($n = 86$)	44.4 (±16.1)	55.5 (±8.3)
day 3 ($n = 86$)	44.4 (±20.0)	57.2 (±7.9)
day 4 ($n = 83$)	43.4 (±17.4)	56.4 (±9.2)
day 5 ($n = 81$)	45.9 (±18.2)	56.8 (±8.6)
ICC (95% ci) ***		
day 1–day 2 ($n = 85$)	0.63 [0.49, 0.74]	0.79 [0.69, 0.86]
day 2–day 3 ($n = 86$)	0.72 [0.60, 0.81]	0.78 [0.68, 0.86]
day 3–day 4 ($n = 83$)	0.64 [0.50, 0.75]	0.75 [0.64, 0.83]
day 4–day 5 ($n = 81$)	0.71 [0.58, 0.80]	0.80 [0.71, 0.87]

STS = sit-to-stand; SD = standard deviation; ICC = intraclass correlation coefficients; ci = confidence interval of ICC; *** all $p < 0.001$.



(**a**) (**b**) (**c**)

Figure 3. Bland–Altman plots: (**a**) number of STS, (**b**) mean angular velocity and (**c**) maximal angular velocity ($n = 86$).

4. Discussion

The purpose of this study was to evaluate the day-to-day variability and year-to-year reproducibility of an accelerometer-based algorithm to detect STS volume and to quantify STS intensity in free-living environments. The results of this study suggest that the algorithm can reliably detect and quantify sit-to-stand transitions in community-dwelling older adults over a year-long follow-up. In addition, the study found a low day-to-day variation in STS volume and intensity. This suggests that STS transitions can be detected, and their intensity quantified reproducibly using a thigh-worn accelerometry in a free-living environment.

The results of the one-year follow-up are congruent with the reproducibility of the number of STS transitions reported for participants with type 2 diabetes, where an excellent agreement (ICC = 0.90, 95% CI 0.79–0.95, $p < 0.001$) has been reported for measurements with at least a one-week time interval [27]. Our study reported better reproducibility of STS transitions than previous reports on the reproducibility of time spent sitting or standing, which showed ICC values of 0.58 for sitting and 0.62 for standing 6 months apart [26]. In addition, the year-to-year ICC values observed in this study are well in line with previously published results when looking at the conventional variables of physical activity. Reproducibility measured with accelerometers has been found to be good between two MVPA measurements among older people within a period of 2–3 years [22], and middle-aged women within a period of 12 months [25]. We are not aware of previous research on the reproducibility of sit-to-stand transition intensity in a free-living environment among older adults, but the test–retest reliability of laboratory-assessed 5x STS test power has been found to be comparable to that of this study [44].

In the current study, day-to-day variability was lower in the intensity of STS transitions than in volume. Abel and colleagues (2019) found slightly higher ICC values than this study, when they studied the variation of STS transitions volume from day to day among older people with dementia using a multi-sensor system [28]. We are not aware of any previous study regarding the day-to-day variability of the intensity of STS transitions. A higher variability in the number of STS transitions compared to the intensity may purely suggest that the number of transitions varies in everyday life more than the intensity, which is more dependent on the performance of individuals. To the authors' best knowledge, minimal detectable change has not been reported previously for STS transitions in free-living environments among older adults. However, in a previous study [43], similar MDC values were observed in the angular velocities of trunk flexion and extension while standing up as in this study. The importance of the minimal detectable change in physical performance assessment should be addressed in future studies.

In this study, participants' lower extremity performance (SPPB), 5x STS test results and self-reported physical activity (YPAS) improved during one year of follow-up. On the other hand, life-space mobility, physical activity monitored by an accelerometer and hand grip force did not change during one-year follow-up. Reviewing other questionnaire data recorded in the trial not reported in this study [29,30] indicated that none of the individuals that took part in the follow-up had a major health-related or psychological setback during the follow-up. In addition, physical activity measured with an accelerometer was concordant with STS variables, i.e., no change over the follow-up, which could indicate that physical behavior had not changed significantly. Therefore, the very good-to-excellent year-on-year agreement of the STS transition assessment seems encouraging and thus the assessment provides a reliable method to measure the volume and intensity of STS transitions in free-living environments.

The presented detection algorithm contains a few limitations that need to be pointed out. The algorithm is only able to identify the first repetition of a multi-STS set (caused by the 2 s stationary epoch prior to an STS requirement) and therefore cannot be directly used to identify, e.g., the performance in the 5x STS. The algorithm can also detect movements other than STS transitions, such as very slow knee lifts or other similar movements where the hip joint is flexed and extended toward the ground at a slow pace. However, the algorithm contains a criterion that requires that there must be no movement before the STS transition, and therefore there should be no interference with other activity types, such as walking, running or climbing stairs. Nevertheless, STS transition detection sensitivity and specificity would need to be examined more rigorously in future studies. The presented algorithm does not require aligning the sensor in any specific orientation with respect to the thigh because the orientation is estimated from the signal. In this study, the equipment was not calibrated separately because the calibration performed by the equipment manufacturer was of sufficient quality. If applying the algorithm to data recorded using a device with marked calibration imprecision, e.g., the autocalibration method proposed by Van Hees and colleagues [45], there is sufficient calibration according to our experimentation.

This study has some limitations that need to be pointed out. Although the year-to-year stability is encouraging, significant changes in the physical performance of an older person may take place over a year-long follow-up [46,47]. Therefore, it was impossible to disentangle physiological changes over the follow-up from the imprecision associated with the measurement. However, no change in physical activity was observed between the two measurements. In addition, the validity of the STS intensity evaluation algorithm remains to be investigated. The strength of this study is that it included a relatively large sample of community-dwelling participants with multiple days (3–7 days) of recording accelerometry. The 3–7-day accelerometry sample is thought to be sufficient for assessing activity patterns [48]. The developed algorithm is independent of the measurement device and can be applied to raw accelerations recorded with any reasonably precise accelerometer. The year-to-year reliability of the STS transition detection and quantification appeared to be acceptable, and we postulate it would be reasonable to apply the technique in further studies. For example, the convergent validity of free-living STS detection and quantification could be evaluated by exploring the associations between laboratory-measured performance capacity and free-living STS transition quantifications.

5. Conclusions

This study provided evidence supporting long-term and day-to-day reproducibility of accelerometer-measured STS volume detection and an intensity quantification algorithm in free-living environment community-dwelling older adults. The algorithm can be used to reliably study STS transitions in free-living environments, which could add value to identifying individuals at increased risk for functional disability.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/s21186068/s1, Figure S1: A visualization of the signals used to detect and quantify sit-to-stand (STS) transitions in a free-living environment. Video S1: Sit-to-stand detection and quantification algorithm sample is available at https://cmj.sport.jyu.fi/sittostand/. Accelerometer-based sit-to-stand transitions algorithm is available at https://github.com/tjrantal/SitToStandSupplement (accessed on 13 June 2021).

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Data Availability Statement: After completion of the study, data will be stored at the Finnish Social Science Data Archive without potential identifiers (open access). Until then, pseudonymized datasets are available to external collaborators subject to agreement on the terms of data use and publication of results. To request the data, please contact Professor Taina Rantanen (taina.rantanen@jyu.fi).

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II

ASSOCIATION BETWEEN FREE-LIVING SIT-TO-STAND TRANSITION CHARACTERISTICS, AND LOWER-EXTREMITY PERFORMANCE, FEAR OF FALLING, AND STAIR NEGOTIATION DIFFICULTIES AMONG COMMUNITY-DWELLING 75 TO 85-YEAR-OLD ADULTS

by

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Research Article

Association Between Free-Living Sit-to-Stand Transition Characteristics, and Lower-Extremity Performance, Fear of Falling, and Stair Negotiation Difficulties Among Community-Dwelling 75 to 85-Year-Old Adults

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Abstract

Background: Good sit-to-stand (STS) performance is an important factor in maintaining functional independence. This study investigated whether free-living STS transition volume and intensity, assessed by a thigh-worn accelerometer, is associated with characteristics related to functional independence.

Methods: Free-living thigh-worn accelerometry was recorded continuously for 3–7 days in a population-based sample of 75-, 80-, and 85-year-old community-dwelling people (479 participants; women $n = 287$, men $n = 192$). The records were used to evaluate the number and intensity (angular velocity of the STS phase) of STS transitions. Associations with short physical performance battery (SPPB), 5-times-sit-to-stand test (5×STS), isometric knee extension force, self-reported fear of falls, and self-reported difficulty in negotiating stairs were also assessed.

Results: The number of STS transitions, mean and maximal angular velocity were lower in older age groups ($p < .05$). All variables were higher in men than in women ($p < .001$) and were positively associated with SPPB total points, knee extension force (r ranged from 0.18 to 0.39, all $p < .001$) and negatively associated with 5×STS ($r = -0.13 - -0.24$, all $p < .05$), lower extremity functional limitations ($p < .01$), fear of falls ($p < .01$), and stair negotiation difficulties ($p < .01$).

Conclusions: Free-living STS characteristics were related to lower-extremity performance, lower extremity functional limitations, self-reported fear of falls, and stair negotiation difficulties, which can be a sensitive indicator of impending functional decline. Moreover, STS transitions may provide an indicator of adequacy of lower-limb muscle strength among older individuals.

Keywords: Chair rise, Functional performance, Geriatric assessment, Physical function, Physical performance

Sit-to-stand (STS) transitions are one of the most common activities of daily life (1) and good STS performance is an important factor in maintaining functional independence (2). STS transitions challenge the older adult's balance and might be a cause of falls when the ability to transfer from STS is limited (3,4). Usually, STS transitions assessment is based on laboratory measurements, for example, using 5-times-sit-to-stand test (5×STS) (5). However, laboratory-measured capacity should not be equated to functioning in free-living environment when measuring older adults without mobility limitations (6,7), as for example, the full maximal capacity is not always utilized in everyday performance. The weakness of the laboratory measurements is that they do not necessarily indicate performance in free-living environment where human intrinsic capacity and environmental factors affect participation and activities (8,9). Therefore, knowledge of behavior in the free-living environment may be of interest.

The recent miniaturization of technology has made prolonged recordings of free-living physical behavior feasible (10). Inexpensive and wearable tri-axial accelerometers have been shown to reliably distinguish body postures and physical activity types (11–13). Accordingly, accelerometers (typically thigh-worn) have been used to assess STS transitions in the free-living environment (1). Previous studies have quantified the volume of STS transitions (ie, number per day) in the free-living environment using 2 accelerometers (sternum and thigh) (14,15). Moreover, inertial measurement units have been used to estimate STS transition duration and power in a laboratory setting (16,17). Kinematics (angular velocity and vertical velocity) are more indicative of the mechanical requirements of the STS transition than just the time taken to complete the transition and hence could reveal further insight compared to the completion time by enabling evaluation of the manner of completing the transition (18). However, the previous free-living STS transition explorations have typically used transition duration to indicate the intensity of the STS transition rather than evaluating the kinematics directly (14,15).

Pickford et al. (2019) have evaluated STS transition kinematics in the free-living environment using a proprietary algorithm to compare peak velocities of STS transitions between stroke survivors and unaffected peers (19). To the best of our knowledge, there is no publicly available algorithm that can detect STS transitions and quantify the STS transition intensity by kinematics based on free-living thigh-worn tri-axial accelerometer records. Therefore, we developed a new algorithm in the current study to detect and quantify STS transitions (Supplementary Code).

The purpose of the present study was to explore whether detected volume and quantified intensity of free-living STS transitions are associated with lower-extremity performance, self-reported fear of falling, and stair negotiation difficulties among community-dwelling 75-, 80-, and 85-year-old people. Based on previous research, which has indicated that limited STS transitioning performance is associated with difficulties in stair negotiation, weak knee-extensor muscles, and high body mass (20–24), we hypothesized a moderate association between the above mentioned laboratory-based performance characteristics and number and intensity of free-living STS transitions. In addition, 5×STS test has been shown to be associated with the risk of falling (25) which we considered a sufficient justification to hypothesize an association between fear of falling and free-living STS performance.

Method

Study Design and Setting

We used data from the AGNES-study (Active Aging—Resilience and external support as modifiers of the disablement outcome; n = 1 021), which was conducted in the Gerontology Research Center, the University of Jyväskylä. AGNES comprises three age cohorts (75, 80, and 85 years-of-age) of people living independently in the city of Jyväskylä, in Central Finland. The study protocol has been published by Rantanen et al. (26) and Portegijs et al. (27), and the study was approved by the ethical committee of the Central Finland Health Care District.

AGNES-study participants were asked to participate in laboratory measurements, which (n = 782) were used to develop algorithms to detect and quantify free-living STS transitions (Supplementary File). All AGNES-study participants who participated in the laboratory testing were also asked for interest in providing a 3–7 days free-living accelerometry record (n = 479), which was used to identify the volume and quantify the intensity of free-living STS transitions. The flow chart of the study has been reported elsewhere (27). The records were obtained between October 2017 and December 2018. Accelerometry was conducted with a thigh-worn accelerometer (tri-axial accelerometer, which sampled continuously at 100 Hz, 13-bit analog-to-digital conversion, acceleration range ±16g, UKK RM42, UKK Terveyspalvelut Oy, Tampere, Finland) taped on using a transparent adhesive film for waterproofing on the anterior aspect of the dominant thigh for 7–10 consecutive days following a home interview. The accelerometers were taped on by a research assistant at participants' home and removed at the research center.

Data Processing

The algorithms were developed using Matlab (R2019b, The MathWorks Inc., Natick, MA, USA). In the first phase, the magnitude (Euclidian norm) of the resultant acceleration for each sampling instant was calculated from raw accelerometer data. Mean amplitude deviation (MAD) was calculated in nonoverlapping 5 s epochs based on the magnitude of the resultant acceleration (28).

To identify the instantaneous orientation of the thigh, we calculated an angle for postural estimation (APE) from resultant acceleration values using the method described by Vähä-Ypyä et al. (13). The calculation requires knowing the direction of gravitational pull when the participant is upright (reference vector). This was defined as the median of the mean X, Y, and Z accelerations of each continuous bout ≥20 s with MAD between 0.035 g and 1.2 g. These MAD cutoffs were identified from the AGNES-study laboratory session 6-minute walking test data to include all participants, and hence, bouts with such characteristics comprise walking. During walking, the mean orientation of the thigh is upright, and the median acceleration is equivalent to that caused by the pull of gravity. The instantaneous acceleration in each of the recorded directions was low-pass filtered with a 1 Hz zero-lag Butterworth filter, and APE was subsequently calculated for each time instant as the vector angle between the instantaneous filtered acceleration vector and the reference vector. After that, the APE-signal was smoothed with a 4th-order Butterworth zero-lag low-pass filter with a 10 Hz cutoff frequency. The filtered APE-signal was transferred into a rectangular signal with a value of 1 when APE < pi/4, and a value of 0 otherwise. That is, upright thigh posture was assigned 1, and horizontal 0. This rectangular signal was then smoothed with a sliding median filter of 23 samples to produce the final posture estimation signal. The 23-sample length for the median filter, as well as the 2 (1 Hz & 10 Hz) Butterworth filter cutoff frequencies were selected based on experimentation.

STS transitions were thereafter identified as follows: all posture estimation signal transitions from 0 (horizontal) to 1 (upright) were considered as candidate STS transitions. A candidate was accepted as a STS transition if the following 3 criteria were met: (a) the variance of the magnitude of the resultant acceleration between 2.5 s and 0.5 s prior to the candidate transition was less than 0.02 g (ie, the participant had been stationary for at least 2 s prior to the transition), (b) starting angle of the STS transition (APE signal) was more than 65 degrees (1.14 rad) and, (c) the movement of the transition ended at an angle of less than 35 degrees (0.61 rad). Due to the variance criterion the algorithm will only detect the first of a set of STS movements (eg, if a person did continuous seat-based squatting starting from a seated posture, only the first STS would be included).

The intensity of an identified STS transition was estimated based on the APE-signal time derivative (ie, angular velocity) as follows: baseline APE (corresponds to thigh angle prior to standing up) was established as the mean between 2.5 s and 1.5 s to the identified transition instant. The last sample at the baseline value prior to the transition instant was thereafter set as the initiation of the angular velocity determination. Linear fits were then applied to each data set from the initiation sample until the transition instant to transition instant + 0.15 s with one sample length increment. The longest fit where the square of the last instant of the fit and the APE differed by less than experimentally determined 0.005 degrees was chosen, and the slope of the chosen fit is reported as the STS transition intensity. The STS transitions detection accuracy of the algorithm was examined using the laboratory session of this study. Prior to the 6-minute walk test, the protocol included two known STS transitions that were defined as the ground truth. Ground truth STS transitions identified by the algorithm were defined as true positives. Ground truth STS transitions that could not be identified were defined as false negatives. No false positives were identified, and we did not attempt to define a true negative. True positives and false negatives were used to calculate detection accuracy, which ranged between 82.7% and 97.5% depending on the age (better accuracy among younger age groups compared to older age groups) and sex (better accuracy among men than women) groups, with an overall accuracy of 93.3% (Supplementary File). The angular velocity quantification accuracy of STS transitions at different velocities was good when the angular velocity detected by the algorithm was compared against 2D motion analysis (Supplementary Video). In addition, the volume and intensity of STS transitions monitored by thigh-worn accelerometer are reproducible from day-to-day to year-to-year (29).

The volume of the STS transitions was determined as the number of transitions per monitoring day, and the STS transitions mean intensity (mean median angular velocity) was determined as the mean of daily median transitions. The maximal intensity (maximal angular velocity) was defined as the median of the ten fastest STS transitions over the entire monitoring period. No participant exceeded 4 rad/s in the laboratory, and therefore we filtered out any STS transitions above 4 rad/s from the data prior to the estimation of the maximum free-living angular velocity. A total of 79 transitions were removed due to this, and this was 0.04% of all 182 103 transitions detected in this data set.

Descriptive Characteristics and Other Measurements

Age and sex were extracted from the population register, body height (stadiometer), body mass (digital scale Seca, Hamburg, Germany), socioeconomical status (self-reported years of education), and cognitive function test (mini-mental state examination, MMSE) were assessed using standardized procedures (26). Lower-extremity performance was assessed in the laboratory (knee extension force) or the participant's home by the short physical performance battery (SPPB). Maximal knee extension force of the dominant lower limb with the knee at 60 degrees was measured in a sitting position using an adjustable dynamometer chair (Metitur LTD, Jyväskylä, Finland). At least 3 attempts were required, and the highest force was chosen for the analyses (30). The SPPB comprised tests on standing balance, walking speed over a 3-m distance, and the 5×STS (5,31). In this study, we used the SPPB total score (maximum of 12 points, higher scores mean better performance) and the time of the 5×STS test as outcomes. Good lower extremity function was defined as 11-12 SPPB total points and limited lower extremity function as 10-3 SPPB total points (32).

Fear of falling was assessed by the question "Are you afraid of falling?" with 4 response options: never, occasionally, often, and constantly (33). In this study, "never" was categorized as "No Fear," and the rest of the response options were merged into "Yes Fear." Difficulties in negotiating stairs were assessed with the question: "Have you noticed any of the following changes in your ability to ascend a flight of stairs?" The responses were categorized as "No difficulties," "I can ascend a flight of stairs, but I have some difficulties," "I can ascend a flight of stairs, but I have a lot of difficulties," "I cannot ascend a flight of stairs without help of another person," or "I cannot ascend a flight of stairs even with help." In the present study, "no difficulties" were categorized as "No difficulties," and the rest of the response options were merged into "Yes difficulties." No participant reported "I cannot ascend a flight of stairs even with help." Self-reported habitual physical activity was assessed using the Yale Physical Activity Survey for older adults (8-item). The total score range was 0–137 and higher scores indicate higher physical activity (34).

Statistical Analyses

Results of STS transitions are reported as mean and standard deviation (*SD*). Associations between variables were tested with Spearman rank correlation coefficients. Number, mean, and maximal angular velocity of STS transitions were categorized into tertiles group comparisons for 5×STS time and knee extension force normalized for body mass. Tertiles (as opposed to quartiles, quintiles, etc.) were selected to maintain sufficient sample sizes in each group. Shapiro-Wilk normality test indicated that some of the variables were not normally distributed, and nonparametric statistical tests were therefore chosen. Sex and age group differences were analyzed with Mann–Whitney U (Wilcoxon rank-sum) test for categorical/dichotomous variables and Kruskal–Wallis test for continuous variables. Tertiles comparisons were performed using the Kruskal–Wallis multiple comparison test and the Dunn's test (Holm-Bonferroni method) in pairwise comparisons. Sensitivity analyzes between sexes and age groups were performed between the variables and the self-reported questions (fear of falling, lower extremity functional limitations, and difficulties in negotiating stairs). Statistical significance was set at $p < .05$ (2-tailed), and analyses were performed in the "*R*" statistical environment (version 4.1.1) (35).

Results

Descriptive characteristics and free-living STS transitions of the participants are presented in Table 1. The number of STS transitions, mean and maximal angular velocity differed between age groups and sexes (all $p < .001$). The 85-year-old women showed 19.6% fewer STS transitions ($p = .005$) and 9.2% lower mean ($p < .001$) and 14.6% lower maximal angular velocity ($p < .001$) in the free-living environment compared to the 75-year-old women. The 85-year-old men showed 18.3% fewer STS transitions ($p = .015$) and 8.9% lower mean ($p = .012$), and 9.4% lower maximal ($p = .042$) angular velocity of the STS transitions compared to the 75-year-old men.

The Spearman rank correlation coefficients between variables are given in Table 2. In the number of STS transitions, mean and

Table 1. Descriptive Characteristics of the Participants and Results of SPPB, Knee-Extension Force, Volume and Intensity of STS Transitions in Each Age Group (Mean ± Standard Deviation [*SD*])

	75 Years (*n* = 244)		80 Years (*n* = 153)		85 Years (*n* = 82)		*p* Value*		*p* Value†
	Women	Men	Women	Men	Women	Men	Ages		Sexes
Variable	*n* = 149	*n* = 95	*n* = 87	*n* = 66	*n* = 51	*n* = 31	Women	Men	
MMSE (points)	27.8 ± 2.2	27.4 ± 2.3	27.7 ± 1.9	27.1 ± 3.0	26.7 ± 2.8	26.5 ± 2.4	.021	.183	.053
Years of education	12.1 ± 4.1	12.3 ± 4.5	11.4 ± 4.1	11.8 ± 3.9	10.3 ± 4.3	10.0 ± 4.9	.003	.022	.454
YPAS (points)	57.8 ± 22.6	61.8 ± 22.6	59.2 ± 20.2	65.3 ± 27.5	50.2 ± 20.6	55.8 ± 24.6	.019	.126	.020
SPPB overall points (points)	10.5 ± 1.6	10.8 ± 1.6	10.4 ± 1.8	10.5 ± 2.0	9.2 ± 2.2	9.7 ± 1.9	.001	.003	.067
Five times STS test time (s)	12.4 ± 3.4	12.2 ± 3.3	12.3 ± 3.5	11.9 ± 4.6	14.1 ± 4.1	13.9 ± 4.8	.029	.048	.301
Knee extension force (N/kg)	4.4 ± 1.2	5.8 ± 1.5	4.2 ± 1.3	5.4 ± 1.4	3.6 ± 1.0	4.8 ± 1.0	<.001	.002	<.001
Number of STS (no/d)	42.8 ± 16.3	50.4 ± 16.8	41.4 ± 15.4	47.3 ± 18.8	34.4 ± 15.2	41.2 ± 14.1	.005	.015	<.001
Mean angular velocity (deg/s)	57.6 ± 8.5	60.6 ± 8.8	56.1 ± 8.4	59.8 ± 9.5	52.3 ± 7.5	55.2 ± 9.0	<.001	.012	<.001
Max angular velocity (deg/s)	109.0 ± 18.8	115.9 ± 20.0	106.5 ± 22.9	112.3 ± 18.6	93.1 ± 14.8	105.0 ± 20.9	<.001	.042	<.001

Notes: MMSE = Mini-Mental State Examination; SPPB = Short Physical Performance Battery; STS = sit-to-stand transitions; YPAS = Yale Physical Activity Survey for older adults.

*Independent-samples Kruskal–Wallis test.

†Independent-samples Mann–Whitney U test.

Table 2. Spearman's Correlation Coefficients Between Free-Living Sit-to-Stand Variables, Physical Activity Behavior and Performance Tests

	Number of STS (no/d)		Mean Angular Velocity (deg/s)		Max Angular Velocity (deg/s)	
Variable	*r*	*p* Value	*r*	*p* Value	*r*	*p* Value
Mean angular velocity (deg/s)	0.53	<.001				
Max angular velocity (deg/s)	0.50	<.001	0.65	<.001		
Five times STS test time (s)	−0.13	<.004	−0.18	<.001	−0.24	<.001
SPPB overall points (points)	0.18	<.001	0.24	<.001	0.33	<.001
Knee extension force (N/kg)	0.25	<.001	0.28	<.001	0.39	<.001

Note: SPPB = Short Physical Performance Battery; STS = sit-to-stand transitions. *p* Value (2-tailed).

maximal angular velocity were positively associated with the SPPB total points and maximal isometric knee extension force (r ranged from 0.18 to 0.39 all $p < .001$) and negatively associated with the 5×STS test ($r = -0.13 - -0.24$, $p < .05$). We also ran the correlation analyses for sexes and age-groups independently as a sensitivity analysis, and the correlations did not differ markedly between sexes and age groups.

Tertiles group comparisons are presented in Table 3. Overall, the tertiles based on maximal and mean angular velocity of STS transitions demonstrate more differences between tertile groups in laboratory-based 5×STS and knee extension force than tertiles based on number of STS transitions. This indicates that lower STS transition velocities are linked to longer 5×STS time and lower knee extension force. In particular, the weakest tertile (T1) seems to differ from the others, while T2 and T3 do not seem to differ from each other.

Individuals who feared falling showed 15.8% fewer STS transitions ($p < .001$) and had 5.5% lower STS mean angular velocity ($p < .001$) and 8.9% maximal angular velocity ($p < .001$) in free-living conditions compared to individuals who reported no fear of falling Figure (1–3). Furthermore, individuals who reported difficulties with stair negotiation had 16.8% fewer STS transitions ($p < .01$) and had 6.9% lower STS mean angular velocity ($p < .001$) and 10.0% maximal angular velocity ($p < .001$) than individuals who reported no difficulties with stair negotiation Figure (1–3). Individuals who have lower extremity functional limitations according to SPPB total score showed 10.8% fewer STS transitions ($p < .01$) and had 5.8% lower STS mean velocity ($p < .001$) and 10.1% maximal angular velocity ($p < .001$) in free-living conditions compared to individuals who do not have lower extremity functional limitations Figure (1–3). Sensitivity analyses where we ran the sexes and ages independently indicated no effect of sex and age in the results.

Discussion

The primary finding of the present study was that the volume and intensity of free-living STS transitions based on thigh-worn accelerometry were positively associated with lower-extremity performance, and negatively associated with lower extremity functional limitations, self-reported fear of falling, and difficulties in negotiating stairs among community-dwelling older people. Furthermore, the volume and intensity of STS transitions in free-living environment were lower in older age groups and differed between sexes. This study expands our understanding of free-living of physical activity by describing one of the most common specific daily activity movement and determining its intensity in community-dwelling 75-, 80-, and 85-year-old men and women. Assessing STS transitions may be a

Table 3. Participants Were Divided into Three Groups, i.e., Lowest, Middle and Highest Tertile, Based on Their STS Performance in the Free-Living Environment (Column 1: Number, Mean, or Maximal Angular Velocity of STS Transitions)

	Women	Men	Women	Men	Women	Men
Tertiles based on number of STS[*]						
	Number of STS (no/d)		5×STS test time (s)		Knee extension force (N/kg)	
Lowest (T1)	24.5 (6.4)	30.8 (8.0)	12.9 (3.8)	12.6 (3.5)	4.0 (1.2)	5.2 (1.6)
Middle (T2)	39.2 (3.9)	45.9 (3.7)	12.8 (3.8)	13.3 (5.1)	4.3 (1.3)	5.5 (1.5)
Highest (T3)	59.1 (11.0)	67.1 (12.5)	12.3 (3.2)	11.2 (3.2)	4.3 (1.2)	5.8 (1.2)
p Value #	<.001[†,‡,§]	<.001[†,‡,§]	.631	.013[‡]	.107	.013[§]
Tertiles based on mean angular velocity[‖]						
	Mean angular velocity (deg/s)		5×STS test time (s)		Knee extension force (N/kg)	
Lowest (T1)	47.2 (3.1)	49.3 (3.8)	13.1 (3.7)	13.1 (4.1)	3.8 (1.1)	5.0 (1.2)
Middle (T2)	55.9 (2.1)	59.5 (1.9)	13.0 (3.8)	11.8 (3.7)	4.3 (1.3)	5.9 (1.8)
Highest (T3)	65.7 (5.6)	69.6 (5.5)	11.9 (3.2)	12.2 (4.5)	4.5 (1.3)	5.6 (1.2)
p Value #	<.001[†,‡,§]	<.001[†,‡,§]	.026[§]	.078	<.001[†,§]	.004[†]
Tertiles based on max angular velocity[¶]						
	Max angular velocity (deg/s)		5×STS test time (s)		Knee extension force (N/kg)	
Lowest (T1)	85.1 (8.7)	91.7 (9.1)	13.7 (3.8)	13.6 (4.3)	3.7 (1.1)	4.9(1.3)
Middle (T2)	104.2 (3.8)	112.8 (5.0)	12.5 (3.8)	11.5 (3.2)	4.3 (1.4)	5.5 (1.3)
Highest (T3)	127.3 (16.3)	134.2 (13.4)	11.8 (2.8)	11.9 (4.4)	4.7 (1.1)	6.1 (1.6)
p Value #	<.001[†,‡,§]	<.001[†,‡,§]	<.001[†,§]	.010[†,§]	<.001[†,‡,§]	<.001[†,§]

Notes: Data (mean [*SD*]) represent values of the different tertiles on lab-based measurements, i.e., 5-times-sit-to-stand test (5×STS time) and knee extension force normalized for body mass. SPPB = Short Physical Performance Battery; *SD* = standard deviation; STS = sit-to-stand transitions.

[*] Women tertiles cutoff: T1 ≤ 33.17, T3 ≥ 46.00; Men tertiles cutoff: T1 ≤ 40.15, T3 ≥ 52.40.

[†] T1–T2 $p < .05$.

[‡] T2–T3 $p < .05$.

[§] T1–T3 $p < .05$.

[‖] Women tertiles cutoff: T1 ≤ 51.66, T3 ≥ 59.74; Men tertiles cutoff: T1 ≤ 55.32, T3 ≥ 62.67.

[¶] Women tertiles cutoff: T1 ≤ 97.22, T3 ≥ 111.21; Men tertiles cut-off: T1 ≤ 103.15, T3 ≥ 120.80.

[#] Independent-samples Kruskal–Wallis test (Pairwise: Dunn's test, Bonferroni-Holm).

good daily performance indicator in future studies when monitoring older adults' physical functioning in a free-living environment.

The number of STS transitions in the present study (women 42.8–34.4 transitions/day, men 50.4–41.2 transitions/day) is congruent with previously published results. Bohannon (2015) stated in his review that the average number of STS transitions are at least 45 per day among most community-dwelling individuals (1). In addition, Pickford and colleagues (2019) studied the mean angular velocity of STS transitions in 61.0 ± 10.1 years of age group and reported higher angular velocity values (70.7 ± 52.2 degree/s) compared to the present study (women 57.6–52.3 degree/s, men 60.6–55.2 degree/s). This is in line with the expected age-related decline in functional performance (36). In the current study, the volume and intensity of STS were lower with advancing age. This is in line with the higher number of STS transitions in younger people (71 ± 4 years) living at home compared to older people (87 ± 7 years) living in an older adult care facility (37). However, the sex difference observed in this study between STS intensity or number of transitions has not been studied in free-living conditions, although it has been found that STS transitions performance in the laboratory (5×STS time) decreases with age more slowly in women than men (23,38).

The associations between lower-extremity performance and number of STS transitions in the current study were relatively weak. Ryan et al. reported no significant (r = −0.12, p = .47) association between 5×STS test and free-living STS events in people with chronic low back pain (39). In addition, the tertile group comparisons in the present study indicated that the number of STS transitions did not seem to be very dependent on lower-extremity performance. This may suggest that the number of STS transitions is more related to the individual and environmental factors than laboratory-measured lower-extremity capacity, as noted for physical activity (40), especially when capacity does not limit STS transition in free-living environment. Furthermore, the intensity of the STS transition performance, as indicated by movement velocity, is influenced by multiple physiological and psychological processes rather than lower-extremity strength (23). Although the above-mentioned factors primarily affect STS transitions intensity, these factors may also have an effect on the number of STS transitions in the free-living conditions.

Knee extension force was more strongly related to the mean and maximal angular velocity of the STS transitions than to the number of STS transitions, indicating that maximal angular velocity, in particular might be a better representation of the capacity of the lower extremities. This is further confirmed by the tertile comparisons. In addition, a pairwise comparison of tertiles showed that the weakest tertile (T1) of mean or maximal angular velocity differed on lab-based lower-extremity performance from the other tertiles (T2 and T3), while no differences were found between tertiles T2 and T3. This could suggest that the mean and maximum angular velocities of the STS transitions only begin to decline when capacity is significantly impaired. Altogether, this could indicate that above a

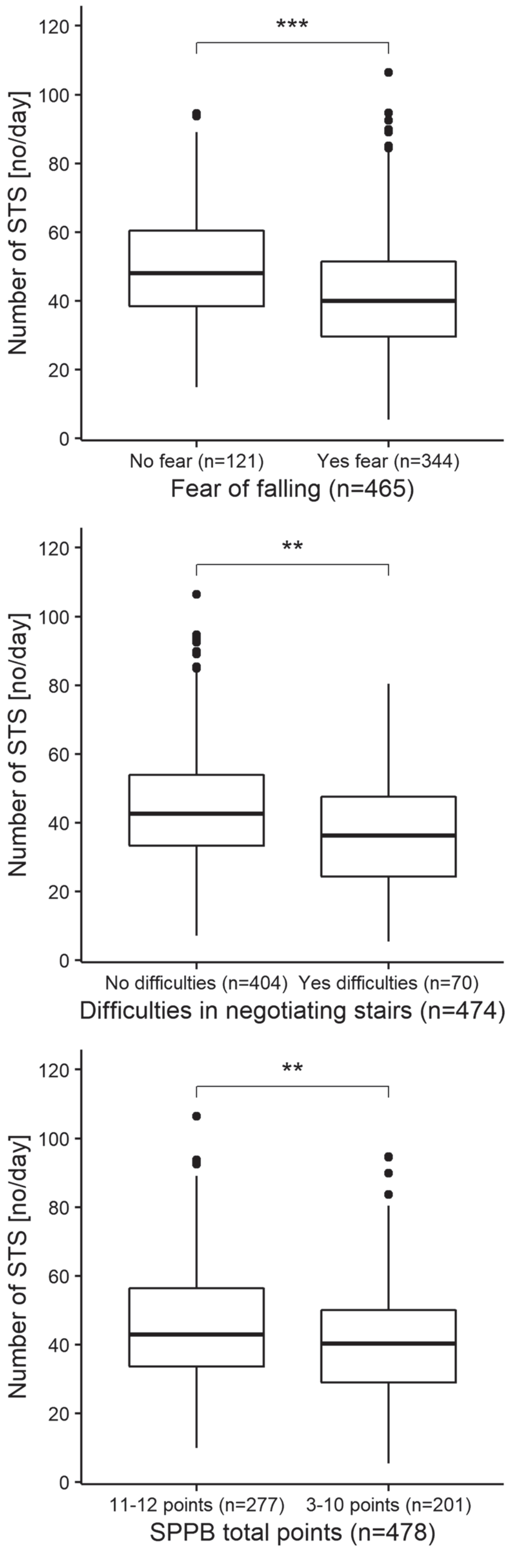

Figure 1. Number of STS transitions group comparisons between self-reported fear of falling, difficulties in negotiating stairs, and lower extremity functional limitations in free-living environment. Independent-Samples (unpaired) Mann–Whitney U Test (Wilcoxon rank-sum). ****p* < .001, ***p* < .01 (2-sided). STS = sit-to-stand.

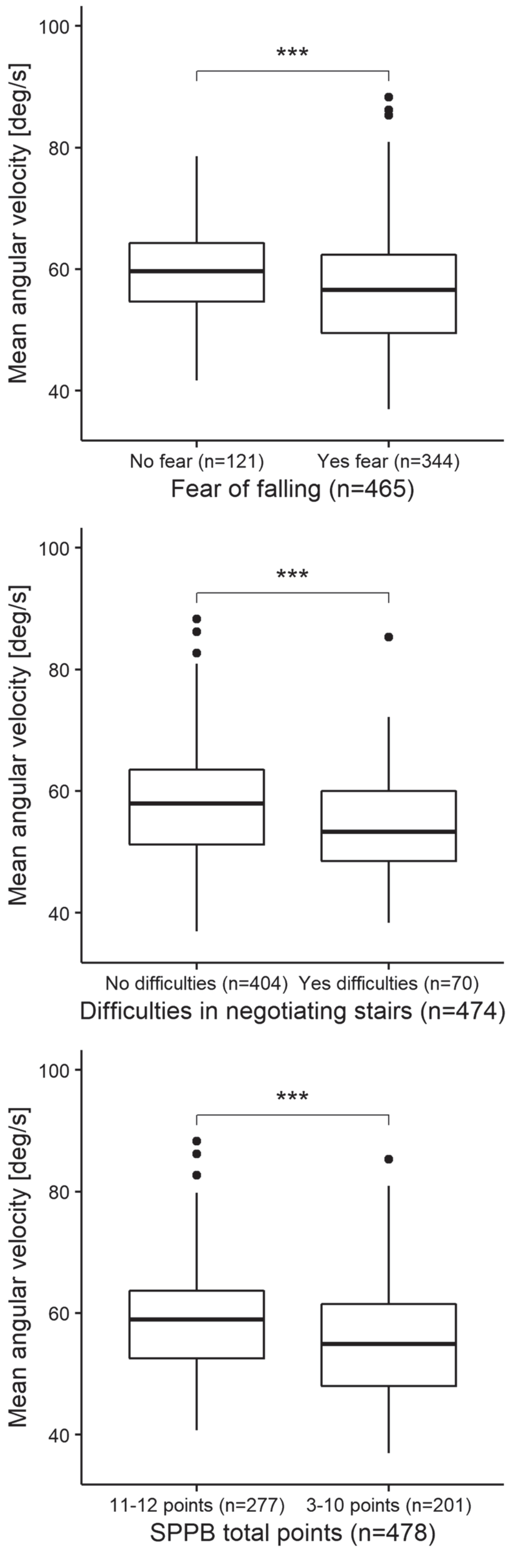

Figure 2. STS transitions mean angular velocity group comparisons between self-reported fear of falling, difficulties in negotiating stairs, and lower extremity functional limitations in free-living environment. Independent-Samples (unpaired) Mann–Whitney U Test (Wilcoxon rank-sum). ****p* < .001 (2-sided). STS = sit-to-stand.

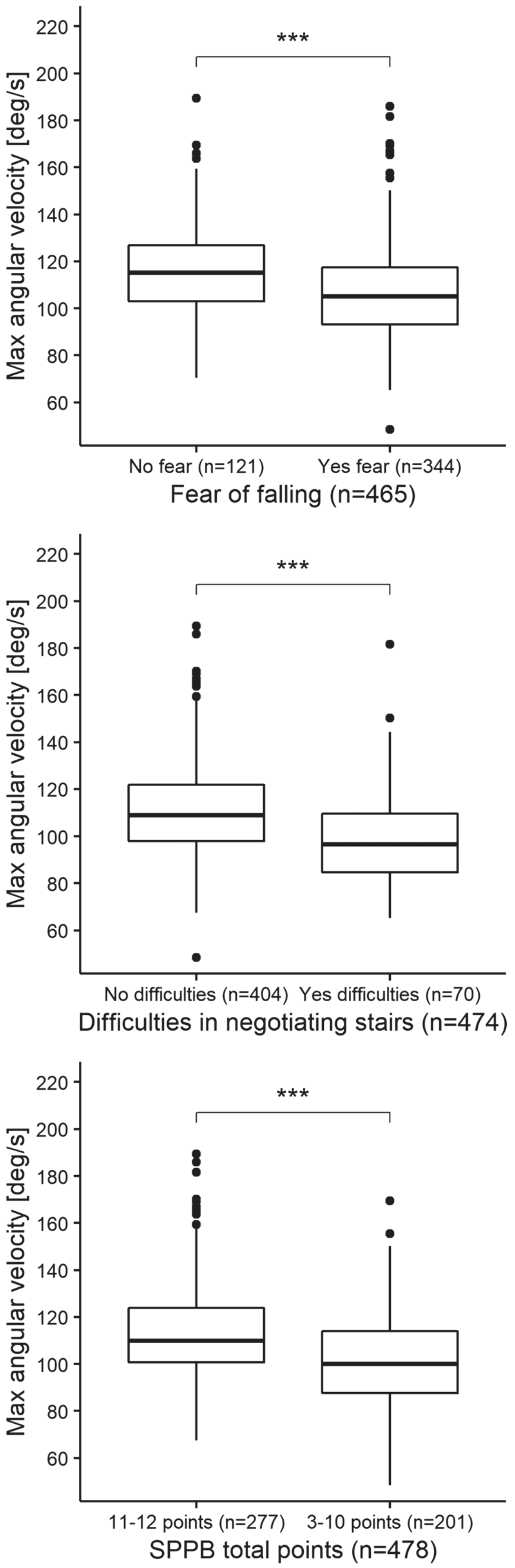

Figure 3. STS transitions maximal angular velocity group comparisons between self-reported fear of falling, difficulties in negotiating stairs, and lower extremity functional limitations in free-living environment. Independent-Samples (unpaired) Mann–Whitney U Test (Wilcoxon rank-sum). ***$p < .001$ (2-sided). STS = sit-to-stand.

certain level of capacity, the intensity of the free-living STS transition does not increase linearly, which is well in line previously reported curvilinear relationship between knee extension force and 5×STS time (41). Therefore, future studies should investigate whether it is possible to identify cutoff points for the number of STS transitions and the angular velocities that would predict a lack of functional capacity.

To the authors' best knowledge, the association between the knee extensor force and the angular velocity of STS transitions in a free-living environment has not been previously reported. Corrigan and Bohannon (2010) found a moderate correlation between knee extension force measured with a hand-held dynamometer and the duration of a single maximal STS transition performed in a laboratory, which is well in line with the correlation between knee extension force and maximal angular velocity of observed in the presents study. The association between 5×STS and STS transitions intensity was low. However, intensity quantified in this study (angular velocity) assessed only the STS phase, whereas 5×STS completion time also includes the stand-to-sit phase and any pauses between phases (18), which may differ between participants. To the best of our knowledge, the association between STS phase mean angular velocity and 5×STS completion time has not been reported, but a moderate association has been reported when comparing 5×STS (stopwatch) to the vertical velocity of the STS phase (42) which could be considered a comparable variable to the angular velocity.

Individuals who reported fear of falling presented a lower number, mean and maximal angular velocity of STS transitions compared to individuals who did not report fear of falling. According to the sensitivity analysis, no sex difference was observed. These results are well in line with the previously published results. Hornyak et al. (2013) have previously reported that fear of falling is related to total daily physical activity (43) and the number of STS transitions measured by accelerometer was weakly ($r = -0.11$, $p = .009$) associated with fear of falling (Fall Efficacy Scale-International, FES-I) in free-living conditions (44). In addition, concerns about falling have been found to be associated with low number of STS transitions among community-dwelling older men and women (45). Exploring difficulties in stair negotiation led to similar findings. Stair negotiating is one of the more demanding free-living activities older people engage with (46), but stair negotiation is challenging to identify from free-living accelerometry recordings (12). Given this challenge and the link between stair negotiation difficulties and STS transitions, examining the latter in free-living conditions seems both feasible and clinically relevant.

The decline in lower-extremity performance begins in middle-age, however, the decrements in physical capacity can be masked up to the age of 60–70 in submaximal activities such as walking (47). As STS transitioning requires a relatively high proportion (at least compared to walking) of the maximal force, we postulate that quantifying free-living STS transitions intensity among older adults could prove to be a sensitive indicator of future constraints in the ability to perform activities of daily living. In particular, the maximum angular velocity of STS transitions can describe a performance reserve that entails the ability to vary transition performance intensity, in the same way as walking speed reserve (48). In addition, the number of STS transitions have previously been used for monitoring frailty status (44). Following a similar line of reasoning, free-living STS transitions could also be linked to fall risk, although all these hypotheses would need to be tested with prospective study designs.

Some limitations need to be kept in mind when interpreting the findings. Firstly, we demonstrated that identification and intensity quantification of STS transitions is possible based on thigh-worn accelerometer data in free-living conditions. However, validity (ie, does the method measure what it purports to measure) could only be examined for STS transitions identification (Supplementary File), while the validity of the intensity quantification should be addressed in future studies. Moreover, the algorithm can only be applied to thigh-worn accelerometers sampling 3-dimensional accelerations. Nevertheless, the present results serve as an early indication of face validity (ie, are the values created by the method congruent with some relevant other measure) for intensity quantification. Secondly, the test–retest reliability of detection and intensity quantification in free-living conditions still remains to be established. To the best of our knowledge, reliability has only been evaluated in the laboratory environment (49). Third, the algorithm is only able to identify the first repetition of the multi-STS set (caused by the 2 seconds stationary epoch prior to a STS requirement) and therefore cannot be directly used to identify for example, the result in the 5×STS. The algorithm could be modified for use as an instrumented 5×STS assessment tool by removing the stationarity requirement from the algorithm. The stationarity requirement is necessary in free-living conditions to prevent false positives due to for example, cycling or walking. Fourth, using the arms during STS transitions cannot be controlled in the free-living environment. This can lead to misinterpretations, especially in determining the intensity, because STS transitions performed without using the arms have been found to have a slightly stronger association with STS performance than if the use of the arms is allowed in the laboratory environment (21). Finally, although the sample population was relatively old and based on a population representative sample, it is well established that those who volunteer for such monitoring are in better physical health or less frail compared to those who do not (26). Therefore, the findings may not be generalizable to the older population at large. On the other hand, the sample was based on a population representative sample.

The strength of this study can be considered a relatively large sample of community-dwelling participants. In addition, this study included multiple days (3–7 days) accelerometry recording, which is thought to be sufficient for assessing activity patterns (50). The strength of the study is also the versatile tests of physical performance performed in the laboratory (knee extension force) and at home (5×STS). In addition, the study protocol includes comprehensive questionnaires to assess participation limitations such as difficulties in negotiating stairs.

Conclusion

Free-living STS volume and intensity were positively associated with higher lower-extremity performance and negatively associated with lower extremity functional limitations, self-reported fear of falling, and stair negotiation difficulties. The number and mean and maximal velocity of STS transitions in free-living situations was lower with advancing age and differed between sexes. The intensity of STS transitions was more strongly related to lower-extremity performance than the number of STS transitions. Due to the strength-demanding nature of transitioning from sitting to standing, we hypothesize that the proposed free-living STS transition quantification may enable identifying those at risk of future limitations in daily activities.

Supplementary Material

Supplementary data are available at *The Journals of Gerontology, Series A: Biological Sciences and Medical Sciences* online.

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Conflict of Interest

None declared.

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Author Contributions

Conceptualization, A.L., L.K., E.P., K.K., T.R., T.F., C.D., E.V.R., and Ti.R.; methodology, A.L., L.K., E.P., K.K., T.R., and Ti.R.; formal analysis, A.L. and Ti.R.; writing—original draft preparation, A.L.; writing—review and editing, A.L., L.K., E.P., K.K., T.R., T.F., C.D., E.V.R., and Ti.R.; supervision, Ti.R., T.F., C.D., and E.V.R.; All authors have read and agreed to the published version of the manuscript.

Data Availability

After completion of the study, data will be stored at the Finnish Social Science Data Archive without potential identifiers (open access). Until then, pseudonymized data sets are available to external collaborators subject to agreement on the terms of data use and publication of results. To request the data, please contact Professor T.R. (taina.rantanen@jyu.fi).

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III

ASSOCIATION OF SIT-TO-STAND CAPACITY AND FREE-LIVING PERFORMANCE USING THIGH-WORN ACCELEROMETERS AMONG 60-90-YEAR-OLD ADULTS

by

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BASIC SCIENCES

Association of Sit-to-Stand Capacity and Free-Living Performance Using Thigh-Worn Accelerometers among 60- to 90-Yr-Old Adults

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[1]Department of Movement Sciences, Physical Activity, Sports and Health Research Group, KU Leuven, Leuven, BELGIUM; [2]Faculty of Sport and Health Sciences and Gerontology Research Center, University of Jyväskylä, Jyväskylä, FINLAND; [3]Department of Public Health and Centre for Population Health Research, University of Turku, Turku University Hospital, Turku, FINLAND; [4]Center for Human Movement Sciences, University Medical Center Groningen, University of Groningen, Groningen, THE NETHERLANDS; and [5]Faculty of Sport and Health Sciences and Neuromuscular Research Center, University of Jyväskylä, Jyväskylä, FINLAND

ABSTRACT

LÖPPÖNEN, A., C. DELECLUSE, K. SUORSA, L. KARAVIRTA, T. LESKINEN, L. MEULEMANS, E. PORTEGIJS, T. FINNI, T. RANTANEN, S. STENHOLM, T. RANTALAINEN, and E. VAN ROIE. Association of Sit-to-Stand Capacity and Free-Living Performance Using Thigh-Worn Accelerometers among 60- to 90-Yr-Old Adults. *Med. Sci. Sports Exerc.*, Vol. 55, No. 9, pp. 1525–1532, 2023. **Purpose:** Five times sit-to-stand (STS) test is commonly used as a clinical assessment of lower-extremity functional ability, but its association with free-living performance has not been studied. Therefore, we investigated the association between laboratory-based STS capacity and free-living STS performance using accelerometry. The results were stratified according to age and functional ability groups. **Methods:** This cross-sectional study included 497 participants (63% women) 60–90 yr old from three independent studies. A thigh-worn triaxial accelerometer was used to estimate angular velocity in maximal laboratory-based STS capacity and in free-living STS transitions over 3–7 d of continuous monitoring. Functional ability was assessed with short physical performance battery. **Results:** Laboratory-based STS capacity was moderately associated with the free-living mean and maximal STS performance ($r = 0.52$–0.65, $P < 0.01$). Angular velocity was lower in older compared with younger and in low- versus high-functioning groups, in both capacity and free-living STS variables (all $P < 0.05$). Overall, angular velocity was higher in capacity compared with free-living STS performance. The STS reserve (test capacity − free-living maximal performance) was larger in younger and in high-functioning groups compared with older and low-functioning groups (all $P < 0.05$). **Conclusions:** Laboratory-based STS capacity and free-living performance were found to be associated. However, capacity and performance are not interchangeable but rather provide complementary information. Older and low-functioning individuals seemed to perform free-living STS movements at a higher percentage of their maximal capacity compared with younger and high-functioning individuals. Therefore, we postulate that low capacity may limit free-living performance. **Key Words:** ACCELEROMETER, LABORATORY ASSESSMENT, OLDER ADULTS, CHAIR RISE, FREE-LIVING, FUNCTIONAL ABILITY

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In order to live independently, individuals should be able to perform a wide variety of activities in the free-living environment. Many of the typical activities performed involve walking and sit-to-stand (STS) and stand-to-sit transitions (1). To elaborate, independent living includes strength-demanding activities such as stair negotiation, housework, and getting out of bed (1), which all require good lower extremity physical capacity (2,3). However, physical capacity (4,5) and relative lower-limb muscle power decline with age beginning from middle age onwards (6), and the decline may compromise the ability to cope with free-living activities.

According to the International Classification of Functioning, Disability and Health, *capacity* describes what a person can do in a standardized, controlled environment, whereas *performance* describes what a person actually does in his/her free-living environment (7). Free-living performance partly depends on laboratory-based test capacity (7). Both laboratory-based capacity and free-living performance can be assessed using wearable sensor technology. Previous studies have examined the relationship between laboratory-based test capacity and free-living performance and found a weak correlation among older adults (8–10), so it has been suggested that these are two different constructs (11). Notably, these conclusions were based on submaximal activities such as walking. However, aging is accompanied by a marked decline in muscle force and power production capacity, and the decline in capacity may start to limit free-living functioning (12). Therefore, we argue that it would be prudent to examine the relationship between laboratory-based test capacity and free-living behavior in more strength-demanding free-living activities than walking, such as STS transitions.

On average, community-dwelling older adults have been reported to perform 45 STS transitions per day (13,14). The combination of the relatively high capacity demand, and the fact that people engage with the STS multiple times a day makes this movement a potential candidate for free-living strength-demanding activity monitoring. Wearable sensor technology has made it possible to measure and detect STS transitions based on thigh angular velocity in free-living environment (14–18). The test capacity of STS transitions in the laboratory and clinical settings has commonly been studied using the 5×STS test completion time (19,20). The 5×STS test can also be assessed in an instrumented form utilizing wearable sensors. The sensor recordings enable including only the STS phase in capacity quantification. With concentrating only on the STS phase of the transition, it becomes possible to quantify the same metric determined identically in the laboratory and the free-living environments (21).

The purposes of this study were 1) to investigate the association between laboratory-based STS capacity and free-living STS performance with the hypothesis that a moderate association would be observed, 2) to investigate differences in laboratory-based STS capacity and free-living STS performance between age-groups with the hypothesis that age-associated differences would be observed, and 3) to investigate the differences in laboratory-based STS capacity and free-living STS performance between individuals with low, medium, and high functional ability with the hypothesis that functional ability is associated with lower laboratory-based STS capacity and lower free-living STS performance.

METHODS

Study populations. Data from three independent studies were included in this study (pooled $n = 497$). The first data set was the Finnish Retirement and Aging (FIREA) study, an ongoing longitudinal cohort study of older public sector workers (22). For the present study, we included participants from the clinical substudy ($n = 290$) (23) and used their baseline measurements when the participants were still working, had at least 3 d of free-living accelerometer data, and had a valid instrumented STS test, resulting in a total of 198 participants (82% women) 60–64 yr old included in the present examination.

The second data set was data from the LEUVEN cross-sectional study. This study aimed at testing the reliability of a sensor-based technology to assess functional ability (stair climbing and STS) in the laboratory and at examining age-related capacity trajectories. Men and women, living independently in Flanders (Belgium), in the following age categories were recruited: 20–39, 40–54, 55–64, and ≥65 yr. The target sample for the youngest two age-groups was $n = 50$ per group (♂25 and ♀25), and the target sample for the oldest two age-groups was $n = 100$ per group (♂50 and ♀50). Participants were asked to participate in free-living accelerometry, although participation was not obligatory. The present study only included participants older than 60 yr of age with at least 3 d of free-living accelerometer recording, resulting in a total of 63 participants (44% women) 60–90 yr old included in the present study.

The third data set was from the AGNES cohort study (24,25) 4-yr follow-up assessment, which was an observational population-based study of people 79, 84, or 89 yr of age living independently in the municipality of Jyväskylä, Finland ($n = 679$). The current study included participants with at least 3 d of free-living accelerometer data and valid instrumented STS test, resulting in a total 236 participants (53% women) included in the present examination.

The study protocols were approved by the appropriate human research Ethics Committee of Hospital District of Southwest Finland (84/1801/2014), Ethical Committees (Ethical Committee Research UZ/KU Leuven (S62540), Ethical Committee of the Central Finland Health Care District (4 U/2021), respectively, and executed in accordance with the principles of the Declaration of Helsinki. All participants provided written informed consent.

Accelerometer instrumentation. In all cohorts, an accelerometer was taped on the anterior aspect of the dominant thigh using transparent adhesive film before the start of the functional capacity measurement. Participants were asked to wear the accelerometer for 7 d in the LEUVEN and AGNES studies and 4 d in the FIREA study, and then return the device to the laboratory. LEUVEN and AGNES used the UKK RM42 triaxial accelerometer (sampling continuously at 100 Hz, 13-bit analog-to-digital conversion, ±16*g* acceleration range; UKK Terveyspalvelut Oy, Tampere, Finland), and the FIREA study used the Axivity AX3 triaxial accelerometer (sampling continuously at 100 Hz, 13-bit analog-to-digital conversion, ±8*g* acceleration range; Axivity Ltd, Newcastle, UK).

Free-living data processing and outcomes. Free-living STS transitions were identified from the accelerometer data using the open access and universal algorithm that we have developed, which detects STS transitions and quantifies the angular velocity of the transition. The structure, source code (26), and properties of the algorithm are described elsewhere (14,15). The quantification accuracy of angular velocity against 2D motion analysis was good, and the detection accuracy of STS transitions was 93.3% (15).

Only complete 24-h measurement days were included, and participants needed at least 3 d to be included in the analyses. In the determination of the mean free-living performance, the median of the angular velocities ($°\cdot s^{-1}$) of the STS transitions was first calculated for each complete monitoring day, and the mean was calculated from these daily means. The maximal free-living performance of the STS transitions was determined as the median of the 10 fastest STS transitions over the monitoring (all complete days) period. The number of STS was determined as the mean of the transitions (number) per complete monitoring day. No participant exceeded 4 $rad\cdot s^{-1}$ in the laboratory (highest was 3.89 $rad\cdot s^{-1}$), and therefore we filtered out any STS transitions above 4 $rad\cdot s^{-1}$ from the data before the estimation of the maximum free-living angular velocity (14). A total of 73 transitions were removed because of this (from 64 participants), and this was 0.036% of all 97,401 transitions detected in this data set.

Measurement of functional ability and data processing and outcome. All participants performed the short physical performance battery (SPPB) (19,20). The SPPB comprised tests on standing balance, walking speed over a 3-m distance, and the STS test. The SPPB total maximum score is 12 points, with higher scores indicating better overall functional ability.

Laboratory-based STS capacity in the LEUVEN and AGNES studies was assessed using the instrumented 5×STS test (19) and in the FIREA study using the instrumented 10×STS test. From the FIREA study, we included the first five repetitions in the analyses. In the AGNES study, the 5×STS test was conducted under the guidance of a research assistant at the participant's home using a standardized procedure, and in the FIREA and LEUVEN studies in a research laboratory.

As per the standard protocol (19), the STS test started seated and ended at the fifth (or tenth) standing position. Participants were asked to stand up as fast as possible to full extension (hips and knees) and to sit down with their back touching the back of the chair for five (or 10) consecutive repetitions. The arms were held across the chest, with the feet firmly on the floor at hip width. The height of the chair used was 45–46 cm.

When determining laboratory-based STS capacity from an STS test, the free-living STS identification was modified to enable detecting multiple consecutive STS transitions. In the free-living STS identification, the variance of the magnitude of the resultant acceleration in a time window between 2.5 and 0.5 s before the candidate transition should be less than 0.02*g* (i.e., the participant had been stationary for at least 2 s before the transition) so that the algorithm only detects the first of a set of STS movements (e.g., continuous seat-based squatting). To determine the median angular velocity of the STS test repetitions, the stationarity criterion of the algorithm was disabled so that repeated transitions could be identified. The stationarity criterion was, however, re-enabled for the free-living analyses. The laboratory-based STS capacity was determined by manually extracting the tests from the first day of the recording and calculated as the median of the thigh angular velocity of five repetitions of the test. The data that included the STS test occurred before the first midnight of the recording and was therefore disregarded in the free-living STS analyses.

Descriptive characteristics and other measurements. In the FIREA and AGNES studies, age and sex were extracted from the population register. In the LEUVEN study, age and sex were self-reported. In all studies, cognitive function test (Mini-Mental State Examination) was conducted using standardized procedures (27).

Statistical analyses. The data from the three studies were combined for statistical analyses. We explored the feasibility of pooling the three studies, and between-studies comparisons are given in Supplemental Figure 1 and Supplemental Table 1 (see Supplemental Digital Content, Scatterplot between angular velocity in laboratory-assessed STS test (Lab capacity) and free-living mean STS performance (Free-living mean) across studies, and scatterplot between angular velocity in laboratory-assessed STS test (Lab capacity) and free-living maximal STS performance (Free-living max) across studies; and Descriptive characteristics and STS indicators in each cohort and in total, http://links.lww.com/MSS/C844). In particular, visual inspection did not show conspicuous differences (similarity of associations and overlap between values) between the cohorts in free-living STS variables, so we concluded that it was reasonable to pool the data sets (see Supplemental Fig. 1, Supplemental Digital Content, http://links.lww.com/MSS/C844). After that, three age-groups were created: 60–70, 71–80, and 81–90 yr. In addition, individuals were identified as low functioning (SPPB = 0–9), medium functioning (SPPB = 10–11), or high functioning (SPPB = 12) based on their overall functional ability level. This division in functional ability groups was based on the distribution of the data and on previous literature (28,29).

Results of STS transitions as well as descriptive characteristics are reported as mean and SD. Shapiro–Wilk normality tests indicated that some of the variables were not normally distributed, and consequently, nonparametric statistical tests were chosen. The sex comparison between laboratory-based STS capacity and free-living mean and maximal STS performance did not show statistical differences (see Supplemental Table 2, Supplemental Digital Content, Sex and age-groups comparison of STS test capacity, and free-living mean and maximal STS performance, http://links.lww.com/MSS/C844), but because the absolute differences were notable,

TABLE 1. Descriptive characteristics of the participants and number of STS transitions in each age-group (mean ± SD).

	60–70 yr		71–80 yr		81–90 yr		*P* Value		
	Women	Men	Women	Men	Women	Men	Age-group[a]		
	n = 180	*n* = 58	*n* = 78	*n* = 72	*n* = 57	*n* = 52	Women	Men	Sex[b]
Age (yr)	63.1 ± 1.7	64.7 ± 2.9	78.7 ± 2.0	78.6 ± 1.9	84.5 ± 2.0	84.7 ± 2.1	<0.001	<0.001	<0.001
MMSE (points)	28.8 ± 1.3	28.8 ± 1.1	28.1 ± 1.8	27.7 ± 2.8	27.1 ± 2.6	27.2 ± 2.4	<0.001	<0.001	0.063
SPPB overall points (points)	11.7 ± 0.7	11.7 ± 0.7	10.7 ± 1.3	11.1 ± 1.1	9.4 ± 2.2	10.4 ± 1.5	<0.001	<0.001	0.687
Five times STS test time (s)	10.0 ± 2.1	9.4 ± 2.4	12.3 ± 2.8	11.4 ± 2.8	13.6 ± 3.5	12.2 ± 3.2	<0.001	<0.001	0.358
Free-living number of STS (no/day)	53.0 ± 16.0	52.6 ± 18.0	43.4 ± 18.0	46.4 ± 13.6	36.3 ± 16.7	42.9 ± 15.5	<0.001	0.007	0.833

[a] Independent-samples Kruskal–Wallis test.
[b] Independent-samples Mann–Whitney *U* test.
MMSE, Mini-Mental State Examination.

the results of the comparison between age-groups are presented separately for men and women. Overall, sex differences were evaluated using the independent-samples Mann–Whitney *U* test (Wilcoxon rank sum test), and differences between age and functional ability groups were evaluated using the independent-samples Kruskal–Wallis test (kruskal.test and pairwise.wilcox.test functions, holm-adjusted) in stats-library (version 3.6.2). The association between the laboratory-based STS capacity and the free-living STS performance for all observations was tested with Spearman rank correlation coefficients. Spearman rank correlation coefficients greater than 0.70 were interpreted to indicate a strong association. A moderate association was defined less than 0.70 but greater than 0.40, and a weak correlation was defined as a correlation coefficient less than 0.40 (30). Statistical significance was set at $P < 0.05$, and analyses were performed in the "R" statistical environment (version 4.2.1) (31) and using SPSS statistical software package (IBM SPSS Statistics Version 28.0.1.1; SPSS Inc., Chicago, IL).

RESULTS

The 5×STS stopwatch time, the SPPB points, and the number of STS transitions differed between age-groups ($P < 0.05$), but not between men and women (Table 1). Laboratory-based STS capacity was moderately associated with the free-living mean STS performance ($r = 0.52$, $P < 0.001$) and free-living maximal STS performance ($r = 0.65$, $P < 0.001$) (see Supplemental Fig. 1, Supplemental Digital Content, http://links.lww.com/MSS/C844). Correlations did not markedly differ between sexes and age-groups (see Supplemental Table 3, Supplemental Digital Content, Sensitivity analysis of Spearman's correlation coefficients by age and sex, http://links.lww.com/MSS/C844).

Figure 1 shows differences between age-groups in the laboratory-based STS capacity, free-living mean, and maximal STS performance. More specifically, angular velocity was lower in older age-groups compared with the youngest age-group for each of the STS conditions ($P < 0.05$). The largest difference in angular velocity between age-groups was observed in the laboratory-based STS capacity, where the difference between the age-group of 60–70 and 81–90 yr was 45% for women and 43% for men ($P < 0.05$). Overall, angular velocity was higher in the laboratory-based STS capacity compared with free-living STS mean and maximal performance. The difference, i.e., reserve, between laboratory-based STS capacity and maximal free-living performance was 39.1°·s^{-1} for women and 39.0°·s^{-1} for men 60–70 yr old and was smaller

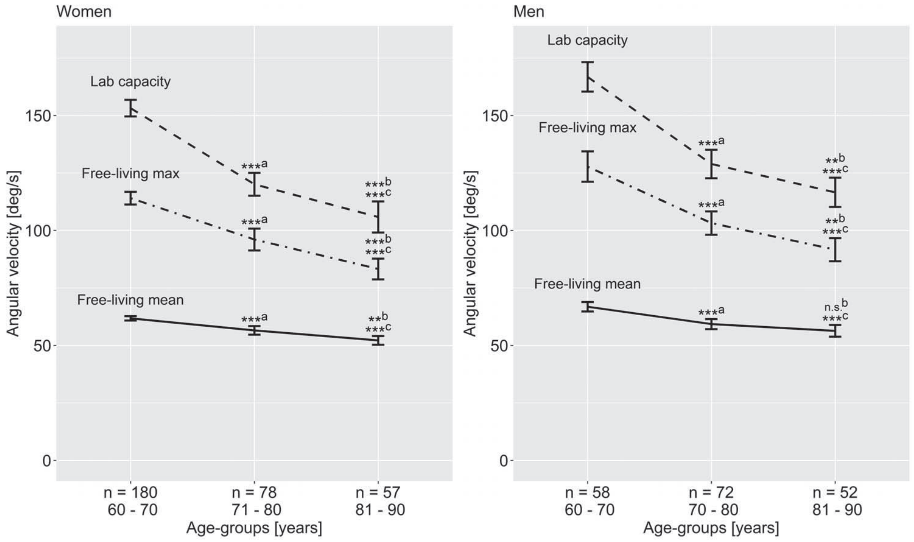

FIGURE 1—Angular velocity in laboratory-based STS (Lab capacity), free-living mean STS performance (Free-living mean), and free-living maximal STS performance (Free-living max) across age-groups in women and men (mean, 95% confidence intervals). Mann–Whitney *U* test (holm-adjusted) comparing results with the previous age-groups: n.s., not significant, *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$. [a]60–70 vs 71–80, [b]71–80 vs 81–90, [c]60–70 vs 81–90.

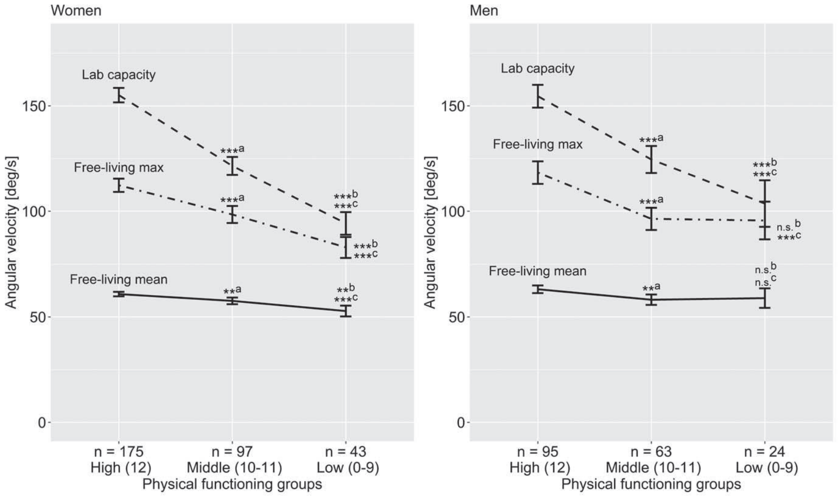

FIGURE 2—Angular velocity in laboratory-based STS (Lab capacity), free-living mean STS performance (Free-living mean), and free-living maximal STS performance (Free-living max) across SPPB groups in women and men (mean, 95% confidence intervals). Mann–Whitney *U* test (holm-adjusted) comparing results with the previous age-groups: n.s., not significant, $*P < 0.05$, $**P < 0.01$, $***P < 0.001$. ^{a}High vs middle, ^{b}middle vs low, ^{c}high vs low.

in the older age-groups (i.e., 24.0°·s^{-1} women and 25.7°·s^{-1} men 71–80 yr old, and 22.6°·s^{-1} women and 24.9°·s^{-1} men 81–90 yr old).

Figure 2 shows differences between the SPPB groups in angular velocity of laboratory-based STS capacity and free-living mean and maximal STS performance. More specifically, angular velocity was lower in the low- and medium-functioning groups compared with the high-functioning group for each of the STS conditions ($P < 0.05$), except for free-living mean and maximal performance in men. The difference, i.e., reserve, between test capacity and maximal free-living performance was larger in the high-functioning group (42.8°·s^{-1} in women and 36.2°·s^{-1} in men) compared with the low-functioning group (11.4°·s^{-1} in women and 8.0°·s^{-1} in men) ($P < 0.05$).

DISCUSSION

The present study examined the differences according to age and levels of functioning in laboratory-based STS capacity and free-living maximal and mean STS performance among community-dwelling older adults (60–90 yr). In addition, the association between capacity and free-living performance was investigated. The results revealed that laboratory-based STS capacity was moderately associated with free-living mean and maximal performance. In addition, angular velocity in both STS capacity and free-living performance was higher in younger compared with older age-groups. This age-associated difference was larger in STS capacity compared with free-living performance. Older age-groups were found to exhibit a reduced reserve capacity compared with younger age-groups, meaning that they had to perform free-living STS transitions at a higher percentage of their maximal capacity. Moreover, low-functioning individuals demonstrated a poorer STS performance in the free-living environment and had a lower reserve capacity compared with high-functioning individuals.

In the present study, laboratory-based STS capacity was moderately associated with free-living STS performance. The association is stronger than previously reported by Giannouli and colleagues (8), who showed that laboratory-based mobility measures play a minor role (r = 0.23–0.46, $P < 0.001$) when predicting free-living performance in adults with no mobility limitations (8). Likewise, multiple studies have previously demonstrated a weak association between test capacity in the laboratory and performance in the free-living environment on walking speed, although it should be noted that these studies measured preferred (not maximal) walking speed in the laboratory (10,11,32,33). It is clear that the capacity measured in the laboratory does not reflect directly on free-living performance, as they are different constructs (11). The free-living STS performance is affected by a variety of factors in addition to lower extremity muscle strength and balance, such as visual contrast sensitivity, lower-extremity proprioception (34), and goal of the activity, which all can affect free-living performance more than laboratory-based STS capacity. In a standardized setting, lighting is often better, the chair is more stable, and the circumstances may be perceived to be safer with a researcher monitoring the transitions. Free-living mean performance describes the velocity at which STS transitions are generally performed, but individuals most likely also desire to perform these transitions safely and comfortably in the free-living environment.

The large difference between age-groups especially in laboratory-based STS capacity is consistent with previous observations showing large age-associated difference in the laboratory-based power production capacity of the lower extremity (6,35) and in 5×STS test time, especially after 70 yr of age (5). According to the current results, the age-associated difference is weaker in the angular velocity of free-living STS transitions compared with the laboratory-based STS capacity, indicating that performance in a free-living environment is not only dependent on laboratory-based STS capacity but also on other factors, such as environmental and individual factors (36–38). It also indicates that older individuals have to perform closer to their maximal capacity, whereas younger individuals will perform at a more comfortable level. A similar conclusion can be drawn when comparing low- to high-functioning individuals: they have less reserve and need more of their maximal capacity to be able to get out of the chair. Interestingly, in men, the oldest two age-groups and the low- and medium-functioning groups did not differ in maximal and mean free-living angular velocity, whereas these groups did differ in women. The reason for this difference is unclear. Therefore, sex differences in free-living performance should be further investigated in future studies.

Apart from a greater reserve capacity in daily life, the high-functioning group also displayed a greater width of velocities (difference between mean and maximal) in free-living STS transitions than the low-functioning group. This finding indicates that higher laboratory-based STS capacity corresponds to greater between-subject variation in the free-living performance. This may in turn suggest that high-functioning individuals can choose to perform free-living STS transitions at a low or a high velocity, i.e., they have more potential for variations in daily life. By contrast, low-functioning individuals may be limited by their capacity to a more constrained amount of variation in free-living STS transitions. A high test capacity thus offers better reserve and enables movement variability (39). Altogether, our findings suggest that it may be beneficial for older adults to take care of their maximum capacity, i.e., their ability to perform daily movements at a high velocity, which is in line with the current recommendations (40). However, we should be aware that our cross-sectional study design does not allow to draw causal conclusions on the protective value of a good test capacity and free-living performance against future functional limitations.

Apart from the cross-sectional study design, other limitations should be considered when interpreting the results. First, the free-living maximal performance was estimated as the maximal thigh angular velocity of the STS transition during a recording period in the present study. The weakness of this estimation is that it is not possible to know with certainty whether this free-living performance is the best possible STS performance that the person is capable. The main concern pertains to the length of the monitoring period. It is unclear how long a monitoring period would be required to identify the highest level of performance in the free-living environment. It has previously been concluded that the monitoring period used in this study (3–7 d continuously) is sufficient for assessing activity patterns (41), but there is no similar understanding of identifying the highest level of free-living performance. The length of an adequate monitoring period should be assessed in future studies, especially as methods of objective physical activity are evolving rapidly. In addition, in this study we did not analyze STS performance separately on weekdays and weekend days because the focus was more on the overall STS performance and the majority of the participants were retired. Therefore, we decided to neglect potential differences between working days and days off. Future studies could examine whether STS performance differs between working days and days off. Second, although we have found the accuracy of identifying STS transitions to be greater than 90% and the angular velocity determination to be accurate (14,15), there are always misclassifications of free-living movements. There is no way to know for sure whether a behavior that appears to be an STS transition in the free-living accelerometer data is actually an STS transition and whether an exceptional technique (e.g., arm utilization, seat height, assistance from another person) was used to perform a given STS transition. Finally, the STS transition algorithm needs a reference posture for the analysis, which was identified based on identifying likely walking bouts from the recording. Participants who are highly sedentary because of limitations in physical function may accumulate few applicable walking bouts, which may result in an imprecise or invalid reference posture estimate. In this study, the reference posture was checked visually, and participants with invalid posture estimates were excluded from consideration (n = 56).

The strength of this study is the free-living accelerometer recording among study populations with a wide age range and heterogeneous functional ability levels, which is combined with an instrumented maximal STS test protocol. This study measured strength-demanding STS movements using the same method (algorithm) in the two different environments, which is a particular strength compared with previous studies that have often used different tests in both environments. In this study, only one low-cost and small-scale accelerometer was attached to the thigh, and no complex multisensor systems were required. In addition, an open algorithm was used that is universal for all triaxial accelerometers if data are recorded with a reasonable sample rate and measurement range.

CONCLUSIONS

Laboratory-based STS capacity and free-living performance were found to be associated. However, capacity and performance are not interchangeable but rather provide complementary information. STS capacity was lower in older compared with younger age-groups and in low- compared with high-functioning participants. The older and low-functioning groups seemed to have a reduced reserve capacity, meaning that they had to perform free-living STS movements at a higher percentage of their maximal capacity in their daily life. These findings can have important implications for designing future studies that intervene on free-living STS performance in older adults at risk of functional limitations. Altogether, our findings suggest that it may be beneficial for older adults to take care of their maximum capacity, i.e., their ability to perform daily movements at a high velocity. However, longitudinal studies are needed to support this claim.

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IV

KNEE-EXTENSION STRENGTH AND DAILY SIT-TO-STAND PERFORMANCE PREDICT FUNCTIONAL DECLINE AMONG OLDER ADULTS OVER A 4-YEAR FOLLOW-UP

by

Löppönen, A., Karavirta, L., Portegijs, E., Rantanen, T., Finni, T., Delecluse, C., Van Roie, E.*, & Rantalainen, T.* 2023.

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