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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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°$\cdot$s^{-1} for women and 39.0°$\cdot$s^{-1} for men 60–70 yr old and was smaller

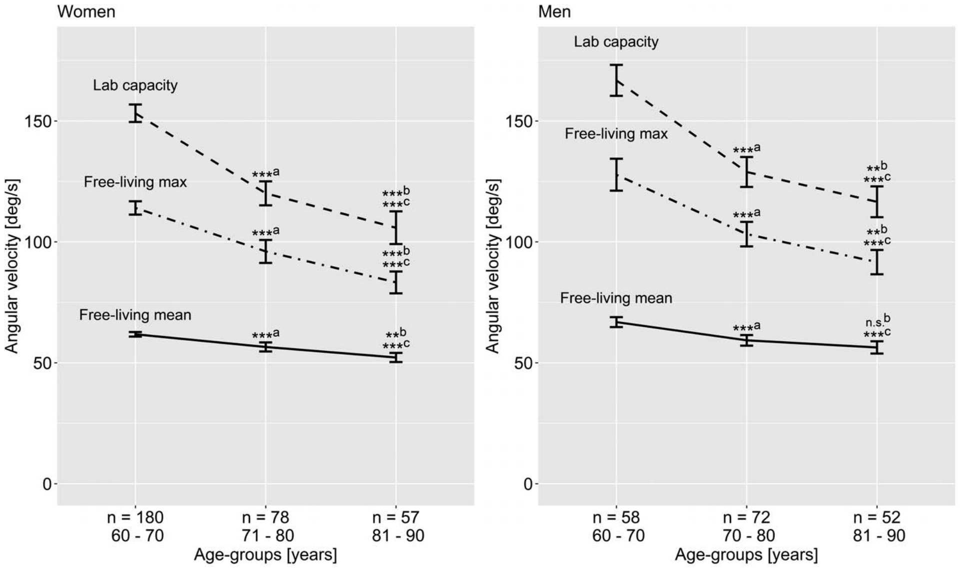

FIGURE 1—Angular velocity in laboratory-based STS (Lab capacity), free-living mean STS performance (Free-living mean), and free-living maximal STS performance (Free-living max) across age-groups in women and men (mean, 95% confidence intervals). Mann–Whitney *U* test (holm-adjusted) comparing results 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.

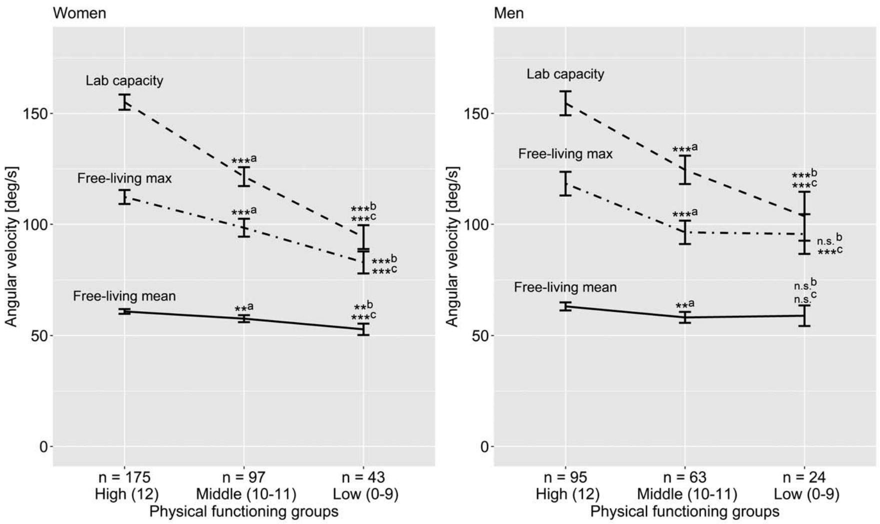

FIGURE 2—Angular velocity in laboratory-based STS (Lab capacity), free-living mean STS performance (Free-living mean), and free-living maximal STS performance (Free-living max) across SPPB groups in women and men (mean, 95% confidence intervals). Mann–Whitney *U* test (holm-adjusted) comparing results 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., $24.0°\cdot\text{s}^{-1}$ women and $25.7°\cdot\text{s}^{-1}$ men 71–80 yr old, and $22.6°\cdot\text{s}^{-1}$ women and $24.9°\cdot\text{s}^{-1}$ 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 ($42.8°\cdot\text{s}^{-1}$ in women and $36.2°\cdot\text{s}^{-1}$ in men) compared with the low-functioning group ($11.4°\cdot\text{s}^{-1}$ in women and $8.0°\cdot\text{s}^{-1}$ 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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