The 1-min sit-to-stand test induces a significant and reliable level of neuromuscular fatigability: insights from a mobile app analysis

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Abstract

Purpose The performance metric associated with the execution of the 1-min sit-to-stand (1STS) typically relies on the number repetitions completed in 1 min. This parameter presents certain limitations (e.g., ceiling effect, motivational factors) which can impede its interpretation. Introducing additional parameters, such as neuromuscular fatigability level, could enhance the informative value of the 1STS and facilitate its interpretation. This study aimed to assess (i) whether the 1STS induces fatigability and (ii) the reliability of the fatigability level.

Methods Forty young, healthy, and active participants underwent the 1STS twice during the same session. Isolated sit-to-stand maneuvers were performed before, immediately, and 1 min after completing the 1STS. A mobile app was utilized to obtain time (STS_T), velocity (STS_V), and muscle power (STS_P) from these sit-to-stand maneuvers. The pre–post change in these parameters served as the fatigability marker. Reliability was assessed using the intra-class correlation coefficient (ICC) and the coefficient of variation (CV).

Results The mean number of repetitions during the 1STS was 63 ± 9. Significant decline in performance was observed for STS_T ($13 \pm 8\%$), STS_V ($-11.2 \pm 6\%$), and STS_P ($-5.2 \pm 3\%$), with more than 74% of participants exhibiting a decline beyond the minimal detectable change. Excellent between-session reliability ($ICC \geq 0.9$; $CV \leq 5.3$) was observed for the mobile app variables.

Conclusion The 1STS induces significant levels of fatigability. The fatigability indicators derived from the mobile app demonstrated remarkable reliability. Utilizing this user-friendly interface for computing fatigability may empower professionals to acquire insightful complementary indicators from the 1STS.

Keywords 1-min sit-to-stand test · Functional exercise testing · Fatigability · Mobile application

Abbreviations

1STS	1-min sit-to-stand test
STS_P	Mean sit-to-stand vertical power extracted from the mobile app
STS_T	Rising time of a single sit-to-stand test extracted from the mobile app
STS_V	Mean sit-to-stand vertical velocity extracted from the mobile app

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Introduction

The assessment of physical fitness is pivotal in understanding the health status of both healthy individual and patients. Parameters related to exercise capacity, such as muscle strength and endurance (Strassmann et al. 2013), or cardiorespiratory fitness (Myers et al. 2015), are frequently measured in different populations to provide valuable insights into overall well-being, to aid in the development of personalized exercise regimens and assess their effectiveness.

A large variety of tests capture these parameters, spanning from laboratory to fields settings. Cardiopulmonary exercise testing is the gold standard to assess cardiorespiratory fitness (Ferrazza et al. 2009; Tran 2018). Yet, it is hampered by several practical limitations, including the need for specialized equipment and expertise, safety concerns due to maximal exertion, extended test duration, and limited applicability in certain populations (Ridgway and Howell 2010). Laboratory tests have also been developed for assessing physical function, with the ability to delve into details as these tests allow for obtaining specific measures related to particular physiological systems. In this regard, specific laboratory tests have been devised to evaluate physical function by assessing muscle strength and endurance [e.g., the quadriceps intermittent fatigue test Bachasson et al. (2013)]. These tests share common drawbacks with others, including the requirement for specific materials and high costs, which usually confine their application to laboratory settings. Additionally, they are frequently conducted under non-ecologically valid conditions (e.g., isometric testing), which restricts the potential transferability of results to real-world scenarios. Field tests offer a solution to some of the aforementioned limitations by allowing an easier access to general fitness and function. However, this comes at the cost of an almost complete inability to access physiological evaluations for delving into the finer details associated with physical function. The 6-min walking test is renowned for its ease of administration and high tolerance among various populations (Pradon et al. 2013; Enright et al. 2003; Priesnitz et al. 2009; Hill et al. 2011), but also because it is a good reflect of activities of daily living. This test was designed to evaluate the exercise and cardiorespiratory fitness of individuals who cannot undergo standard laboratory procedures (Peeters and Mets 1996). However, it does not provide insights into muscle function (e.g., strength, power), which can be valuable in both public health and specific clinical contexts, and can be sometimes difficult to administer for logistical reasons, e.g., the need of a 30–40-m corridor (Fell et al. 2022).

For these reasons, the use of the 1-min sit-to-stand test (1STS) may be of interest (Bohannon 1995). The 1STS captures the number of times a participant can stand up and sit down in 1 min, which is the sole accepted marker of performance associated with this specific test (Saynor et al. 2023). This test offers numerous advantages, including its swift implementation and measurement, its minimal equipment demands, and its suitability for employment in limited spaces (Bohannon and Crouch 2019). Consequently, it stands as one of the most popular field test for assessing physical fitness within the general population (Haile et al. 2021; Bohannon and Crouch 2019; Kuhn et al. 2023), as well as in a variety of clinical conditions (Gruet et al. 2016; Zanini et al. 2015; Briand et al. 2018). The 1STS offers a safe and feasible integrated test of both aerobic fitness and muscle performance, making it a desirable functional test that may supplement aerobic testing (Saynor et al. 2023). However, this test has some limitations. First, the constructs measured remain unclear. While some suggests that the 1STS is a surrogate of muscle strength (Zanini et al. 2015), others propose that it offer insights into muscle endurance (Strassmann et al. 2013), i.e., the failure of a muscle or muscle group to maintain a required or expected force (Bemben 1998). The assertion that the 1STS can effectively capture information on muscle endurance lacks intuitive support and is inadequately substantiated by convincing evidence. One way to determine if the 1STS informs on muscle endurance would be to determine whether it induces neuromuscular fatigability (i.e., a decline in an objective measure of muscle performance), also referred to as performance fatigability (Enoka and Duchateau 2016), as it typically develops progressively in various endurance tests [e.g., Bachasson et al. (2013); Doyle-Baker et al. (2017); Souron et al. (2024)]. Second, the 1STS may display a ceiling effect, which complicates its interpretation (Saynor et al. 2023). This is especially relevant in the general population where this test is used for preventive purposes (Strassmann et al. 2013, Haile et al. 2021), and also in mild profile of some chronic diseases (Saynor et al. 2023; Radtke et al. 2016). In such cases, the number of repetitions completed during the test may not effectively inform on physical fitness or be sensitive to any interventions, such as exercise training program. Then, it is particularly relevant to investigate additional outcomes (e.g., neuromuscular fatigability) that could augment the informative value of this test.

Ruiz-Cardenas et al. (2018) developed the Sit to Stand mobile application which is an innovative, valid, and reliable method for measuring time, velocity, and muscle power during a single sit-to-stand maneuver performed from a chair. This application allows for the measurement of physical performance immediately after exercise cessation, thereby addressing the issue of rapid post-exercise recovery that may impact the accuracy of fatigability levels (Froyd et al. 2013; Gruet et al. 2014). Recently, we illustrated the feasibility of detecting progressive levels of fatigability through the discernment of changes in sit-to-stand time, as detected by this application, throughout an intermittent isometric wall-squat test (Souron et al. 2024). In this study, velocity and power values were not analyzed. However, it is worth noting that sit-to-stand time, velocity, and power derived from this app serve as complementary measures of physical function. The importance of measuring velocity or power as variables independent from traditional sit-to-stand time has been previously elucidated. This is mainly because each variable has shown different relationships with functional outcomes, adverse events, age-related changes, and even different response to an exercise intervention (Glenn et al. 2017a, b; Regterschot et al. 2014; Cheng et al. 2014). Here, our objective was to employ these measures Pre and Post 1STS to ascertain whether fatigability could be consistently detected and replicated, with the aim of enhancing the comprehension of the constructs measured by this test (i.e., muscle strength and/or endurance), and to provide a rationale for integrating this measure as an affordable method to complement the information provided by the 1STS.

This study was designed to evaluate in healthy young participants: (i) whether the 1STS induces neuromuscular fatigability, defined as an increase in sit-to-stand time computed using our mobile app, and (ii) the intra-day reliability of the level of fatigability at the conclusion of the 1STS. We hypothesized the 1STS would induce a significant level of fatigability as detected by the mobile application, and that this measure would demonstrate a good test–retest reliability.

Methods

Study design and participants

The research protocol consisted of one visit conducted at the Movement, Interactions and Performance laboratory of Nantes University. The study received approval from the local ethics committee (IRB00012476-2022-10-03-160), and all participants provided written informed consent before participating in the study. Forty young, healthy Caucasian participants were recruited. Non-inclusion criteria encompassed cardiovascular, neurological, neuromuscular, or orthopedic diseases that could affect the ability to perform study procedures. We also did not include participants reporting very high levels of physical activity, defined here as more than 8 h of vigorous physical activity per week. Before being involved in the experimental procedure, each participant completed the International Physical Activity Questionnaire [IPAQ; short format evaluation tool of physical activity; Craig et al. (2003)] with the aim of assessing the potential influence of physical activity levels on fatigability levels and their reliability. Descriptive data about our participants are presented in Table 1.

Procedure

The experimental procedures lasted approximately 90 min and comprised two data collection sessions separated by 30 min. Participants were first accustomed with all experimental procedures, including the instruction for the proper execution of sit-to-stand exercises and the reporting of perceptual measurements related to muscle and respiratory efforts. After a 15-min break, participants performed the first round of 1STS following standard guidelines. Three isolated sit-to-stand maneuvers, each separated by a 10-s resting period, were performed at each of the time point: (i) before (Pre), (ii) immediately after (Post), and (iii) 1 min after ($Post_{1MIN}$) completing the 1STS. After an additional 30-min break, participants performed the exact same procedures to assess intra-day reliability of the test outcomes.

Table 1 Participant characteristics

	Total ($n=40$)	Men ($n=21$)	Women ($n=19$)
Age (years)	23 ± 5	25 ± 6	22 ± 3
Weight (kg)	69 ± 14	76 ± 15	62 ± 8
Height (cm)	173 ± 10	180 ± 6	165 ± 7
Min/week sitting time	443 ± 145	453 ± 165	433 ± 123
MET-min/week VPA	2116 ± 1370	2320 ± 1538	1891 ± 1157
MET-min/week MPA	764 ± 897	662 ± 617	878 ± 1138
MET-min/week walking	819 ± 718	958 ± 850	666 ± 519
MET-min/week total	3699 ± 1760	3940 ± 1708	3435 ± 1825

MET metabolic equivalent task; *VPA* vigorous physical activity; MPA moderate physical activity

1STS

The 1STS was performed using a standardized chair of 46 cm in height without armrests, following recommended procedures (Haile et al. 2021). The chair was placed against a wall to ensure the safety of participants. Standardized instructions informed participants to stand completely straight (i.e., complete knee extension) and immediately sitting back (i.e., the chair had to be touched by the buttocks) as many times as possible in 1 min. No verbal encouragement was provided by the experimenter during the test. After 45 s of effort, participants were informed of the remaining time, in a neutral tone (Haile et al. 2021). The entire exercise was recorded on video by the experimenter and later analyzed to exclude repetitions deemed invalid (i.e., lacking full extension or failure to touch the chair with the buttocks). The number of valid repetitions performed in the first and second round of 1STS was used for further analysis.

Sit to stand performance

We used the *Sit to Stand* mobile application (iPad Pro, 240 fps; Apple Inc., California, USA) to calculate the rising time of a single sit-to-stand test (STS_T) performed during the isolated STS maneuvers at Pre, Post and $Post_{1MIN}$. The iPad was positioned on a 0.7 m high tripod placed 3 m from the lateral side of the participant (Fig. 1). For these isolated STS maneuvers, we used an adjustable chair featuring a flat seat and devoid of armrests. This kind of chair allowed us to adjust the knee angle to be exactly at 90° for each participant (Ruiz-Cardenas et al. 2018). This chair was placed adjacent to the standard chair utilized for the 1STS to ease the transition at the completion of the 1STS for post-measurements. Participants started from a sitting position with their legs hip-width and the ankle, knee, and

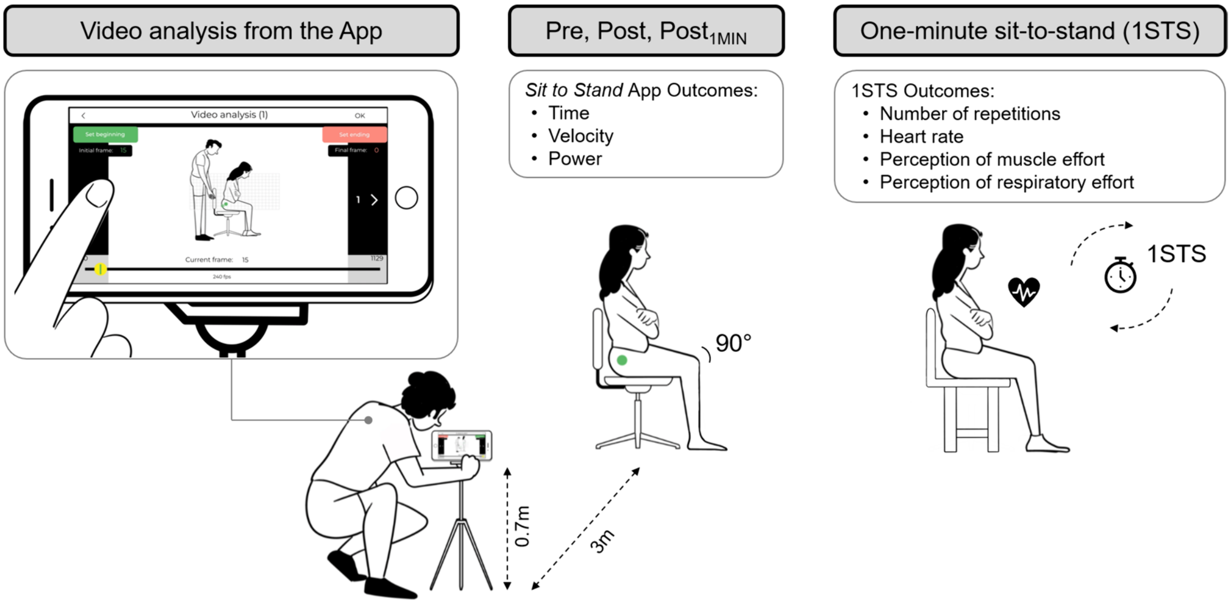

Fig. 1 Graphical representation of the experimental protocol. Participants first started with three isolated sit-to-stand exercises (Pre), followed by the 1-min sit-to-stand test (1STS). Immediately (Post) and 1 min ($Post_{1MIN}$) after the completion of the 1STS, participants performed again three sit-to-stand exercises. Sit-to-stand time and associated power and velocity parameters were recorded using an iPad Pro® (240 fps). The mobile device was positioned on a 0.7 m high tripod at 3 m of the participant' side. We asked participants to report their perception of muscle and respiratory efforts at the beginning (i.e., 3-s in) and the end of the 1STS. Heart rate was monitored throughout the 1STS

hip joints at 90°, and were asked to stand up once as fast as possible, which represented one transition from sitting to standing, while maintaining their arms crossed over the chest. A trial was deemed valid if the participant achieved full knee extension while keeping the heel on the ground (i.e., no heel raise).

The calculation of the STS_T involved a manual process consisting of selecting two frames after video recording. According to the instruction of the mobile application, a colored sticker was placed on the greater trochanter to facilitate the detection of both frames. The first frame was identified when the pelvis initiated forward movement following anterior trunk tilt and was synchronized with the moment the sticker crossed the initial horizontal grid line on the mobile application screen. The second frame marked the conclusion of the movement cycle, characterized by full extensions of the hip and knee in an upright stance (see Fig. 1 or Fig. 2 in Ruiz-Cardenas et al. (2018) for a zoomed display). This position was time-aligned with the point when the sticker reached its highest vertical position during the upright movement cycle. Additionally, this mobile application enabled the computation of mean vertical velocity (m/s) and mean vertical power (W/kg). Vertical velocity (STS_V) is calculated from vertical displacement (d) and the time to rise from the chair (t) using the Newtonian equation:

$$STS_V = d/t,$$

where the vertical displacement (d) is equal to the femur length that is the distance between the superior aspect of the greater trochanter and lateral condyle of the femur, when the participant sat at 90° of the knee joints. Mean sit-to-stand vertical power (STS_P) was estimated from the following validated equation (Ruiz-Cardenas et al. 2018):

$$STS_P = 2.773\text{–}6.228 \times t + 18.224 \times d.$$

The best trial (i.e., the lowest STS_T) performed at Pre and $Post_{1MIN}$, and the first trial performed at Post (i.e., the closest to 1STS termination) were kept for statistical analysis. Although STS_T is the only variable allowed to vary in a test–retest analysis, incorporating individual's femur length into the calculation of STS_V and STS_P affects the absolute differences between repeated measures for these outcomes. Therefore, STS_V and STS_P were also included in the reliability analysis. Additionally, these outcomes can be used for between-participant comparisons.

Perceptual measurements

Participants were asked to verbally report their perception of muscular and respiratory efforts both at the really beginning (3-s in) and at the end of the 1STS. Briefly, they were asked to rate both the intensity of perceived leg effort and perceived work/effort of breathing, using the Borg CR10 scale (Borg 1971).

Hear rate

The heart rate (beats per min) was monitored throughout the 1STS (Polar Vantage M watch, Polar Electro, Kempele, Finland). The peak heart rate value obtained during the 1STS was expressed at a percentage of the theoretical maximal heart rate that was calculated using the following equation (Gellish et al. 2007):

$$\text{Maximal heart rate} = 192 - 0.007 \times \text{age}^2.$$

Sample size estimation

Sample size was estimated using the software G*Power 3.1. Sample size was estimated for each aim and the higher sample size was used as the minimum required. To analyze whether the *Sit to Stand* application detects fatigability induced by the 1STS, an expected moderate effect size ($f \geq 0.25$) with a statistical power $\geq 90\%$ for two-tailed test and an alpha error of 0.5 reported a minimum desirable sample size of 36 participants. To analyze whether the level of fatigability is reliable, a minimum acceptable reliability of $\rho H0 \geq 0.5$ and an expected reliability of $\rho H1 \geq 0.8$ (Ruiz-Cárdenas et al. 2023) for two-tailed test reported a minimum required sample size of 38 participants.

Statistical analysis

Statistical analyses were performed using JASP software 0.17.1. (JASP Team, Netherlands). Values are given in the text as mean and standard deviation or range of the mean with 95% confidence intervals (CIs). Time data from *Sit to Stand* application were log transformed due to evidence of non-normality, as confirmed by the Shapiro–Wilks test. The level of statistical significance was set at $p \leq 0.05$.

Intra-day reliability for number of repetitions performed during the 1STS, *Sit to Stand* variables (STS_T, STS_V, and STS_P), peak heart rate, as well as perceptions of muscle and respiratory efforts was assessed by the intra-class correlation coefficient two-way mixed effects consistency (ICC_{3-k}), which was interpreted as poor (< 0.5), moderate (0.50–0.74), good (0.75–0.89), and excellent (> 0.9) (Fleiss 1981). Absolute reliability was assessed using typical error expressed as a coefficient of variation (CV_{TE}), which was calculated using the online spreadsheet of Hopkins (2000). Pre–Post changes in the perception of muscle and respiratory efforts and between-session differences were assessed using two-way repeated-measures ANOVAs (time × session, with the session factor being the first versus second round of 1STS).

Decrease in performance for *Sit to Stand* variables and between sessions differences was assessed using two-way repeated-measures ANCOVAs (time × session) with physical activity level as covariate. Where Mauchly's test indicated assumption of sphericity was violated, the Greenhouse–Geisser correction was used. If significant main effects were observed, these were followed up by post hoc Bonferroni-corrected pairwise comparisons. Partial eta square (η_p^2) was reported as an estimate of effect size, with $\eta_p^2 \geq 0.07$ and $\eta_p^2 \geq 0.14$ used as moderate and large effects, respectively. Additionally, Pearson correlation coefficient was used to assess the construct validity between changes in performance for *Sit to Stand* variables and changes in perceived muscle and respiratory efforts, peak heart rate, and 1STS performance. The minimal detectable change (MDC_{95}) was calculated as $SEM \times \sqrt{2} \times 1.96$ and expressed as absolute and percentage of change. The MDC_{95} can be interpreted as the minimal amount of change in the score of an instrument that must occur in an individual in order to be sure that the change in score is not simply attributable to a measurement error. Between sessions agreement for STS variables to detect fatigable participants (i.e., those above the minimal detectable change) was calculate using Kappa coefficient (κ) and interpreted as ≤ 0.2 indicating no agreement, 0.21–0.40 as fair, 0.41–0.60 as moderate, 0.61–0.80 as substantial, and 0.81–1.00 as almost perfect agreement.

Results

Number of repetitions

The mean number of repetitions during the 1STS was 62 ± 9 (range: 43–80 repetitions) and 64 ± 9 (range: 45–85 repetitions) for sessions 1 and 2, respectively. The reliability between sessions was excellent (ICC = 0.93; 95% CI: 0.88–0.96) and the variability was low ($CV_{TE} = 3.6\%$; 95% CI: 2.9–4.6).

Sit to Stand application variables

A main effect of time was found for STS_T ($p < 0.001$; $\eta_p^2 = 0.15$), with data recorded at Post being significantly increased (i.e., decrease in performance) when compared with Pre ($+13 \pm 8\%$; $p < 0.001$). One minute of recovery was sufficient for STS_T to not significantly differ from baseline values ($p = 0.68$ for Pre versus $Post_{1MIN}$). A main effect of time was found for STS_V ($p < 0.001$; $\eta_p^2 = 0.25$) and STS_P ($p < 0.001$; $\eta_p^2 = 0.15$), with data recorded at Post being significantly decreased when compared with Pre ($-11.2 \pm 6\%$ and $-5.2 \pm 3\%$ for velocity and power, respectively; both $p < 0.001$). One minute of recovery was sufficient for STS_V and STS_P to not significantly differ from baseline values ($p = 0.3$ and 0.68, respectively). No time × session interaction was found for any STS-related parameters ($p > 0.05$). Additionally, no interaction effect between time and physical activity level was found for any STS-related variables ($p > 0.05$).

A total of 30 participants (75%) showed a decrease in performance above the minimal detectable change reported for STS_T (MDC_{95}: 0.032 s) and STS_P (MDC_{95}: 0.198 W/kg) (Fig. 2). Three additional participants showed a decrease in performance above the minimal detectable change reported for STS_V (MDC_{95}: 0.052 m/s). Individual data analysis revealed substantial agreement for STS_P ($\kappa = 0.62$) and moderate agreement for STS_T ($\kappa = 0.43$) and STS_V ($\kappa = 0.48$) for sessions 1 and 2 to detect fatigable participants, i.e., those beyond the minimal detectable change. Between sessions reliability was excellent for *Sit to Stand* application variables at Pre, Post, and $Post_{1MIN}$ (Table 2).

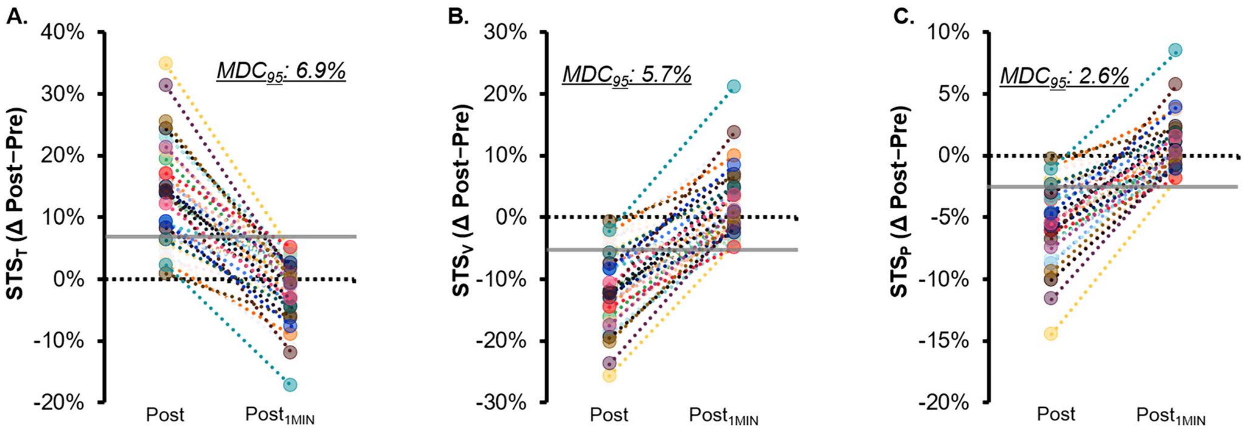

Fig. 2 Individual data for sit-to-stand time (STS_T, panel **A**), velocity (STS_V, panel **B**) and power (STS_P, panel **C**) recorded at the end (Post) and 1-min after the end ($Post_{1MIN}$) of the 1-min sit-to-stand test. Data are the Post − Pre delta (first point) and $Post_{1MIN}$ − Pre delta (second point), expressed as a percentage. For the panel **A**, note that an increase in STS_T indicates a lower performance, i.e., development of neuromuscular fatigability. The horizontal gray line shows the minimal detectable change (MDC_{95}) expressed as percentage of change for STS time, velocity, and power

Table 2 Between sessions reliability for sit-to-stand time (STS_T), velocity (STS_V), and power (STS_P) recorded before (Pre), at the end (post), and 1-min after the end ($Post_{1MIN}$) of the 1-min sit-to-stand test

	Session 1	Session 2	Bias (± 1.96 SD)	CV_{TE} (95% CI)	ICC (95% CI)
Pre					
STS_T (s)[a]	0.467	0.467	< 0.001 (–0.046 to 0.044)	3.5 (2.9 to 4.5)	0.95 (0.91 to 0.97)
STS_V (m/s)	0.911	0.911	< 0.001 (–0.074 to 0.074)	2.9 (2.4 to 3.7)	0.97 (0.94 to 0.98)
STS_P (W/kg)	7.553	7.549	0.004 (–0.277 to 0.284)	1.3 (1.1 to 1.7)	0.99 (0.98 to 0.99)
Post					
STS_T (s)[a]	0.529	0.522	0.006 (–0.071 to 0.083)	5.3 (4.3 to 6.8)	0.91 (0.83 to 0.95)
STS_V (m/s)	0.808	0.818	–0.010 (–0.108 to 0.088)	4.4 (3.6 to 5.6)	0.94 (0.89 to 0.97)
STS_P (W/kg)	7.166	7.205	–0.039 (–0.518 to 0.439)	2.4 (2.0 to 3.1)	0.97 (0.94 to 0.98)
$Post_{1MIN}$					
STS_T (s)[a]	0.458	0.467	–0.009 (–0.065 to 0.047)	4.4 (3.6 to 5.6)	0.92 (0.85 to 0.96)
STS_V (m/s)	0.927	0.912	0.015 (–0.088 to 0.117)	4.0 (3.3 to 5.1)	0.94 (0.88 to 0.96)
STS_P (W/kg)	7.604	7.548	0.056 (–0.294 to 0.405)	1.7 (1.4 to 2.1)	0.97 (0.94 to 0.98)

Data are given as mean

SD standard deviation; *95% CI* 95% confidence interval; *CV* coefficient of variation

[a]Data were log transformed prior to analysis due to evidence of non-normality

Heart rate and perceptual measurements

The mean peak heart rate obtained during the 1STS was 87% ± 8 of theoretical maximal heart rate in both sessions. An excellent reliability (ICC = 0.94; 95% CI: 0.90–0.97) and low variability (CV_{TE} = 2.1%; 95% CI: 1.7–2.7) was reported between sessions. The perception of muscle effort at the end of the 1STS was 4.9 ± 1.8 and 5.7 ± 1.8 for sessions 1 and 2, respectively. It was 5.0 ± 1.5 and 5.4 ± 1.7 for the perception of respiratory effort. A significant time effect with large effect sizes was found for both muscle ($p < 0.001$; $\eta_p^2 = 0.88$) and respiratory efforts ($p < 0.001$; $\eta_p^2 = 0.89$) with values recorded at the end of the 1STS being significantly higher than at the beginning of the test. We found no time × session interaction. Moderate between sessions reliability was found for the perception of muscle (ICC = 0.62; 95% CI: 0.4–0.78) and respiratory effort (ICC = 0.65; 95% CI: 0.42–0.8) when recorded at the beginning of the protocol, and good reliability was found (ICC = 0.81; 95% CI: 0.68–0.9; ICC = 0.8; 95% CI: 0.65–0.89, respectively) when recorded at the end of the 1STS.

Relation between changes in sit to stand application variables and perceptual measurements, heart rate, and 1STS performance

The 1STS performance was related to changes in STS_T ($r = 0.502$; $p < 0.001$), STS_V ($r = 0.299$; $p = 0.031$), and STS_P ($r = 0.505$; $p < 0.001$), i.e., those participants who showed better performance during the 1STS test were less fatigable. The perception of muscle effort at the end of the 1STS was related to changes in STS_T ($r = -0.303$; $p = 0.028$), STS_V ($r = -0.306$; $p = 0.027$), and STS_P ($r = -0.301$; $p = 0.03$). Similarly, the perception of respiratory effort at the end of the 1STS was related to changes in STS_T ($r = -0.321$; $p = 0.022$), STS_V ($r = -0.247$; $p = 0.06$), and STS_P ($r = -0.315$; $p = 0.024$). No associations were found for heart rate and *Sit to Stand* App variables.

Discussion

This study aimed to investigate whether the 1-min sit-to-stand test (1STS) induces neuromuscular fatigability, as determined by an increase in rising time (STS_T) and decrease in vertical velocity (STS_V) and power (STS_P) parameters extracted through a mobile application. The findings revealed a decline in performance across all participants concerning rising time, vertical velocity, and power. Remarkably, over 74% of participants experienced a substantial performance decrease surpassing the minimal detectable change reported by the mobile application. This study also showed excellent intra-day reliability regarding the level of fatigability, as determined by the decrease in performance indicators collected from the application after the 1STS.

STS protocol and neuromuscular fatigability: not a new story, but a novel approach

Previous studies have employed various versions of the sit-to-stand protocol to induce fatigability in both healthy and clinical participants. These protocols range from shorter versions involving ten repetitions to more extended versions conducted until task failure (Petrella et al. 2005; Helbostad et al. 2007; Barbieri et al. 2013; Lindemann et al. 2016; Gephine et al. 2020; Cuesta-Vargas et al. 2020; Wood Magee et al. 2022). In a task failure approach where participants were instructed to continue the STS protocol until feeling too exhausted to perform more repetitions, Helbostad et al. (2007) reported a 15% decline in STS_V between the first and last five repetitions in older adults. Lindemann et al. (2016), utilizing a shorter version of repeated STS over a 90-s period, observed a 20% decrease in STS_V for 77% (38/49) of healthy older participants by the 21st repetition. Similar to our approach, Gephine et al. (2020) employed the 1STS and reported a 15% reduction in quadriceps twitch force in only 42% (5/12) of healthy older participants. This low proportion of fatigable individuals may be attributed to the time of rest between the 1STS protocol and the measurement of the fatigability indicator since quadriceps twitch force was measured 10 min after 1STS cessation. Using a direct measure derived from the STS protocol could minimize recovery time and enhance the detection of more fatigable participants. Our analysis aligns with this, showing that a 60-s resting period was sufficient for participants to recover.

Moreover, although the quadriceps significantly contribute to STS performance, measuring neuromuscular fatigability in an isolated muscle group during an isometric effort might lack task specificity compared to employing a direct measurement from the sit-to-stand protocol. The latter could potentially be more sensitive in detecting fatigability after the protocol. Therefore, the selected fatigability indicator and the time duration between the STS protocol and fatigability measurement could play a crucial role in detecting fatigable participants, more so than the protocol duration itself—a proposition supported by previous studies. For example, Cuesta-Vargas et al. (2020) used a 30-s STS protocol and demonstrated a decline in STS acceleration after 10 s of starting the test in breast cancer survivors. Petrella et al. (2005) reported a substantial 27% decline in peak STS_P at the 10th repetition in both young and older adults, translating to a 12% and 20% decline in STS peak force and STS_V, respectively. These findings underscore the efficacy of the STS protocol in inducing fatigability without necessitating test continuation until exhaustion.

Task-specific fatigability indicators: insights from test–retest analysis

In our study, STS time, velocity, and power derived from the mobile application exhibited a substantial and consistently parallel rate of decline ($\eta_p^2 \geq 0.14$) at the end of the 1STS. More than 74% (30/40) of participants demonstrated a decline surpassing the minimal detectable change for STS time, velocity, and power. To ascertain genuine changes, where the difference between testing sessions must exceed measurement error and the inherent variability associated with repeated measurements, we opted for a test–retest analysis of the parameters extracted from the mobile application. This approach contrasts with the utilization of arbitrary fatigability thresholds adopted in prior STS-related studies (Gephine et al. 2020; Lindemann et al. 2016). The adoption of task-specific fatigability indicators, coupled with a non-arbitrary threshold derived from a test–retest analysis featuring low variability, may account for our ability to detect more fatigable participants compared to previous studies involving older adults (Gephine et al. 2020). These findings are particularly noteworthy as our fatigability indicators identified a substantial proportion of fatigable participants even within a sample of young adults reporting good physical activity levels, with a number of repetitions associated with the 1STS ranging between the 75th and 97.5th percentiles (Strassmann et al. 2013). Changes in our fatigability indicators were unrelated to self-reported physical activity, but as others (Helbostad et al. 2007), we observed that individuals with higher number of repetitions during the 1STS exhibited lower levels of fatigability. While we can express confidence that ecologically valid parameters extracted from this mobile application are capable of identifying comparable or even higher proportions of fatigable individuals in clinical populations marked by altered muscle function and high level of fatigability, e.g., cancer (Brownstein et al. 2022), chronic respiratory diseases (Gruet 2018), further studies are needed to confirm this assertion.

Performance-related fatigability: beyond the number of repetitions

The number of repetitions performed during the 1STS is a widely employed surrogate measure of muscle strength and endurance, particularly in environments where limitations exist in terms of equipment, space and time (Bohannon and Crouch 2019). This performance parameter has demonstrated reliability (ICC > 0.8, CV < 13%) in older adults and in people with chronic obstructive pulmonary disease or those undergoing hemodialysis (Bohannon and Crouch 2019). In extending these observations to young, physically active adults, we found low variability (CV < 4%) and excellent intra-day reliability (ICC = 0.93). While the number of repetitions associated with 1STS performance is a commonly used metric (Bohannon 1995; Bohannon and Crouch 2019; Strassmann et al. 2013), its limitations necessitate a more nuanced interpretation to gauge changes in physical fitness induced by a training intervention for example. The exclusive reliance on this measure may present challenges due to the constrained available time for test completion. Consequently, individuals may reach their maximum potential, encountering a ceiling effect that renders it challenging to discern intervention-induced improvements, even in the presence of genuine changes in muscle strength and/or endurance occur. Our approach effectively addresses this limitation associated with these scenarios where a ceiling effect is expected, such as in healthy individuals or those with a mild profile of certain chronic diseases. Further, the exclusive reliance on the number of repetitions may be influenced by monotony-induced motivational alterations, especially when the test is reiterated over an evaluation session or a training program (Jung et al. 2014). The brief duration of the isolated STS maneuver (< 1 s) suggests that it may be less susceptible to volitional effort and more resistant to motivational factors compared to the full test, which spans 1 min. Then, and to enhance the comprehensiveness of the 1STS, we recommend to report collectively on STS repetitions, perception of effort, and neuromuscular fatigability. Incorporating these factors is particularly valuable when assessing the effectiveness of interventions over time, as it offers a broader perspective on the participant's physical capabilities and responses. By embracing a multi-faceted assessment strategy, researchers and practitioners can better navigate the challenges posed by ceiling effects and motivational influences, providing a more accurate representation of the impact of chronic interventions on STS performance.

Moreover, it is important to recognize the emancipatory role of evaluation, particularly when facilitated through engaging and immersive mobile applications. By providing positive affective experiences, these emerging technologies can play a pivotal role in enhancing hedonic motivation—defined as the enjoyment or pleasure derived from using a technology (Hayotte et al. 2021). For example, it has been reported a high level of hedonic motivation among obese individuals using mobile applications as part of a technology-based physical activity intervention (Hayotte et al. 2021). This type of technology can exert positive influence on participants' motivation and adherence to the evaluation and testing processes (Feter et al. 2019; Núñez de Arenas-Arroyo et al. 2021). The interactive features of mobile applications, combined with a user-friendly interface, transform the evaluation process into an engaging experience. Immediate feedback, visually appealing elements, and the ease of use of these applications not only contribute to participants' better understanding of results but also create an overall positive experience. This initiates a virtuous cycle where positive affective experiences propel participants' motivation to actively participate in subsequent evaluations.

Limitations

This study was performed in healthy young and active adults, so the extent of these observations may not be transferable to a clinical population. However, the fact that fatigability was detected in most of our participants with (i) good self-reported physical activity and (ii) 1STS performance greater that 75th percentile is a strength of this study and suggests that it could be potentially detected in clinical populations with altered peripheral muscle function.

Further, our protocol may constrain the ecological validity of the mobile application in scenarios where an adjustable height chair is unavailable, as the application was validated for a chair height that induces a knee angle of 90° (Ruiz-Cardenas et al. 2018). Conversely, we used a standard height chair for performing the 1STS, as this test was originally validated with the consistent use of a chair set at a height of 46–48 cm for all participants, irrespective of their stature. This standardized approach remains prevalent in most settings. However, a recent study involving young, healthy adults revealed that tailoring the 1STS starting position to a 90° knee flexion angle had an impact on the number of repetitions compared to the conventional starting position (Kuhn et al. 2023). It remains uncertain whether employing an individualized chair height for the 1STS would influence the level of fatigability. Further investigations are necessary to investigate this specific issue.

Finally, our primary emphasis was on intra-day reliability. Given the excellent inter-day reliability regarding the number of repetitions (Ritchie et al. 2005; Segura-Ortí and Martínez-Olmos 2011; Radtke et al. 2016), which is probably a key determinant of neuromuscular fatigability at the individual level, it is reasonable to anticipate satisfactory inter-day reliability for the level of fatigability induced by the 1STS. This specific point warrants confirmation through future research.

In conclusion, this study marks the first exploration into whether the widely used 1STS method induces a significant and reliable level of neuromuscular fatigability among young adults with commendable levels of physical activity. Our findings reveal that the 1STS elicits significant level of fatigability, as evidenced by changes in rising time, vertical velocity, and power parameters, all measured through a mobile application. The fatigability indicators generated by our mobile application exhibited remarkable reliability and minimal variability under specific condition where (i) the 1STS is executed using a standard chair with a height of 46 cm height and (ii) the isolated STS maneuvers are performed with an adjustable chair allowing for a starting knee angle of 90°. Further investigations could help enhance the practicability of measuring fatigability induced by the 1STS using a single chair (instead of two in our study) with consistent adjustment (e.g., maintaining a knee angle of 90° for both the 1STS and isolated STS maneuvers). Nevertheless, the fatigability indicators gathered in this study offer additional outcomes that could enrich the interpretative value of the 1STS and simplify its interpretation, especially when assessing changes in muscle performance after a chronic intervention. The mobile application used to compute fatigability has an easy-to-use interface and automatic data processing which may provide the clinicians the opportunity of obtaining insightful complementary indicators from the 1STS in short-time periods, emphasizing its clinical utility.

Author contributions R. Souron: conceptualization; data curation; formal analysis; methodology; supervision; writing—original draft. JD. Ruiz-Cárdenas: conceptualization; methodology; formal analysis; writing—review and editing. M. Gruet: conceptualization; methodology; writing—review and editing.

Data availability The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Declarations

Conflict of interests The authors have no relevant financial or non-financial interests to disclose.

References

Bachasson D, Millet GY, Decorte N, Wuyam B, Levy P, Verges S (2013) Quadriceps function assessment using an incremental test and magnetic neurostimulation: a reliability study. J Electromyogr Kinesiol 23(3):649–658. https://doi.org/10.1016/j.jelekin.2012.11.011

Barbieri FA, dos Santos PC, Vitório R, van Dieën JH, Gobbi LT (2013) Effect of muscle fatigue and physical activity level in motor control of the gait of young adults. Gait Posture 38(4):702–707. https://doi.org/10.1016/j.gaitpost.2013.03.006

Bemben MG (1998) Age-related alterations in muscular endurance. Sports Med 25:259–269. https://doi.org/10.2165/00007256-199825040-00004

Bohannon RW (1995) Sit-to-stand test for measuring performance of lower extremity muscles. Percept Mot Skills 80(1):163–166. https://doi.org/10.2466/pms.1995.80.1.163

Bohannon RW, Crouch R (2019) 1-Minute sit-to-stand test: systematic review of procedures, performance, and clinimetric properties. J Cardiopulm Rehabil Prev 39(1):2–8. https://doi.org/10.1097/hcr.0000000000000336

Borg G (1971) The perception of physical performance. In: Shephard RJ (ed) Frontiers of fitness. Charles Thomas, Springefield, pp 280–294

Briand J, Behal H, Chenivesse C, Wémeau-Stervinou L, Wallaert B (2018) The 1-minute sit-to-stand test to detect exercise-induced oxygen desaturation in patients with interstitial lung disease. Ther Adv Respir Dis. https://doi.org/10.1177/1753466618793028

Brownstein CG, Twomey R, Temesi J, Medysky ME, Culos-Reed SN, Millet GY (2022) Mechanisms of neuromuscular fatigability in people with cancer-related fatigue. Med Sci Sports Exerc 54(8):1355–1363. https://doi.org/10.1249/MSS.0000000000002919

Cheng YY, Wei SH, Chen PY, Tsai MW, Cheng IC, Liu DH, Kao CL (2014) Can sit-to-stand lower limb muscle power predict fall status? Gait Posture 40(3):403–407. https://doi.org/10.1016/j.gaitpost.2014.05.064

Craig CL, Marshall AL, Sjöström M, Bauman AE, Booth ML, Ainsworth BE, Pratt M, Ekelund U, Yngve A, Sallis JF (2003) International physical activity questionnaire: 12-country reliability and validity. Med Sci Sports Exerc 35(8):1381–1395. https://doi.org/10.1249/01.MSS.0000078924.61453.FB

Cuesta-Vargas AI, Pajares B, Trinidad-Fernandez M, Alba E, Roldan-Jiménez C (2020) Inertial sensors embedded in smartphones as a tool for fatigue assessment based on acceleration in survivors of breast cancer. Phys Ther 100(3):447–456. https://doi.org/10.1093/ptj/pzz173

Doyle-Baker D, Temesi J, Medysky ME, Holash RJ, Millet GY (2017) An innovative ergometer to measure neuromuscular fatigue immediately after cycling. Med Sci Sports Exerc 50(2):375–387. https://doi.org/10.1249/MSS.0000000000001427

Enoka RM, Duchateau J (2016) Translating fatigue to human performance. Med Sci Sports Exerc 48(11):2228–2238. https://doi.org/10.1249/MSS.0000000000000929

Enright PL, McBurnie MA, Bittner V, Tracy RP, McNamara R, Arnold A, Newman AB (2003) The 6-min walk test: a quick measure of functional status in elderly adults. Chest 123(2):387–398. https://doi.org/10.1378/chest.123.2.387

Fell B, Hanekom S, Heine M (2022) A modified six-minute walk test (6MWT) for low-resource settings-a cross-sectional study. Heart Lung 52:117–122. https://doi.org/10.1016/j.hrtlng.2021.12.008

Ferrazza AM, Martolini D, Valli G, Palange P (2009) Cardiopulmonary exercise testing in the functional and prognostic evaluation of patients with pulmonary diseases. Respiration 77(1):3–17. https://doi.org/10.1159/000186694

Feter N, dos Santos TS, Caputo EL, da Silva MC (2019) What is the role of smartphones on physical activity promotion? A systematic review and meta-analysis. Int J Public Health 64(5):679–690. https://doi.org/10.1007/s00038-019-01210-7

Fleiss JL (1981) The measurement of interrater agreement. Stat Methods Rates Proport 2:212–236

Froyd C, Millet GY, Noakes TD (2013) The development of peripheral fatigue and short-term recovery during self-paced high-intensity exercise. J Physiol 591(5):1339–1346. https://doi.org/10.1113/jphysiol.2012.245316

Gellish RL, Goslin BR, Olson RE, McDonald A, Russi GD, Moudgil VK (2007) Longitudinal modeling of the relationship between age and maximal heart rate. Med Sci Sports Exerc 39(5):822–829. https://doi.org/10.1097/mss.0b013e31803349c6

Gephine S, Bergeron S, Tremblay Labrecque P-F, Mucci P, Saey D, Maltais F (2020) Cardiorespiratory response during the 1-min sit-to-stand test in chronic obstructive pulmonary disease. Med Sci Sports Exerc 52(7):1441–1448. https://doi.org/10.1249/MSS.0000000000002276

Glenn JM, Gray M, Binns A (2017a) Relationship of sit-to-stand lower-body power with functional fitness measures among older adults with and without sarcopenia. J Geriatr Phys Ther (2001) 40(1):42–50. https://doi.org/10.1519/jpt.0000000000000072

Glenn JM, Gray M, Vincenzo J, Paulson S, Powers M (2017b) An evaluation of functional sit-to-stand power in cohorts of healthy adults aged 18–97 years. J Aging Phys Act 25(2):305–310. https://doi.org/10.1123/japa.2016-0031

Gruet M (2018) Fatigue in chronic respiratory diseases: theoretical framework and implications for real-life performance and rehabilitation. Front Physiol 9:1285. https://doi.org/10.3389/fphys.2018.01285

Gruet M, Temesi J, Rupp T, Levy P, Verges S, Millet GY (2014) Dynamics of corticospinal changes during and after high-intensity quadriceps exercise. Exp Physiol 99(8):1053–1064. https://doi.org/10.1113/expphysiol.2014.078840

Gruet M, Peyré-Tartaruga LA, Mely L, Vallier J-M (2016) The 1-minute sit-to-stand test in adults with cystic fibrosis: correlations with cardiopulmonary exercise test, 6-minute walk test, and quadriceps strength. Respir Care 61(12):1620–1628. https://doi.org/10.4187/respcare.04821

Haile SR, Fühner T, Granacher U, Stocker J, Radtke T, Kriemler S (2021) Reference values and validation of the 1-minute sit-to-stand test in healthy 5–16-year-old youth: a cross-sectional study. BMJ Open 11(5):e049143. https://doi.org/10.1136/bmjopen-2021-049143

Hayotte M, Martinent G, Nègre V, Thérouanne P, d'Arripe-Longueville F (2021) Acceptability of technology-based physical activity intervention profiles and their motivational factors in obesity care: a latent profile transition analysis. Int J Obes 45(7):1488–1498. https://doi.org/10.1038/s41366-021-00813-6

Helbostad JL, Leirfall S, Moe-Nilssen R, Sletvold O (2007) Physical fatigue affects gait characteristics in older persons. Gerontol A Biol Sci Med Sci 62(9):1010–1015. https://doi.org/10.1093/gerona/62.9.1010

Hill K, Wickerson LM, Woon LJ, Abady AH, Overend TJ, Goldstein RS, Brooks D (2011) The 6-min walk test: responses in healthy Canadians aged 45 to 85 years. Appl Physiol Nutr Metab 36(5):643–649. https://doi.org/10.1139/h11-075

Hopkins WG (2000) Measures of reliability in sports medicine and science. Sports Med 30(1):1–15

Jung ME, Bourne JE, Little JP (2014) Where does HIT fit? An examination of the affective response to high-intensity intervals in comparison to continuous moderate-and continuous vigorous-intensity exercise in the exercise intensity-affect continuum. PLoS ONE 9(12):e114541. https://doi.org/10.1371/journal.pone.0114541

Kuhn M, Vollenweider S, Clarenbach CF, Kohlbrenner D (2023) The effects of standardised versus individualised seat height on 1-minute sit-to-stand test performance in healthy individuals: a randomised crossover trial. Eur J Appl Physiol 123(7):1–9. https://doi.org/10.1007/s00421-023-05174-8

Lindemann U, Klenk J, Becker C (2016) Assessment of fatigability of older women during sit-to-stand performance. Aging Clin Exp Res 28(5):889–893. https://doi.org/10.1007/s40520-015-0495-0

Myers J, McAuley P, Lavie CJ, Despres J-P, Arena R, Kokkinos P (2015) Physical activity and cardiorespiratory fitness as major markers of cardiovascular risk: their independent and interwoven importance to health status. Prog Cardiovasc Dis 57(4):306–314. https://doi.org/10.1016/j.pcad.2014.09.011

Núñez de Arenas-Arroyo S, Cavero-Redondo I, Alvarez-Bueno C, Sequí-Domínguez I, Reina-Gutiérrez S, Martínez-Vizcaíno V (2021) Effect of eHealth to increase physical activity in healthy adults over 55 years: a systematic review and meta-analysis. Scand J Med Sci Sports 31(4):776–789. https://doi.org/10.1111/sms.13903

Peeters P, Mets T (1996) The 6-minute walk as an appropriate exercise test in elderly patients with chronic heart failure. J Gerontol A Biol Sci Med Sci 51(4):M147-151. https://doi.org/10.1093/gerona/51a.4.m147

Petrella JK, Kim JS, Tuggle SC, Hall SR, Bamman MM (2005) Age differences in knee extension power, contractile velocity, and fatigability. J Appl Physiol 98(1):211–220. https://doi.org/10.1152/japplphysiol.00294.2004

Pradon D, Roche N, Enette L, Zory R (2013) Relationship between lower limb muscle strength and 6-minute walk test performance in stroke patients. J Rehabil Med 45(1):105–108. https://doi.org/10.2340/16501977-1059

Priesnitz CV, Rodrigues GH, da Silva SC, Viapiana G, Cabral CP, Stein RT, Marostica PJC, Donadio MVF (2009) Reference values for the 6-min walk test in healthy children aged 6–12 years. Pediatr Pulmonol 44(12):1174–1179. https://doi.org/10.1002/ppul.21062

Radtke T, Puhan MA, Hebestreit H, Kriemler S (2016) The 1-min sit-to-stand test—a simple functional capacity test in cystic fibrosis? J Cyst Fibros 15(2):223–226. https://doi.org/10.1016/j.jcf.2015.08.006

Regterschot GR, Folkersma M, Zhang W, Baldus H, Stevens M, Zijlstra W (2014) Sensitivity of sensor-based sit-to-stand peak power to the effects of training leg strength, leg power and balance in older adults. Gait Posture 39(1):303–307. https://doi.org/10.1016/j.gaitpost.2013.07.122

Ridgway ZA, Howell SJ (2010) Cardiopulmonary exercise testing: a review of methods and applications in surgical patients. Eur J Anaesthesiol 27(10):858–865. https://doi.org/10.1097/EJA.0b013e32833c5b05

Ritchie C, Trost S, Brown W, Armit C (2005) Reliability and validity of physical fitness field tests for adults aged 55 to 70 years. J Sci Med Sport 8(1):61–70. https://doi.org/10.1016/s1440-2440(05)80025-8

Ruiz-Cardenas JD, Rodriguez-Juan JJ, Smart RR, Jakobi JM, Jones GR (2018) Validity and reliability of an iPhone App to assess time, velocity and leg power during a sit-to-stand functional performance test. Gait Posture 59:261–266. https://doi.org/10.1016/j.gaitpost.2017.10.029

Ruiz-Cárdenas JD, Montemurro A, del Mar Martínez-García M, Rodríguez-Juan JJ (2023) Concurrent and discriminant validity and reliability of an Android App to assess time, velocity and power during sit-to-stand test in community-dwelling older adults. Aging Clin Exp Res 35(8):1631. https://doi.org/10.1007/s40520-023-02451-6

Saynor ZL, Gruet M, McNarry MA, Button B, Morrison L, Wagner M, Sawyer A, Hebestreit H, Radtke T, Urquhart DS (2023) Guidance and standard operating procedures for functional exercise testing in cystic fibrosis. Eur Respir Rev 32(169):230029. https://doi.org/10.1183/16000617.0029-2023

Segura-Ortí E, Martínez-Olmos FJ (2011) Test–retest reliability and minimal detectable change scores for sit-to-stand-to-sit tests, the six-minute walk test, the one-leg heel-rise test, and handgrip strength in people undergoing hemodialysis. Phys Ther 91(8):1244–1252. https://doi.org/10.2522/ptj.20100141

Souron R, Colard J, Ruiz-Cardenas JD, Beltran A, Duché P, Gruet M (2024) Development and assessment of test-retest reliability of a new field test to evaluate lower-limb muscle fatigability in young adults. Mov Sport Sci 124:37–45. https://doi.org/10.1051/sm/2024001

Strassmann A, Steurer-Stey C, Lana KD, Zoller M, Turk AJ, Suter P, Puhan MA (2013) Population-based reference values for the 1-min sit-to-stand test. Int J Public Health 58(6):949–953. https://doi.org/10.1007/s00038-013-0504-z

Tran D (2018) Cardiopulmonary exercise testing. Methods Mol Biol (Clifton, NJ) 1735:285–295. https://doi.org/10.1007/978-1-4939-7614-0_18

Wood Magee LJ, Kneiss J, Wechsler S, Singh AB, Fox AB, Peppercorn J, Pirl WF (2022) Increased fatigability in women with persistent cancer-related fatigue after breast cancer treatment: a pilot study. Rehab Oncol 40(3):135–144. https://doi.org/10.1097/01.REO.0000000000000305

Zanini A, Aiello M, Cherubino F, Zampogna E, Azzola A, Chetta A, Spanevello A (2015) The one repetition maximum test and the sit-to-stand test in the assessment of a specific pulmonary rehabilitation program on peripheral muscle strength in COPD patients. Int J Chron Obstruct Pulmon Dis. https://doi.org/10.2147/COPD.S91176