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Sensitivity of sensor-based sit-to-stand peak power to the effects of training leg strength, leg power and balance in older adults

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ABSTRACT

Increasing leg strength, leg power and overall balance can improve mobility and reduce fall risk. Sensor-based assessment of peak power during the sit-to-stand (STS) transfer may be useful for detecting changes in mobility and fall risk. Therefore, this study investigated whether sensor-based STS peak power and related measures are sensitive to the effects of increasing leg strength, leg power and overall balance in older adults. A further aim was to compare sensitivity between sensor-based STS measures and standard clinical measures of leg strength, leg power, balance, mobility and fall risk, following an exercise-based intervention. To achieve these aims, 26 older adults (age: 70–84 years) participated in an eight-week exercise program aimed at improving leg strength, leg power and balance. Before and after the intervention, performance on normal and fast STS transfers was evaluated with a hybrid motion sensor worn on the hip. In addition, standard clinical tests (isometric quadriceps strength, Timed Up and Go test, Berg Balance Scale) were performed. Standard clinical tests as well as sensor-based measures of peak power, maximal velocity and duration of normal and fast STS showed significant improvements. Sensor-based measurement of peak power, maximal velocity and duration of normal STS demonstrated a higher sensitivity (absolute standardized response mean (SRM): $\geq$0.69) to the effects of training leg strength, leg power and balance than standard clinical measures (absolute SRM: $\leq$0.61). Therefore, the presented sensor-based method appears to be useful for detecting changes in mobility and fall risk.

1. Introduction

Muscle strength and muscle power decline during aging [1,2]. Muscle power can be defined as the speed with which muscular forces produce movement of body segments [3]. The decline in leg strength and leg power in older adults is related to difficulties with mobility related activities, i.e. activities that require moving the center of mass (CoM) from one place to another. For example, lower leg strength and leg power are related to a reduced sit-to-stand (STS) performance [2,4]. Lower leg strength and leg power are also associated with a higher fall risk [5]. Falls often result in major injuries, leading to reduced quality of life and increased health care usage and costs [6]. However, studies show that training of leg strength, leg power and balance can improve mobility and reduce fall risk in older adults [7,8].

Evaluation of leg strength and leg power is important to identify older persons with a low functional status and an increased risk of falling, and to monitor changes in functional status and fall risk over time. Usually leg strength and leg power are assessed using laboratory methods, such as computerized dynamometers. These methods are expensive and require skilled lab personnel. Mobility is often evaluated by using simple field tests, such as the Timed Up and Go (TUG) test and the Five Times Sit To Stand Test [9–12]. However, these field tests only provide duration as an outcome measure. Therefore, accessible and practical methods are needed to measure leg strength and leg power during mobility related activities.

Zijlstra et al. (2010) introduced a new method for assessing the power required to lift the body's CoM during the STS transfer [3]. Assuming that trunk kinematics are indicative of CoM kinematics,

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this study estimated the vertical power required to elevate the body's CoM during STS transfers based on the vertical acceleration signals of small hybrid motion sensors worn on the trunk in young and older adults. Results demonstrated that a sensor worn on the right side of the hip provided the most accurate single sensor-based estimation of vertical CoM acceleration during STS. Furthermore, the results by Zijlstra et al. (2010) showed fair to excellent correlations between sensor-based STS peak power and STS peak power as measured with force plates. Thus, this study showed that vertical peak power during the STS transfer can be estimated with hybrid motion sensors in young and older adults.

However, so far it is unknown whether STS peak power as estimated with hybrid motion sensors can detect changes in mobility and fall risk. If sensor-based STS peak power is sensitive to the effects of training leg strength, leg power and balance, then this method could be useful for detecting changes in mobility and fall risk over time. Therefore, the aim of this study was to determine the sensitivity of sensor-based STS peak power and related measures to the effects of training leg strength, leg power and balance in older adults. A further aim was to compare sensitivity between sensor-based STS measures and standard clinical measures of leg strength, leg power, balance, mobility and fall risk, following an exercise-based intervention.

2. Methods

2.1. Participants

In total 26 older adults (16 females, 10 males) voluntarily participated in this study. Inclusion criteria were: age ≥70 years, being able to walk ≥10 meters without or with a wheeled walker or cane, being able to stand up from a chair without using the armrests, living independently or in sheltered accommodation. Exclusion criteria were: Cardiovascular/respiratory disorders, neurological disorders, severe comorbidity that influences mobility or participation in the exercise program, acute orthopedic conditions, cognitive disorders that affect comprehension or execution of the exercises, simultaneous participation in another intervention or exercise program. Age of the participants ranged from 70 to 84 years (mean ± SD: 77.7 ± 3.7 years), height ranged from 1.48 to 1.87 m (1.67 ± 0.1 m) and body mass ranged from 43.0 to 113.9 kg (80.0 ± 15.8 kg). Eleven participants reported they fell at least once during the year before the start of the intervention. A fall was defined as 'unintentionally coming to rest on the ground, floor or other lower level' [13]. Number of falls in the previous year ranged from 0 to 3. All participants received detailed information about the study and signed an informed consent. The study was approved by the Medical Ethical Committee of the University Medical Center Groningen (UMCG), Groningen, the Netherlands.

2.2. Exercise intervention

The exercise program was based on best-evidence protocols for improving leg strength, leg power and balance in older persons [7]. The duration of the exercise program was eight weeks. Subjects participated in two group training sessions per week (one hour per session) under supervision of a physical therapist. Subjects also received instructions for daily exercises at home (about 30 min/day). The group and home exercises consisted of: Knee extension movements while sitting on a chair, STS movements, hip abduction movements while standing next to a chair, hip abduction movements while sitting on a chair, knee flexion movements while standing behind a chair, hip extension movements with straight leg while standing behind a chair, heel raise exercises while standing, knee lifting exercises while sitting on a chair, standing still with eyes closed, stair walking, large forward step movements, moving body weight from one leg to the other. Participants were instructed to perform concentric contractions with high velocity and eccentric contractions with low velocity. Progression in the training program was achieved by a weekly increase of training intensity or training volume. Intensity was elevated by using therabands and ankle weights.

2.3. Procedures

Assessments were performed before and after the exercise program. During the pre-intervention and post-intervention assessments participants performed three STS transfers at normal rising speed and three STS transfers at as fast as possible rising speed. Prior to standing, participants sat against the back of the chair. All STS transfers were performed without using the armrests. After rising up, participants stood still for five seconds before sitting down again. After sitting down, participants sat still for five seconds before standing up again. A chair of standard height was used (0.47 m).

After the STS transfers, participants performed several standard clinical tests. First, the Berg Balance Scale (BBS) was performed [14]. This test consists of 14 balance-challenging tasks. Performance of each task was rated on a 5-point ordinal scale of 0 (low performance) to 4 (high performance). The final score (range: 0–56) was calculated by summing all 14 scores. Next three trials of the TUG were performed [9], preceded by one practice trial. Participants also performed three trials of an "as fast as possible" version of the TUG (without running). The use of walking aids (wheeled walker or cane) was allowed during the TUG. For the normal and the fast TUG, time needed to complete the test was measured and the final score was the average time of the three trials. Also maximal isometric quadriceps strength of the left and right leg was measured three times at two different knee angles (90° and 40° knee flexion) with a quadriceps force measuring device consisting of a chair and measurement equipment [15]. The final score per knee angle was the average of the three trials performed with the right and left leg. The same evaluator conducted all standard clinical tests.

2.4. Data acquisition

Participants wore a small hybrid motion sensor (π-Node, Philips) on the right side of the hip (just above the trochanter major femoris) during the normal and fast STS transfers (Figs. 1 and 2). The sensor contained a 3D accelerometer to measure accelerations (±2 g), a 3D gyroscope to measure angular velocities (±300 deg/s) and a 3D magnetometer (±2 Gauss) to measure orientation in the Earth's magnetic field [16]. Sampling frequency was 50 Hz and data

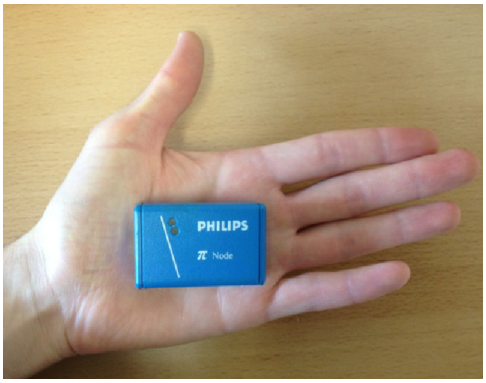

Fig. 1. The hybrid motion sensor.

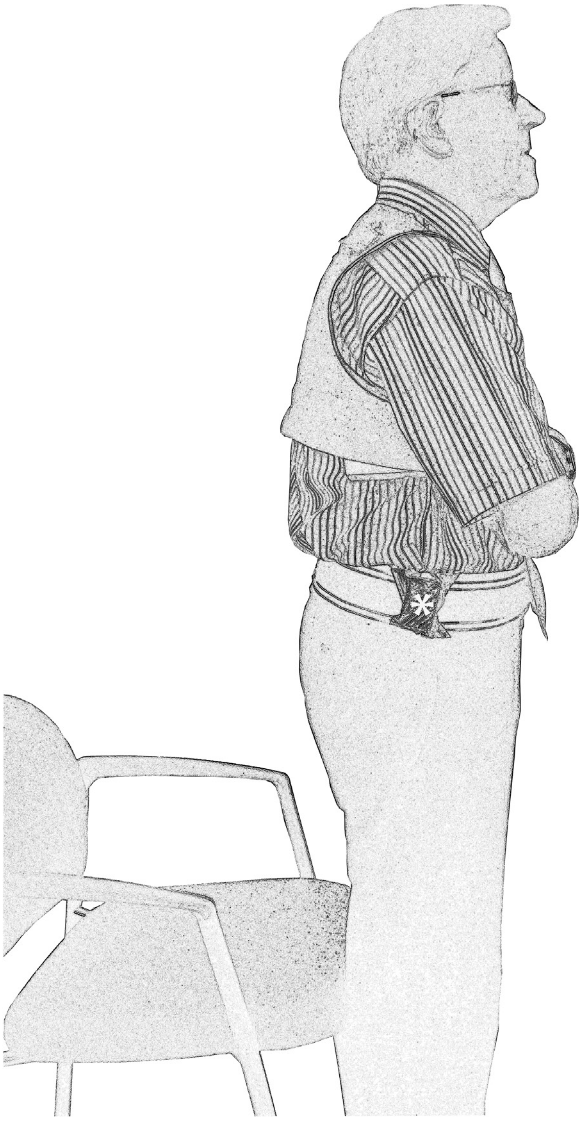

Fig. 2. The hybrid motion sensor was worn on the right side of the hip, just above the trochanter major femoris. The sensor is marked with an asterisk.

was wirelessly transmitted to a nearby PC by means of a proprietary multipoint packetized radio protocol [17].

2.5. Data analysis

2.5.1. Data processing

All sensor data was analyzed using Matlab (The Mathworks, Inc.; version 7.12). First, sensor orientations in the global frame of reference were estimated by using a quaternion solution and 3D data of the accelerometer, gyroscope and magnetometer [16]. Next data were further processed by applying a low-pass Butterworth filter with a cut-off frequency of 3 Hz.

2.5.2. Calculation of sensor-based STS measures

Based upon the low-pass filtered vertical acceleration data the following STS measures were calculated:

1. **STS duration**: Time between the start of the forward trunk movement before standing up (defined as the first deflection of the acceleration signal compared to gravity; point A in Fig. 3) and the time at which the acceleration signal intersects with the acceleration due to gravity, after the negative acceleration peak (point B in Fig. 3).

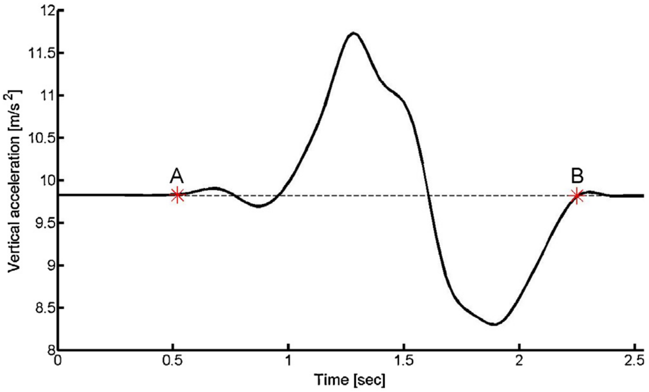

Fig. 3. Typical vertical acceleration pattern of a STS movement measured at the right side of the hip. STS duration was defined as the interval between point A and point B.

2. **Maximal acceleration**: The highest acceleration during the interval of STS duration.
3. **Maximal jerk**: The maximal positive jerk during the acceleration phase of the rising movement. Jerk was calculated as: $\text{Jerk}(i) = (a(i+1)–a(i))/(1/\text{fs})$. In this formula, a represents acceleration, i the sample and fs the sample frequency.
4. **Maximal velocity**: The peak velocity during the interval of STS duration. Velocity was calculated by numerical integration of acceleration. It was assumed that velocity was equal to 0 m/s at the start of the STS transfer (point A in Fig. 3).
5. **Peak power**: The peak power during the interval of STS duration. First, force was calculated as: $F = m \cdot a$, where m represents body mass. Next power was estimated by multiplying force and velocity: $P = F \cdot v$.

2.5.3. Statistical analysis

For each sensor-based STS measure, statistical analysis was based on the average of the three normal STS trials and the average of the three fast STS trials. Differences between pre-intervention and post-intervention scores were analyzed with paired t-tests. Wilcoxon signed-rank tests were used to compare pre-intervention and post-intervention scores of BBS, fast TUG and quadriceps strength at 40° knee flexion, because the BBS measures is an ordinal scale and the other two outcome measures were not normally distributed. Statistical significance was set at $p < 0.05$.

Sensitivity to change is an important measurement property for the evaluation of an intervention [18]. The standardized response mean (SRM) was used as an indicator of sensitivity to change and calculated as: *SRM = mean change/SD of change* [18]. Cohen's criteria for interpretation of effect sizes were applied to the SRM values [19]. A SRM between $0.20 \leq 0.50$ was considered as small, between $0.50 \leq 0.80$ as moderate and ≥ 0.80 as large [20]. Statistical analyses were performed with SPSS Statistics (IBM; version 20).

3. Results

3.1. Sensor-based STS measures

In total 299 STS trials were assessed in the analysis: 72 normal STS trials and 75 fast STS trials performed during the pre-intervention measurement as well as 78 normal STS trials and 74 fast STS trials performed during the post-intervention measurement. Ten STS trials were excluded from the analysis to prevent influence of missing samples on STS outcomes. Three other STS trials were excluded because it was not possible to determine the start point and/or end point of these STS transfers with certainty.

Table 1
Outcomes on sensor-based STS measures and standard clinical tests ($n = 26$). Also test statistics and standardized response mean (SRM) values are shown.

Outcome measure	Pre (mean ± SD)	Post (mean ± SD)	% change	SD change	Test statistic	*P*-value[a]	SRM
Normal STS							
Duration (s)	2.17 ± 0.44	1.93 ± 0.33	10.8%	0.30	$t = 3.924$ (df = 25)	0.001[*]	−0.77
Maximal acceleration (m/s^2)	11.22 ± 0.42	11.44 ± 0.43	1.9%	0.37	$t = -2.930$ (df = 25)	0.007[*]	0.57
Maximal jerk (m/s^3)	8.61 ± 3.14	9.98 ± 3.62	15.9%	2.97	$t = -2.346$ (df = 25)	0.027[*]	0.46
Maximal velocity (m/s)	0.52 ± 0.13	0.61 ± 0.15	17.6%	0.12	$t = -3.784$ (df = 25)	0.001[*]	0.74
Peak power (W)	423.4 ± 141.1	504.8 ± 183.5	19.2%	118.3	$t = -3.510$ (df = 25)	0.002[*]	0.69
Fast STS							
Duration (s)	1.74 ± 0.33	1.59 ± 0.31	8.8%	0.30	$t = 2.625$ (df = 25)	0.015[*]	−0.51
Maximal acceleration (m/s^2)	11.86 ± 0.77	12.04 ± 0.66	1.5%	0.75	$t = -1.192$ (df = 25)	0.245	0.23
Maximal jerk (m/s^3)	12.26 ± 4.82	13.62 ± 5.25	11.1%	4.66	$t = -1.484$ (df = 25)	0.150	0.29
Maximal velocity (m/s)	0.70 ± 0.19	0.78 ± 0.16	11.3%	0.15	$t = -2.747$ (df = 25)	0.011[*]	0.54
Peak power (W)	585.5 ± 221.7	645.3 ± 187.3	10.2%	137.0	$t = -2.227$ (df = 25)	0.035[*]	0.44
Standard clinical tests							
Normal Timed Up and Go (s)	10.94 ± 2.42	10.44 ± 2.51	4.6%	1.18	$t = 2.176$ (df = 25)	0.039[*]	−0.43
Fast Timed Up and Go (s)	9.29 ± 2.44	8.77 ± 2.48	5.6%	0.84	$z = -2.731$ ($n = 26$)	0.006[*]	−0.61
Berg Balance Scale	50.8 ± 3.6	51.7 ± 4.0	1.9%	2.1	$z = 2.211$ ($n = 26$)	0.027[*]	0.47
Quadriceps strength 90° (Nm)[b,c]	75.60 ± 25.19	79.55 ± 22.66	5.2%	9.47	$t = -2.083$ (df = 24)	0.048[*]	0.42
Quadriceps strength 40° (Nm)[b,d]	73.38 ± 24.50	75.83 ± 22.33	3.3%	11.15	$z = 1.400$ ($n = 24$)	0.162	0.22

[a] Two-tailed *p*-value.
[b] Average isometric quadriceps strength of left and right leg are reported for 90° and 40° knee flexion.
[c] Based on 25 subjects.
[d] Based on 24 subjects.
[*] $p < 0.05$: indicating a significant effect.

All normal STS measures showed a significant improvement (Table 1). Improvements ranged from 1.9% (maximal acceleration) to 19.2% (peak power). The absolute SRM's ranged from 0.46 (maximal jerk) to 0.77 (duration).

All fast STS measures demonstrated a significant improvement, except maximal acceleration and maximal jerk (Table 1). Significant improvements ranged from 8.8% (duration) to 11.3% (maximal velocity). The absolute SRM's ranged from 0.23 (maximal acceleration) to 0.54 (maximal velocity).

3.2. *Standard clinical measures*

Not all participants performed all standard clinical tests. One participant was not able to perform the quadriceps strength tests. Another participant was not able to perform the quadriceps strength test with the left leg at 40° knee flexion during the post-intervention measurement.

All standard clinical measures showed a significant improvement, except quadriceps strength at 40° knee flexion (Table 1). Improvements ranged from 1.9% (BBS) to 5.6% (fast TUG). Absolute SRM's ranged from 0.22 (quadriceps strength 40°) to 0.61 (fast TUG).

4. Discussion

This study investigated whether sensor-based STS peak power and related measures can be used to detect changes in mobility and fall risk over time. Training leg strength, leg power and balance can improve mobility and reduce fall risk [7,8]. Therefore, sensitivity of sensor-based STS measures to the effects of training leg strength, leg power and balance was investigated in older adults. Furthermore, sensitivity to the effects of training leg strength, leg power and balance was compared between sensor-based STS measures and standard clinical measures of leg strength, leg power, balance, mobility and fall risk. Results demonstrated significant improvements of the exercise program on almost all sensor-based STS measures and standard clinical measures. Absolute SRM's of sensor-based STS measures ranged from 0.23 (small) to 0.77 (moderate). Absolute SRM's of standard clinical measures ranged from 0.22 (small) to 0.61 (moderate). Thus, sensor-based STS measures showed larger intervention effects than standard clinical measures and are therefore more sensitive to the effects of training leg strength, leg power and balance.

Sensor-based peak power, duration and maximal velocity demonstrated higher sensitivity to change than maximal acceleration and maximal jerk. Other studies also showed that STS duration measures are sensitive to effects of strength training in older adults [12,21]. Maximal velocity improved much more than maximal acceleration (which reflects muscle strength). This suggests that the improvements in STS performance were primarily due to improved coordination. Peak power was calculated based upon velocity and acceleration, and therefore showed a sensitivity to change smaller than maximal velocity but larger than maximal acceleration. While the mean improvement of maximal jerk was large, the standard deviation of change (reflecting inter-individual variability in intervention effects) was also large leading to relatively small SRM values for maximal jerk.

All sensor-based STS measures demonstrated higher sensitivity to change during normal STS than during fast STS. Average fast STS duration during the post-intervention measurement (1.59 s) was in the range of young adult's natural STS duration as determined with the same sensor-based method [3]. Therefore, the smaller improvements in fast STS performance compared to normal STS performance may indicate the limits of possible improvements in older adults by training. Since normal STS performance does not require maximal physical exertion, it has more potential to improve during an exercise program. Thus, especially sensor-based measurement of peak power, maximal velocity and duration of normal STS are sensitive to the effects of training leg strength, leg power and balance in older adults.

The improvements in standard clinical tests in the present study were small compared to findings of other studies of similar exercise interventions [22,23]. However, almost all standard clinical tests showed consistent and significant improvements. This strongly suggests that the relatively small changes in standard clinical tests were meaningful improvements. Several study limitations may explain that our results only indicate small improvements. First, to maximize adherence of the participants to the exercise program, the duration of the exercise intervention was limited to only eight weeks. Strength, balance and mobility improvements are possible after an exercise intervention of eight weeks [22]. However, longer intervention duration may be necessary to demonstrate greater improvements [7]. Second, adherence to the home exercises was not evaluated. Third, participants already had a relatively high performance level at the start of the intervention and therefore they had less potential to improve. For example, the average normal TUG performance was 10.94 s during the pre-intervention measurement, indicating a relatively good mobility performance [24].

Given the small intervention effects on usual clinical tests, the larger sensitivity to change of the reported sensor-based results needs to be carefully evaluated. A number of observations suggest that the improvements in STS measures were meaningful changes. First, improvements were consistent, since almost all sensor-based STS measures improved. Furthermore, the pre-intervention measurements of fast STS performance clearly indicated higher peak powers and shorter STS durations than during normal STS performance. The post-intervention measurements of normal STS performance demonstrated a substantial shift toward the pre-intervention values for fast STS performance. In addition, fast STS performance showed a significant improvement after the intervention. These observations indicate an overall consistency of our results, as well as a significant improvement toward overall faster STS performances. These considerations suggest that the observed improvements on measures of STS performance indicate meaningful changes.

In this study STS performance was assessed during standardized conditions. However, it may be possible to obtain similar results in daily life conditions, because sensor-based methods currently used for assessment of mobility and physical activity in daily life [25] are also suitable for assessment of STS peak power and related measures. Therefore, future research should include STS peak power and related measures in daily life assessments.

A limitation of the presented sensor-based method was the difficulty to determine the start and end of three specific STS trials, which were therefore excluded from further analysis. The vertical acceleration data of these three STS trials showed repeated accelerations and decelerations before initiation and completion of the STS transfer. Future research should investigate ways to circumvent these problems by designing appropriate algorithms. It should be noted that sensor-based power estimates may have some inaccuracy depending on the motion between the trunk and other body segments, and that it cannot indicate whether leg power production during STS is distributed symmetrically over both legs. An additional limitation is that the clinical relevance of increased maximal jerk is not yet clear. A notable finding of this study was that in this population, quadriceps strength did not really change with increasing knee angle, which stands in contrast to findings of a previous study in healthy young adults [15].

In conclusion, this study demonstrated that sensor-based STS peak power and related measures have a higher sensitivity to detect effects of training leg strength, leg power and balance than standard clinical measures of leg strength, leg power, balance, mobility and fall risk. Therefore, the sensor-based approach appears to be useful for detecting changes in mobility and fall risk over time. Test–retest reliability of the presented sensor-based method needs to be investigated. For that reason, studies investigating test–retest reliability of the sensor-based STS measures are in progress, as well as studies that include STS measures in sensor-based daily life assessments.

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Conflict of interest statement

The authors have no conflicts of interest.

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