Aging Clinical and Experimental Research (2020) 32:491–503
https://doi.org/10.1007/s40520-019-01395-0

ORIGINAL ARTICLE

Robotic balance assessment in community-dwelling older people with different grades of impairment of physical performance

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Received: 3 May 2019 / Accepted: 19 October 2019 / Published online: 5 November 2019

Abstract

Background Impaired physical performance is common in older adults and has been identified as a major risk factor for falls. To date, there are no conclusive data on the impairment of balance parameters in older subjects with different levels of physical performance.

Aims The aim of this study was to investigate the relationship between different grades of physical performance, as assessed by the Short Physical Performance Battery (SPPB), and the multidimensional balance control parameters, as measured by means of a robotic system, in community-dwelling older adults.

Methods This study enrolled subjects aged ≥ 65 years. Balance parameters were assessed by the *hunova* robot in static and dynamic (unstable and perturbating) conditions, in both standing and seated positions and with the eyes open/closed.

Results The study population consisted of 96 subjects (62 females, mean age 77.2 ± 6.5 years). According to their SPPB scores, subjects were separated into poor performers (SPPB < 8, *n* = 29), intermediate performers (SPPB = 8–9, *n* = 29) and good performers (SPPB > 9, *n* = 38). Poor performers displayed significantly worse balance control, showing impaired trunk control in most of the standing and sitting balance tests, especially in dynamic (both with unstable and perturbating platform/seat) conditions.

Conclusions For the first time, multidimensional balance parameters, as detected by the *hunova* robotic system, were significantly correlated with SPPB functional performances in community-dwelling older subjects. In addition, balance parameters in dynamic conditions proved to be more sensitive in detecting balance impairments than static tests.

Keywords Physical function · Physical performance · Balance · Assessment · Robotic device

Introduction

Each year, approximately 30% of adults aged > 65 years and 50% of adults aged > 80 suffer falls, which may result in injuries (with or without fractures), hospitalization, reduced mobility, loss of independence, and even death [1]. Several age-related factors increase the risk of falling, such as impaired physical function, gait and balance deficits, visual impairments, cognitive deterioration, depression and chronic diseases [1].

Among these factors, physical function is a multidimensional concept that includes mobility, dexterity, axial ability and ability to carry out instrumental activities of daily living, usually evaluated by physical performance tests [2]. The Short Physical Performance Battery (SPPB) is one of the tests most frequently used to examine several aspects of

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physical performance [3]. Clinical studies have suggested that SPPB could be used to initially screen older subjects for the risk of falls [4–7]. Together with impaired physical function, balance deficits have been identified as a major risk factor for falls [1]. The control of balance relies on the complex integration of information from the somatosensory, vestibular and visual systems, which work together with the nervous–muscular system to maintain an upright posture over a base of support (static balance) or to maintain stability during walking (dynamic balance) [8]. A comprehensive clinical assessment of balance is important in order to evaluate fall-risk, and ordinal scales are the most commonly applied tools to assess balance in clinical practice [9]. To date, however, there is no agreed-upon comprehensive, satisfactory diagnostic procedure for ascertaining balance control in the elderly, and traditional balance measures are limited by subjectivity in scoring [10–12]. Technology-based solutions can provide more sensitive, specific and responsive balance monitoring [13]. In particular, posturography parameters have been used in several studies, and their validity and reliability in evaluating elderly patients has been proved [14–16]. Sway parameters are reported to be greater in elderly subjects [17–19], and several studies have described their use in predicting falls [20] or in distinguishing “non-fallers” from “fallers” [20, 21]. Moreover, several studies have investigated the correlation between static posturography parameters and clinical outcome in elderly people [22–24].

However, stabilometric tests allow us only to evaluate the components of static balance and, while subjects may not exhibit abnormal oscillations when simply standing on a static surface, they may show different performances when challenged with perturbations of equilibrium [25].

Hunova is a new robotic device developed by the Italian Institute of Technology (IIT, Genoa, Italy; now commercialized by Movendo Technology, Genoa, Italy) that enables the evaluation of traditional stabilometric parameters and allows the implementation of different dynamic environments that stimulate postural responses. Given that both impaired physical function and balance deficits contribute to increasing the risk of falling, the aim of this study was to investigate the complex relationship between these factors. Specifically, balance parameters were measured by the *hunova* robot in community-dwelling older adults with different levels of physical performance, as assessed by the SPPB.

Subjects and methods

Subjects

Subjects consecutively admitted in a 6-month period to the outpatient clinic of the ‘Geriatric Care, Orthogeriatrics and Rehabilitation Department’ of Galliera Hospital (Genoa, Italy) were screened to participate in this study. The following inclusion criteria were applied: age ≥ 65 years (both males and females), normal or slightly impaired cognitive function (at least 6/10 correct answers in the Short Portable Mental Status Questionnaire [26]). Exclusion criteria were: speech and/or aphasia disorders, moderate–severe cognitive impairment or dementia, presence of severe heart disease or respiratory failure, presence of a degenerative neurological disease (e.g., Parkinson’s disease, multiple sclerosis), life expectancy less than 6 months, non-femoral bone fracture in the previous 6 months or femoral fracture in the 12 months prior to enrolment.

The study conformed to the ethical standards laid down in the 1964 Declaration of Helsinki, which protects research subjects, and was approved by the ethics committee of the regional health authority (reference number: 169REG2016). All subjects included in the study signed the informed consent form according to these guidelines.

Clinical evaluation

Short Physical Performance Battery

The SPPB [3] is a scale that explores the reduction of physical performance in older persons. It consists of three motor tests (balance, five timed chair stands, and a gait-speed measurement) that provide information on several motor domains, such as static and dynamic balance, coordination, and strength of lower limbs. The SPPB test consists of three tasks: a hierarchical assessment of standing balance, a short walk at the usual elderly pace, and standing five times from a seated position in a chair. Each task has a maximum score of 4. To test balance, participants were asked to stand with their feet side-by-side, in a semi-tandem position, and in a tandem position. Balance was scored on an ordinal scale: for the first two positions, a score of 0 (position held for less than 10 s) or 1 (position held for 10 s) was assigned; for the third position, the maximum score was 2 (position held for 10 s), while 1 and 0 were assigned if the subject maintained the position for 3–10 s and for less than 3 s, respectively.

To assess gait speed, the participants were asked to walk 4 m at their normal speed; this test was performed twice and the shorter time was recorded. According to the speed, a score from 0 to 4 was assigned.

To test standing from a chair, participants were asked to sit on a chair, with arms crossed over the chest, and then to stand up and sit down again five times as quickly as they could. The number of repetitions completed and the time taken were recorded and converted into an ordinal score. The final score is the sum of the ordinal scores of the three tasks, the maximum score being 12. According to their SPPB score, subjects were divided into three groups: low

(SPPB score < 8), medium (SPPB score = 8–9) and high (SPPB score > 9) physical performance.

Robotic device

Hunova ([27–29]) is a robotic device for the functional sensory–motor evaluation and rehabilitation of the ankle, lower limbs and trunk. *Hunova* is a commercial, CE-marked device, consisting of two electromechanical and sensorized platforms with two degrees of freedom (forwards/backwards and left/right), one at foot level and one at seat level (Fig. 1). The two robotic platforms allow subjects to be evaluated and trained in both standing and sitting positions. The device operates in conjunction with a wireless 9-axis sensor (Inertial Movement Unit—IMU, including accelerometer, gyroscope and magnetometer, which is a part of the device and is certified with the full system) located on the subject's torso, to monitor trunk movements. The exercises are accompanied by graphic and audio feedback (for technical details see [27–29]).

The device can work in both static (no movement of the platforms) and dynamic modes (movements of the platforms). Indeed, thanks to its robotic modules, the device can control both the movement of the platform/seat, in order to induce continuous or random movements, thereby causing perturbation to the subject, and the resistance of the platform to the subject's movements.

Specifically, we differentiate between two different operating conditions: the passive and the active modes. In the passive mode, the system controls the speed and interaction with the subject (force and torque). In this modality, the movements of the platform do not depend on the subject; they are totally controlled by the system and the subject has to react to these movements. In the active mode, the subject controls the movement of the platform, and the platform can exert a certain resistance to the subject's movement.

Robotic evaluation

During the robotic evaluations, subjects had to keep still and maintain their balance in different positions and conditions. Subjects were tested in two different positions (sitting and standing) and in four different conditions (static, dynamic unstable, dynamic perturbating—with continuous or random perturbation), in a single evaluation session.

The tests performed in the standing position were aimed at investigating balance capability in static and dynamic—i.e., not static—situations [25–30], by providing different environments that could challenge reactive and anticipatory postural response and postural adjustment (unstable platform, continuous perturbating platform, random perturbating platform). The test involving the unstable platform was performed in order to test the use of somatosensory feedback [31]; the test with the continuous or random perturbating platform was performed to test the ability to react to perturbation that was not controlled by the subject [32, 33].

The tests performed in the sitting position are designed to investigate balance capability in the sitting position, which is related to trunk control and core stability [34].

When possible, i.e., when it was considered safe for the subjects (standing static condition and all the conditions in the sitting position), the test was performed with the eyes closed, in order to test proprioception [25, 35].

Some of these tests have already been used to characterize postural control strategies in patients with Parkinson's disease [36].

In detail, the following tests were carried out:

1. Balance on static platform (*STATIC*) tested subject's static stability, i.e., the ability to maintain the position of the center of mass in unsupported stand when the base of support does not change [10].

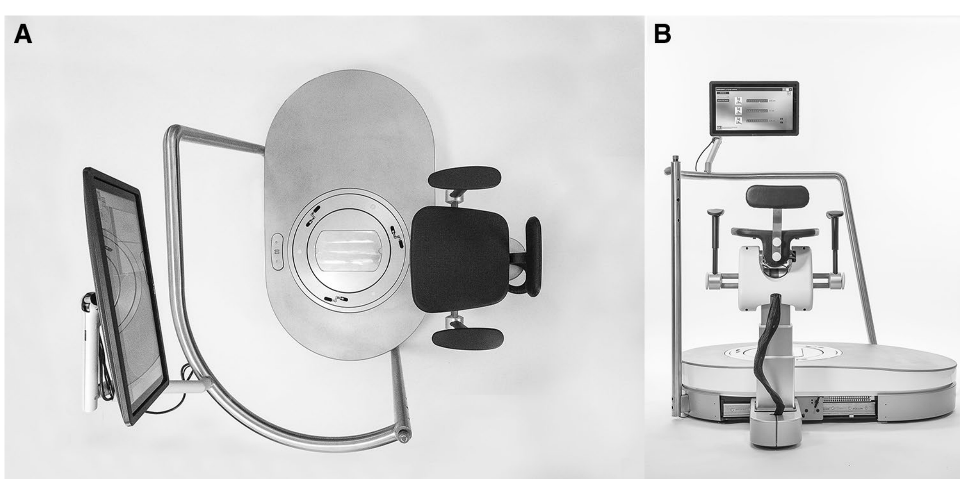

Fig. 1 *Hunova* robot. *Hunova* device is shown from above (**a**) and from behind (**b**)

The test lasted 30 s and was carried out with open (OE) and closed eyes (CE) in the sitting and standing positions.

2. Balance on dynamic unstable platform *(UNSTABLE*) estimated the subject's stability in a non-static situation in which the movement of the platform depends on the subject's movement (active modality). The test lasted 30 s and was carried out with OE and CE only during the sitting evaluation.
3. Balance on dynamic perturbating platform. This test evaluated the reactive postural control component of balance, defined as the ability to recover stability after an external perturbation. Two different perturbative tests were performed:

    3.1 Balance on continuous perturbating platform (*CONTINUOUS PERTURBATING*), in which the platform movements follow a circular default trajectory (see Fig. 2c). This test lasted 30 s and was run with OE and with CE only during the sitting evaluation.

    3.2 Balance on random perturbating platform (*RANDOM PERTURBATING*), in which the platform generates random perturbation with impulses of 6 degrees in different directions (forward, left, right, Fig. 2a, b). Three perturbations in each direction were provided in random order. The timing of the perturbation was variable. The duration of the evaluation was between 60 s and 90 s. This evaluation was run only in the standing position and with OE. The experimental setup and patient position for this test are reported in Fig. 2a.

The different conditions tested are summarized in Table 1.

The experimental procedure followed the same order in all subjects: standing static, standing dynamic unstable, standing dynamic continuous perturbating, standing dynamic random perturbating, sitting static, sitting dynamic unstable and sitting dynamic perturbating.

Robotic balance parameters

During the robotic tests, we recorded data from the platforms (seat or base) and from the trunk sensor. In order to estimate the balance performances, several indicators were evaluated.

Regarding the platform, the following parameters were assessed:

- *Sway area* (*SA*) The area of the 95% confidence ellipse of the statokinesigram of the center of pressure (CoP) (in standing static condition [cm^2]) or of the load shift, i.e., the torque signal divided by the subject's weight (in seated static condition [cm^2]) or of the projection of the angular displacement of the platform (in stand-

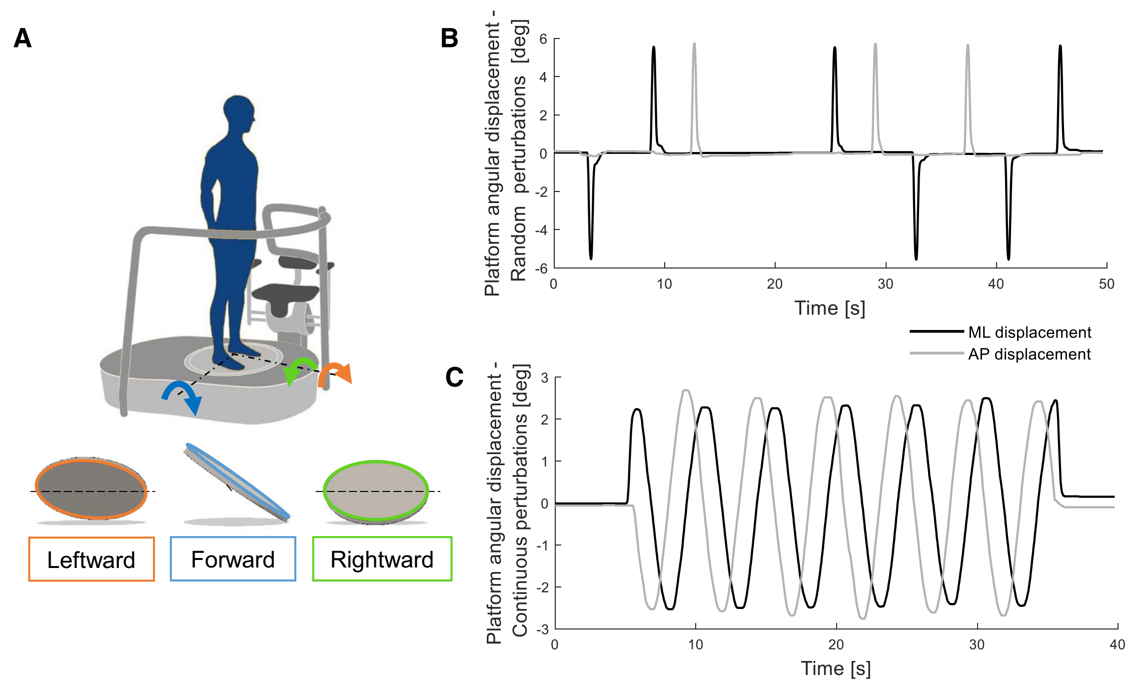

Fig. 2 Experimental setup for the perturbative tasks. **a** Standing patient's position on *hunova* and reference system; platform's inclinations for the random perturbating test. **b** Mediolateral (X axis) and anteroposterior (Y axis) angular displacement vs time for the platform in the random perturbating task. **c** Mediolateral (X axis) and anteroposterior (Y axis) angular displacement vs time for the platform in the continuous perturbating task

Table 1 Robotic evaluation

Static		Unstable		Continuous perturbating		Random perturbating
OE	CE	OE	CE	OE	CE	OE
Standing position						
✓	✓	✓		✓		✓
Sitting position						
✓	✓	✓	✓	✓	✓	

Conditions tested by *hunova*

OE open eyes, *CE* closed eyes

ing and seated dynamic unstable condition [cm^2]). The 95% confidence ellipse can be defined as the surface that contains (with 95% probability) the individual points that make up the statokinesigram.
- *Sway path* (*SP*) The measure of the length of the oscillation path of the CoP (in standing static condition, [cm]), or of the load shift (in seated static condition, [cm]) or of the projection of the angular displacement of the platform (in standing and seated dynamic unstable condition [cm].
- Anterior–posterior and mediolateral range of oscillation (APO and MLO, respectively) of the CoP (in standing static condition, [cm]) or of the load shift (in seated static condition [cm]) or of the projection of the angular displacement of the platform (in standing and seated dynamic unstable conditions [cm]).

These indicators are proportional to the instability of the subjects: the greater the values, the lesser the subject's ability to maintain balance [22, 37].

The following parameters were assessed for the trunk:

- Anterior–posterior and mediolateral range of oscillation (APO_{trunk} and MLO_{trunk}, respectively) of the trunk. These indicators evaluate the degrees of oscillation in the anterior–posterior or mediolateral directions. In the *random perturbating* condition, the oscillation range in the mediolateral and anteroposterior directions was computed after each perturbation in each direction. Mean values for each direction and the mean value between directions were considered. These indicators provide information on the trunk compensations and trunk control strategies required to maintain balance.
- *Trunk variability* (*VA*) is the standard deviation of the trunk accelerations measured by the IMU; it is a measure of the extent of movements of the trunk during the task.

Data analysis and statistics

Main descriptive statistics were mean, standard deviation, median and interquartile range (IQR) for quantitative parameters; qualitative factors were summarized by using absolute and relative frequencies.

According to their SPPB scores, participants were separated into three groups: poor performers ($n = 29$), intermediate performers ($n = 29$), good performers ($n = 38$). Differences between clinical characteristics across SPPB-ordered groups were evaluated by means of ANOVA (for continuous variables) and the χ^2 test (for categorical variables).

In order to adjust the analyses for the age of subjects and to test the linear association between SPPB score and balance parameters, we used linear regression modeling. We ran one linear model for each specific situation, setting the balance parameter as the dependent factor and the SPPB score as the independent (continuous) variable, on adjusting for age. We checked the normality of each parameter visually and, in the case of non-Gaussian or skewed distribution, we applied the best transformation (logarithm and square root were the most frequently applied) in order to obtain normality. All p values were two-tailed and statistical significance was defined by alpha error < 0.05. Owing to the exploratory nature of the study (pilot), no multiple testing correction techniques were applied. All data analyses were performed by means of MATLAB (MathWorks, Natick, MA, USA) and STATA (StataCorp. 2015. Stata Statistical Software: Release 14. College Station, TX: StataCorp LP).

Results

During the study period, 100 subjects fulfilled the inclusion criteria and were enrolled in the study. After inclusion, four subjects dropped out from the study owing to difficulties in attending the scheduled visits. The study population consisted of 96 older subjects (34 males and 62 females), with a mean

Table 2 Baseline demographic and clinical characteristics of the study sample ($n=96$)

Characteristics	All subjects	SPPB < 8 $n=29$ (30.2%)	SPPB = 8–9 $n=29$ (30.2%)	SPPB > 9 $n=38$ (39.6%)	p value
Age (years)	77.2 ± 6.5	82.6 ± 5.0	75.4 ± 6.2	74.4 ± 5.2	$p<0.001$
Gender					
Male	34 (35.4%)	10 (34.5%)	13 (44.8%)	11 (28.9%)	$p=0.287$
Female	62 (64.6%)	19 (65.5%)	16 (55.2%)	27 (71.0%)	
BMI (kg/m^2)	26.4 ± 4.6	26.5 ± 5.1	27.1 ± 4.0	25.9 ± 4.6	$p=0.579$

Values are expressed as mean ± standard deviation or number (%)

BMI body mass index, *SPPB* Short Physical Performance Battery

age of 77.2 ± 6.5 years. The characteristics of the participants are summarized in Table 2. Interestingly, there was a statistically significant association between SPPB score and age.

Tables 3 and 4 show the balance parameters recorded by the *hunova* device from the platform and the trunk sensors, respectively, for each group in the standing position.

Subjects with a lower SPPB score performed worse than those with a higher SPPB score, showing impaired trunk control in most of the standing balance tests, especially in dynamic conditions. Indeed, significant associations with SPPB score were observed between all balance parameters assessed by the trunk sensor in unstable (APO_{trunk}: $p=0.002$, MLO_{trunk}: $p=0.001$, VA: $p=0.003$) and perturbating conditions, both with continuous (APO_{trunk}: $p=0.04$, MLO_{trunk}: $p=0.01$, VA: $p=0.01$) and random (APO_{trunk}: $p=0.003$, MLO_{trunk}: $p=0.01$) perturbation, with OE (see Table 4 and Fig. 3). Subjects with lower SPPB scores also showed worse balance control in the only condition tested with CE in the standing position: indeed, in the static condition with CE, SA ($p=0.02$) and MLO ($p=0.009$) were more impaired in poor performers (Table 3) as was trunk control (MLO_{trunk}: $p=0.009$; VA: $p=0.03$, Table 4). In the seated position, subjects with lower SPPB had the worst control when seated on an unstable seat with OE (SA: $p=0.01$; MLO: $p=0.01$; SP: $p=0.003$), and the worst trunk control when seated on an unstable (OE: APO_{trunk}: $p=0.03$; VA: $p=0.01$; CE: APO_{trunk}: $p=0.01$; VA: $p=0.004$) or perturbating seat (OE: APO_{trunk}: $p=0.002$; MLO_{trunk}: $p=0.03$; VA: $p<0.001$; CE: APO_{trunk} $p<0.001$; MLO_{trunk} $p=0.006$; VA: $p<0.001$) both with OE and with CE (see Tables 5 and 6).

No associations were observed between SPPB score and any of the balance parameters in the seated position with a static platform, except for a difference in anteroposterior control with CE (APO: $p=0.02$) (Table 5).

Discussion

Age-related changes in physical performance have consistently been documented. The phenomenon is associated with the accumulation of deficits across multiple physiological components of balance, such as sensory (vibration, proprioception, vision, vestibular), effector (ankle, knee, hip strength, range of motion), and central processing (response time to perturbations) [38]. Consequently, a practical approach to identifying elderly people at high risk of falls is to assess, apart from the history of a previous fall, the presence of limited mobility and impaired physical functioning [39]. It is well known that balance disorders are also associated with recurrent falls in elderly people [40, 41] and that abnormal control of balance and lower-limb muscle strength are strictly associated [42]. Specifically, several studies have shown that lower-limb physical performance tests are able to predict falls in the elderly, including traumatic falls and those complicated by femoral fracture [43–45]. Furthermore, a clear correlation between clinical tests of lower-limb strength and balance measurements derived from instrumental assessments has recently been documented [46]. Given this correlation between physical performance of the lower limbs and fall-risk, our goal was to determine whether our new robotic platform was able to show different postural control profiles according to the different physical performance profiles measured by means of the SPPB. This first step will enable us to conduct further studies to assess whether the different postural profiles identified by the robotic platform can provide information on a given individual's risk of falling. The results of the present study highlight the correlation between performance levels, as assessed by the SPPB, and impairments of balance control. This correlation increases when the subject's balance is perturbed by unstable conditions imposed by the robot (in standing position: in static condition with CE, in dynamic or perturbating conditions; in seated condition: in dynamic or perturbating conditions), indicating that reduced physical performance can diminish the ability to recover from dynamic instabilities.

Moreover, our data show that the ineffective balance response in demanding environments is counterbalanced by increased oscillations of the trunk. Indeed, the differences in parameters assessed by the trunk sensor between subjects with different SPPB scores were greater in dynamic

Table 3 Balance parameters for SPPB classes, standing position

	Parameters	SPPB classes	Standing position			
			Static	Dynamic		
				Unstable	Continuos perturbating	Random perturbating
			Median (IQR 25–75%)	Median (IQR 25–75%)	Median (IQR 25–75%)	Median (mean between directions) (IQR 25–75%)
Platform data (OE)	Sway area [cm^2]	SPPB < 8 SPPB = 8–9 SPPB > 9	2.61 (1.60–4.85) 1.57 (0.81–3.19) 1.39 (0.66–2.88) *p = 0.190*	94.01 (48.11–141.69) 71.53 (28.62–132.00) 36.50 (17.63–83.28) *p = 0.438*	n.a.	n.a.
	Oscillation range—AP [cm]	SPPB < 8 SPPB = 8–9 SPPB > 9	1.81 (1.24–2.18) 1.48 (0.97–2.00) 1.36 (1.06–1.95) *p = 0.556*	7.54 (5.77–9.90) 7.21 (5.02–9.87) 6.36 (4.16–7.89) *p = 0.431*	n.a.	n.a.
	Oscillation range—ML [cm]	SPPB < 8 SPPB = 8–9 SPPB > 9	1.95 (1.28–2.99) 1.36 (1.06–1.87) 1.07 (0.80–1.89) *p = 0.073*	11.69 (8.09–16.91) 8.52 (6.67–12.82) 6.30 (4.88–10.91) *p = 0.270*	n.a.	n.a.
	Sway path [cm]	SPPB < 8 SPPB = 8–9 SPPB > 9	16.67 (11.30–20.67) 14.37 (10.30–17.25) 12.76 (9.89–17.18) *p = 0.366*	65.37 (41.65–88.14) 59.18 (37.46–80.80) 43.83 (27.63–60.86) *p = 0.756*	n.a.	n.a.
Platform data (CE)	Sway area [cm^2]	SPPB < 8 SPPB = 8–9 SPPB > 9	4.36 (2.02–8.99) 3.45 (1.87–9.04) 2.14 (1.28–3.78) ***p = 0.029***	n.a.	n.a.	n.a.
	Oscillation range—AP [cm]	SPPB < 8 SPPB = 8–9 SPPB > 9	2.51 (1.78–3.29) 2.39 (1.89–3.89) 1.76 (1.48–2.91) *p = 0.131*	n.a.	n.a.	n.a.
	Oscillation range—ML [cm]	SPPB < 8 SPPB = 8–9 SPPB > 9	2.24 (1.27–3.95) 1.70 (1.21–3.51) 1.58 (1.06–2.24) ***p = 0.017***	n.a.	n.a.	n.a.
	Sway path [cm]	SPPB < 8 SPPB = 8–9 SPPB > 9	20.89 (15.67–40.90) 21.24 (15.04–29.45) 17.90 (15.04–23.57) *p = 0.135*	n.a.	n.a.	n.a.

Data from platform sensors

p values are related to the SPPB parameter estimates from the linear regression models, adjusting for age; in bold *p* values < 0.05

n.a. not available, *SPPB* Short Physical Performance Battery, *OE* open eyes, *CE* closed eyes

and perturbating conditions than in static conditions (both with OE and CE).

Several studies have already reported that dynamic situations that challenge a subject's balance can be more effective in detecting balance deficits and their correlation with physical impairments [25, 47]. Dynamic reaction to perturbation, in both standing and sitting positions, requires trunk control and muscle strength, and these

Table 4 Balance parameters for SPPB classes, standing position

	Parameters	SPPB classes	Standing position			
			Static	Dynamic		
				Unstable	Continuos perturbating	Random perturbating
			Median (IQR 25–75%)	Median (IQR 25–75%)	Median (IQR 25–75%)	Median (mean between directions) (IQR 25–75%)
Trunk data (OE)	Oscillation range—AP [°]	SPPB < 8 SPPB = 8–9 SPPB > 9	3.02 (2.44–3.74) 2.46 (1.92–3.35) 2.59 (2.08–3.23) *p = 0.177*	6.85 (5.18–10.53) 5.90 (4.21–7.71) 4.15 (3.34–5.16) ***p = 0.002***	9.50 (7.67–11.17) 7.36 (5.63–10.29) 6.28 (4.63–7.98) ***p = 0.040***	8.40 (5.83–9.46) 6.20 (4.46–7.06) 6.21 (4.39–8.07) ***p = 0.003***
	Oscillation range—ML [°]	SPPB < 8 SPPB = 8–9 SPPB > 9	2.05 (1.59–2.62) 1.42 (1.01–2.15) 1.24 (1.05–1.85) ***p = 0.010***	8.09 (6.39–13.25) 6.22 (3.80–9.50) 4.55 (3.21–5.53) ***p = 0.001***	8.55 (6.69–10.39) 5.89 (4.93–8.20) 5.46 (4.35–7.49) ***p = 0.014***	7.76 (6.53–9.77) 6.40 (5.30–7.66) 6.66 (5.71–8.01) ***p = 0.011***
	Variability [°/s^2]	SPPB < 8 SPPB = 8–9 SPPB > 9	0.04 (0.03–0.06) 0.036 (0.03–0.04) 0.04 (0.03–0.05) *p = 0.089*	0.09 (0.08–0.12) 0.08 (0.07–0.11) 0.06 (0.05–0.08) ***p = 0.003***	0.11 (0.09–0.15) 0.09 (0.07–0.12) 0.08 (0.07–0.12) ***p = 0.018***	n.a.
Trunk data (CE)	Oscillation range—AP [°]	SPPB < 8 SPPB = 8–9 SPPB > 9	3.05 (2.20–5.32) 2.81 (2.23–4.15) 2.92 (2.24–3.84) *p = 0.077*	n.a.	n.a.	n.a.
	Oscillation range—ML [°]	SPPB < 8 SPPB = 8–9 SPPB > 9	2.38 (1.37–4.00) 1.70 (0.97–2.58) 1.46 (1.07–1.96) ***p = 0.009***	n.a.	n.a.	n.a.
	Variability [°/s^2]	SPPB < 8 SPPB = 8–9 SPPB > 9	0.048 (0.037–0.063) 0.042 (0.036–0.051 0.043 (0.033–0.051) ***p = 0.039***	n.a.	n.a.	n.a.

Data from trunk sensor

p values are related to the SPPB parameter estimates from the linear regression models, adjusting for age; in bold *p* values < 0.05

n.a. not available, *SPPB* Short Physical Performance Battery, *OE* open eyes, *CE* closed eyes

aspects can be correlated with physical performance [48, 49].

Core strengthening can improve trunk control, postural alignment and balance in the elderly [48], and previous studies have shown a correlation between trunk muscle strength and balance and functional mobility, as measured by the SPPB in community-dwelling older adults [49]. Moreover, trunk extensor endurance has recently been identified as one of the main targets of motor rehabilitation in the elderly, together with the functionality of the lower limbs [50].

The present study confirms that the application of new technologies to the analysis of human movements constitutes an important adjunct to traditional clinical tests, and helps to provide an objective, precise and complete assessment of balance. Indeed, most validated standardized tools for assessing balance in adults include subjective assessment and analyze only a few components of balance [10]. So far, several new technological devices have been utilized to integrate traditional rating tools [51] or to examine the relationship between physical function and balance components [52]. Static posturography has been used in several studies to evaluate balance performance in the elderly [14–16], which have reported increasing instability with age [17–19] and a greater risk of falls [20, 21]. However, while such instrumented tools successfully provide more objective evaluations, they do not investigate the various components of balance.

The device used in this study, *hunova*, provides more objective measures of balance and balance evaluation in various conditions, such as the dynamic perturbative environment.

Although this research on the use of a robotic platform can be considered a pilot study, it is important to highlight the validity and relevance of this new and comprehensive evaluation of balance in the elderly. It would be interesting to carry out comparative studies of the parameters assessed

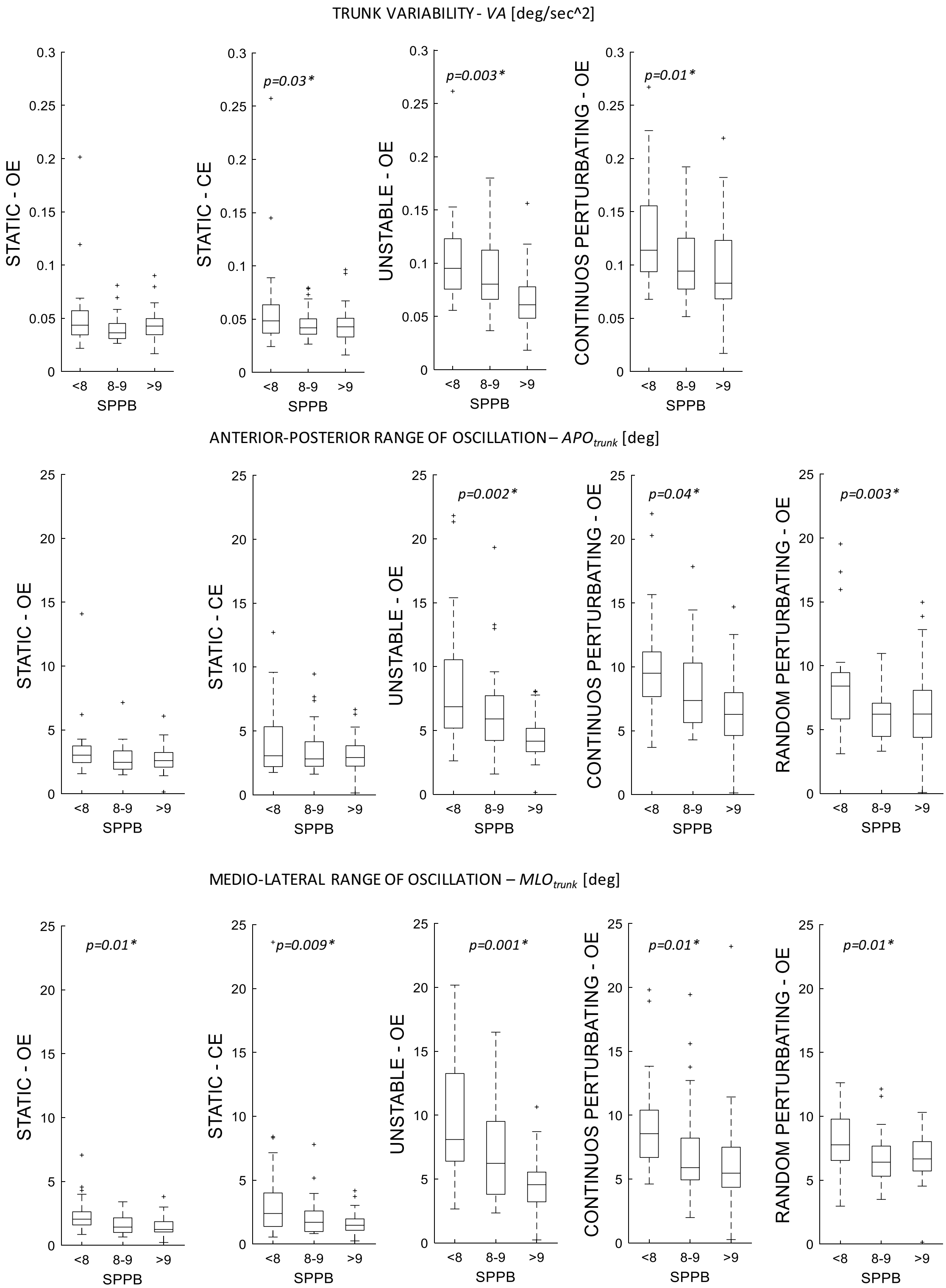

Fig. 3 Balance parameters assessed from the trunk in subjects with different levels of SPPB score. Box- and whisker-plots show comparison of three balance parameters assessed in standing position (static, unstable and dynamic conditions), in subjects with different levels of SPPB score. *SPPB* Short Physical Performance Battery, *OE* open eyes, *CE* closed eyes. *p* values are related to the SPPB parameter estimates from the linear regression models, adjusting for age

Table 5 Balance parameters for SPPB classes, seated position

	Parameters	SPPB classes	Seated position			
			Static	Dynamic		
				Unstable	Continuos perturbating	Random perturbating
			Median (IQR 25–75%)	Median (IQR 25–75%)	Median (IQR 25–75%)	Median (mean between directions) (IQR 25–75%)
Platform data (OE)	Sway area [cm^2]	SPPB < 8 SPPB = 8–9 SPPB > 9	0.10 (0.06–0.18) 0.12 (0.07–0.19) 0.10 (0.06–0.18 *p = 0.853*	43.37 (8.72–94.09) 26.45 (3.12–142.32) 13.29 (3.49–61.70) ***p = 0.010***	n.a.	n.a.
	Oscillation range—AP [cm]	SPPB < 8 SPPB = 8–9 SPPB > 9	0.37 (0.31–0.69) 0.45 (0.31–0.79) 0.38 (0.25–0.72) *p = 0.665*	2.68 (1.44–4.50) 3.17 (2.13–5.85) 2.37 (1.12–3.78) *p = 0.096*	n.a.	n.a.
	Oscillation range—ML [cm]	SPPB < 8 SPPB = 8–9 SPPB > 9	0.37 (0.27–0.50) 0.45 (0.33–0.59) 0.42 (0.31–0.58) *p = 0.121*	16.16 (10.09–22.78) 9.04 (3.69–30.75) 13.93 (3.50–19.96) ***p = 0.014***	n.a.	n.a.
	Sway path [cm]	SPPB < 8 SPPB = 8–9 SPPB > 9	3.93 (2.96–5.01) 3.98 (3.01–4.58) 3.61 (2.91–5.12) *p = 0.959*	*43.40 (23.43–71.79)* *28.00 (11.62–63.31)* *26.35 (9.28–43.28)* ***p = 0.003***	n.a.	n.a.
Platform data (CE)	Sway area [cm^2]	SPPB < 8 SPPB = 8–9 SPPB > 9	0.04 (0.03–0.10) 0.04 (0.03–0.08) 0.04 (0.03–0.05) *p = 0.103*	13.77 (4.54–42.58) 10.04 (4.44–46.58) 7.14 (2.25–26.08) *p = 0.219*	n.a.	n.a.
	Oscillation range—AP [cm]	SPPB < 8 SPPB = 8–9 SPPB > 9	0.31 (0.25–0.45) 0.24 (0.18–0.33) 0.24 (0.21–0.31) ***p = 0.020***	1.69 (0.75–4.31) 2.90 (0.99–4.58) 1.94 (0.71–3.23) *p = 0.772*	n.a.	n.a.
	Oscillation range—ML [cm]	SPPB < 8 SPPB = 8–9 SPPB > 9	0.23 (0.20–0.31) 0.29 (0.25–0.35) 0.27 (0.21–0.32) *p = 0.972*	7.55 (5.47–17.14) 7.42 (5.22–15.45) 7.68 (4.40–12.78) *p = 0.214*	n.a.	n.a.
	Sway path [cm]	SPPB < 8 SPPB = 8–9 SPPB > 9	3.41 (2.71–4.07) 3.01 (2.52–3.65) 2.87 (2.42–3.39) *p = 0.083*	21.18 (12.16–42.94) 18.45 (13.47–35.85) 21.56 (11.01–32.23) *p = 0.191*	n.a.	n.a.

Data from seat sensors

p values are related to the SPPB parameter estimates from the linear regression models, adjusting for age; in bold *p* values < 0.05

n.a. not available, *SPPB* Short Physical Performance Battery, *OE* open eyes, *CE* closed eyes

by conventional assessment scales and the data provided by new technologies, in order to implement comprehensive assessments of fall-risk and to develop suitable rehabilitation programs.

Our exploratory study has some limitations. First of all, we did not analyze the potential impact of specific clinical characteristics (polypharmacy, multimorbidity, history of falls, etc.) on SPPB results and probably also on robotic parameters. Secondly, we are aware of the need to validate these correlations between functional and robotic data in prospective studies with relevant clinical outcomes (falls, disability, hospitalization).

Table 6 Balance parameters for SPPB classes, seated position

	Parameters	SPPB classes	Seated position			
			Static	Dynamic		
				Unstable	Continuos perturbating	Random perturbating
			Median (IQR 25–75%)	Median (IQR 25–75%)	Median (IQR 25–75%)	Median (mean between directions) (IQR 25–75%)
Trunk data (OE)	Oscillation range—AP [°]	SPPB < 8	2.91 (2.27–3.70)	5.76 (3.49–12.78)	8.30 (7.26–11.32)	n.a.
		SPPB = 8–9	3.06 (2.10–4.25)	6.33 (3.63–11.06)	8.98 (7.57–10.25)	
		SPPB > 9	2.72 (1.82–4.47)	5.25 (3.70–6.56)	6.14 (5.17–8.17)	
			p = 0.800	***p = 0.033***	***p = 0.002***	
	Oscillation range—ML [°]	SPPB < 8	1.47 (1.10–2.19)	9.24 (5.31–14.78)	10.08 (7.67–14.60)	n.a.
		SPPB = 8–9	1.51 (1.08–2.00)	7.18 (3.55–19.91)	8.63 (6.98–10.77)	
		SPPB > 9	1.69 (0.97–2.37)	5.74 (3.53–10.19)	8.83 (6.53–10.48)	
			p = 0.775	*p = 0.053*	***p = 0.033***	
	Variability [°/s²]	SPPB < 8	0.04 (0.03–0.05)	0.07 (0.05–0.11)	0.09 (0.08–0.12)	n.a.
		SPPB = 8–9	0.04 (0.03–0.05)	0.07 (0.04–0.11)	0.09 (0.07–0.11)	
		SPPB > 9	0.04 (0.03–0.06)	0.06 (0.04–0.09)	0.07 (0.06–0.09)	
			p = 0.964	***p = 0.011***	***p < 0.001***	
Trunk data (CE)	Oscillation range—AP [°]	SPPB < 8	2.11 (1.95–3.22)	5.29 (3.07–8.82)	9.62 (6.94–12.13)	n.a.
		SPPB = 8–9	1.99 (1.39–3.14)	4.15 (3.02–6.86)	6.76 (6.22–9.14)	
		SPPB > 9	1.97 (1.33–2.43)	3.80 (2.43–5.66)	5.89 (4.69–7.23)	
			p = 0.124	***p = 0.014***	***p < 0.001***	
	Oscillation range—ML [°]	SPPB < 8	0.94 (0.66–1.43)	5.11 (3.15–7.55)	10 (8.20–16.03)	n.a.
		SPPB = 8–9	1.09 (0.89–1.66)	5.22 (3.65–7.70)	8.29 (7.13–11.92)	
		SPPB > 9	1.03 (0.74–1.45)	4.51 (3.78–8.46)	8.50 (6.46–10.98)	
			p = 0.319	*p = 0.416*	***p = 0.006***	
	Variability [°/s²]	SPPB < 8	0.03 (0.02–0.04)	0.05 (0.04–0.08)	0.08 (0.07–0.11)	n.a.
		SPPB = 8–9	0.03 (0.03–0.04)	0.05 (0.04–0.07)	0.07 (0.07–0.10)	
		SPPB > 9	0.03 (0.03–0.04)	0.04 (0.04–0.06)	0.06 (0.05–0.08)	
			p = 0.263	***p = 0.004***	***p < 0.001***	

Data from trunk sensor

p values are related to the SPPB parameter estimates from the linear regression models, adjusting for age; in bold *p* values < 0.05

n.a. not available, *SPPB* Short Physical Performance Battery, *OE* open eyes, *CE* closed eyes

Conclusions

In conclusion, our findings show that low SPPB scores are associated with greater difficulty in controlling balance, especially in dynamic environments, and that balance is maintained by increasing trunk movements. All these findings suggest that, under different conditions of postural control, *hunova* is able to detect parameters that are significantly associated with the level of physical function, as assessed by means of SPPB, and also the compensatory mechanisms implemented by subjects in order to maintain their balance. In addition, our results highlight the importance of evaluating subjects in dynamic conditions (both unstable and perturbating). Indeed, dynamic tests are more sensitive in detecting equilibrium impairments than static tests, as they challenge all the mechanisms involved in balance control. Robotic interventional trials involving subjects with low SPPB scores might clarify whether robotic training focused on dynamic balance can increase motor performance and, consequently, reduce the risk of falling.

In conclusion, in community-dwelling older subjects, balance assessment by means of the *hunova* robot could be useful: (1) in assessing balance deficits in static and dynamic conditions; (2) in identifying older people with impaired physical function who are at risk of falls; (3) in selecting older subjects who potentially may benefit from a rehabilitation program.

Funding There was no external source of funding for this research.

Compliance with ethical standards

Conflict of interest A.D.L., V.S., J.S. and C.S. are employees of Movendo Technology (Genova, Italy). S.P. is a consultant for Movendo Technology (Genova, Italy).

Research involving human participants and/or animals The study conforms to the ethical standards laid down in the 1964 Declaration of Helsinki, which protects research subjects, and was approved by the ethics committee of the regional health authority (reference number: 169REG2016).

Informed consent All subjects involved in the study signed the informed consent form.

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