MethodsX 7 (2020) 100964

Contents lists available at ScienceDirect

MethodsX

journal homepage: www.elsevier.com/locate/mex

Method Article

A comprehensive method for assessing postural control during dynamic balance testing

Dimitris G. Mandalidis*, Dimitris N. Karagiannakis

Sports Physical Therapy Laboratory, School of Physical Education and Sports Science, National and Kapodistrian University of Athens, Greece

ABSTRACT

Postural control, despite its complexity, has been investigated based on single or multiple domain parameters, mainly under static conditions. The purpose of this study was to investigate whether semi-squatting in one leg, in contrast to simply standing in one leg, can challenge the postural control in a more dynamic manner similar to those encountered during sporting activities, using posturographic-based parameters coupled with EMG data of the ankle musculature. Our findings revealed that the decreased stability induced with single-leg semi-squatting (SLSQ) required primarily the contribution of the tibialis anterior and the peroneus brevis, as opposed to the medial gastrocnemius and lateral gastrocnemius who were the main controllers of body posture during single-leg standing (SLST) with open eyes. The lower variability found in the CoP-based parameters and the EMG activity of the muscle under investigation suggests that postural control can be more accurately assessed under dynamic conditions such as with SLSQ compared to the more static SLST test. Multi-factorial analysis of postural control combining posturographic and EMG data, particularly under dynamic conditions, can provide useful information in the diagnosis and rehabilitation of clinical cases where the assessment of muscle dysfunction is required to design a rehabilitation program and monitor patient progress.

- Simultaneous recordings of posturographic-based parameters and the EMG activity of the ankle/foot musculature suggest that postural control is challenged more during SLSQ.
- Postural control with SLSQ is mainly controlled by the tibialis anterior and peroneus brevis in response to a greater anteroposterior- compared to mediolateral-directed sway of the body.
- The limited body sway elicited with the traditional SLST test is mainly controlled by the gastrocnemius muscle.
- Postural control may be assessed more accurately under dynamic conditions such as with SLSQ as opposed to the standard SLST test.

DOI of original article: 10.1016/j.humov.2019.102563

* Corresponding author.
E-mail address: dmndldis@phed.uoa.gr (D.G. Mandalidis).

https://doi.org/10.1016/j.mex.2020.100964

ARTICLE INFO
Method name: A posturographic combined with electromyography evaluation of dynamic body balance
Keywords: Postural control, Body balance, Single-leg-stance, Single-leg-squat, EMG of ankle muscles, Center-of-pressure parameters
Article history: Received 26 February 2020; Accepted 10 June 2020; Available online 13 June 2020

Specifications Table

Subject Area:	Medicine and Dentistry
More specific subject area:	Physical Therapy and Rehabilitation
Method name:	A posturographic combined with electromyography evaluation of dynamic body balance
Name and reference of original method:	
Resource availability:	

Method details

Postural control assessment

All participants required to perform single-leg semi-squats (SLSQ) with the supportive lower limb while reaching as far as possible with the contralateral limb in the anterior (A), anteromedial (AM), medial (M), posteromedial (PM), posterior (P), anterolateral (AL), lateral (L) and posterolateral (PL) direction in a manner similar to the one required for execution of the Star Excursion Balance Test. The supportive lower limb was determined in each subject according to the Waterloo Footedness Questionnaire – Revised [1]. Reaching in the aforementioned directions was controlled by instructing each participant to slide a rectangular wooden reach-indicator along each one of four aluminum tubes, which were attached to the four sides of a 41.5 cm (Length) x 19.0 cm (Width) x 4.5 cm (Height) rectangular wooden frame. Two of the tubes were fixed firmly on the two short sides of the rectangular frame enabling reaching in the A and P direction. The other two, which were hingedly attached on the long sides of the frame, could be positioned and secured in such a way that enabled reaching in directions spaced 45° apart, medially and laterally to the anteroposterior axis of the stance foot, namely in the AM, M and PM directions as well as in the AL, L and PL directions, respectively.

Postural control was assessed by recording simultaneously the CoP-based parameters, as well as the EMG activity of selected ankle and foot musculature, with each participant standing barefoot on a pressure distribution platform (FDMS, Zebris Co., Medical GmbH, Germany) having planted his/her foot inside the frame, which was placed at the center of the platform. The contact of the frame with the platform was prevented by mounting the frame on two wooden bases that were projected towards its short sides and placed on the ground. The aluminum tubes remained parallel to the ground without having contact with the platform throughout testing by regulating height-adjusters that had been fixed at the distal end of each tube.

Posturographic analysis

Posturographic measurements were performed in terms of the total track length (TTL), the 95% of confidence ellipse area (95%CEA), and the anteroposterior (y-component of foot pressure vector) and mediolateral (x-component of foot pressure vector) displacements (APd, MLd) of CoP using the pressure distribution platform. These parameters were selected due to their frequent use in clinical cases and the information they provide in posturographic analysis. The total track length (TTL) of the CoP that is the summation of the actual distances between successive CoP locations is a frequently used parameter and it can be implemented in the calculation of CoP velocity (by dividing the total track length by the trial duration) [2]. The 95% confidence ellipse area (95% CEA) provides an indication of the dispersion of the 95% of the CoP locations so that the larger this area, the more reduced the postural control will be. The anteroposterior and mediolateral displacements (APd, MLd) of the CoP are two parameters that, in contrast to the previous ones, provide directional-related information regarding postural control [2]. Such information is very important in the assessment of many clinical cases as it enables clinicians to distinguish individuals with different pathologies and/or monitor the progress of their rehabilitation [3]. The foot pressure signals were recorded at a sampling rate of 120 Hz and analyzed with the WinFDMS computer software (WinFDMS v.0.1 for Windows, Zebris Medical GmbH, Germany).

EMG recordings

The EMG activity of the tibialis anterior (TA), the peroneus brevis (PB), the medial gastrocnemius (GM) and the lateral gastrocnemius (GL) of the supportive lower limb were measured by placing disposable, self-adhesive, Ag-AgCl disc-shape (0.9-cm in diameter) electrodes (Red Dot™ type 2223, 3 M Health Care, St Paul, MN) on the selected muscles with an inter-electrode distance of 2-cm, following the recommendations of Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) [4] using an MP 100 Biopac System (Biopac Systems Inc. CA, USA). The electrodes were placed (i) at 1/3 on the line between the tip of the fibula and the tip of the medial malleolus for TA, (ii) anterior to the tendon of the peroneus longus at 25% of the line from the tip of the lateral malleolus to the head of the fibula for PB, (iii) at 1/3 of the line between the head of the fibula and the heel for GL and (iv) on the most prominent bulge of the muscle for GM. A single electrode was placed on each participant's lateral malleolus to serve as a reference (earth) electrode [4].

The raw EMG signals were recorded at a sampling rate of 1000 Hz using a 10 to 500 Hz bandpass filter. Skin impedance was reduced by shaving any hair and abrading skin surface with ethylic alcohol before electrode placement. Data acquisition and analysis were performed using the AcqKnowledge® v.3.9.1.6 computer software (Biopac Systems, Inc., CA, USA). The raw EMG signals that were recorded on each test attempt, were processed into root mean square (RMS) data using a time window of 30-ms. The mean EMG activity that was recorded during the 3 test attempts in each one of the eight reaching directions, was normalized and expressed as a percentage of the mean EMG activity produced by each muscle's maximum voluntary isometric contraction (MVIC). All muscle MVICs were measured prior to the testing protocol with the lower limb positioned at postures used in clinical manual muscle tests to achieve maximal contractions [5]. Each participant performed three 5-seconds attempts against manual resistance that was provided by the main investigator towards (i) inversion coupled with dorsal flexion and eversion coupled with plantar flexion of the ankle for TA and PB, respectively with each participant lying supine [6,7] and (ii) plantar flexion of the foot for GL and GM with each participant lying prone [6]. The EMG activity that corresponded to each muscle's MVIC was determined based on the average of the time interval between the 2nd and 4th seconds of each one of the three repetitions. Fatigue was prevented by allowing a 1-min break between each repetition.

The EMG activities of the ankle/foot musculature were recorded simultaneously with the CoP-based parameters by synchronizing a digital camera (LifeCam VX 2000, 1.3 MP, 30-Hz, Microsoft Corporation, USA) with the EMG recording device. The use of this camera enabled the investigators of this study to monitor and visualize testing conditions and, eventually, to identify the time frame during which an attempt was performed.

Method validation

Postural control during SLSQ was compared with the standard single-leg-stance (SLST) with open-eyes test in 28 physically active students (14 males and 14 females; mean ± SD of age 25.6 ± 4.5 yrs, height: 172.5 ± 8.2 cm, bodyweight: 67.7 ± 13.6 kg) with no systematic involvement in sporting activities of either amateur or professional level or intensive motor activities of everyday life. All participants reported also no history of (i) pain or inability of fully weight-bearing and walk without limping for at least 3 months before participation to this study and/or (ii) lower limb/spine injury and neurologic, visual, vestibular, or body balance disorders. The study protocol was approved by the University's Human Research Ethics Committee, and each participant signed a written consent before testing.

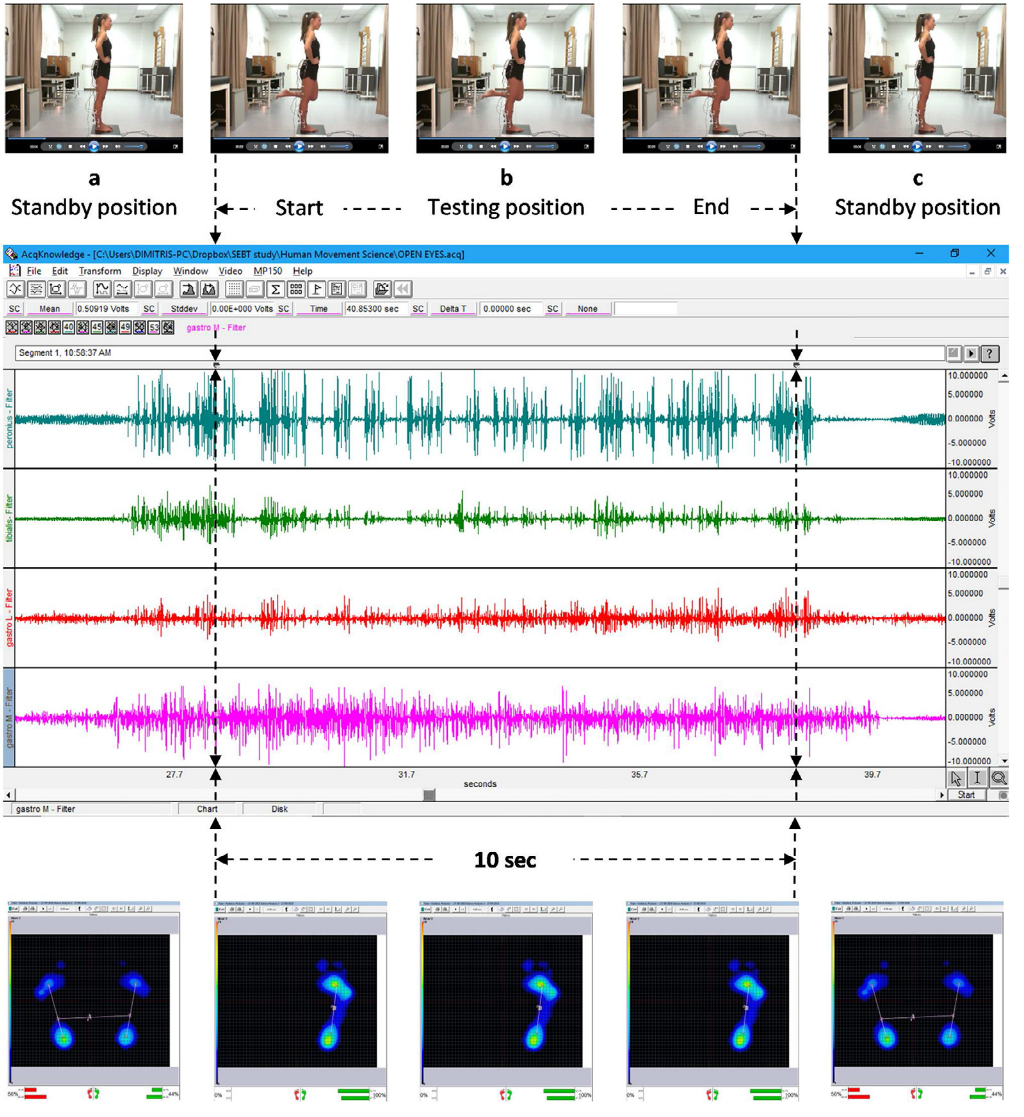

Fig. 1. Sequence of events and graphical presentation of peroneus brevis (cyan), tibialis anterior (green), medial gastrocnemius (magenta) and lateral gastrocnemius (red) filtered EMG activity (in Volts) as well as plantar pressure recordings during a 10–sec test attempt of SLST.

Sequence of events for postural control assessment during SLST and SLSQ

Each participant, during SLST, required to (i) stand with both feet on the platform facing forward with the eyes open and place the hands on the hips (standby position), (ii) lift the foot off the platform by bending the knee of the non-tested lower limb to 90° (testing position) and to maintain this position for 10–sec and (iii) return to the standby position without moving the stance foot, removing the hands from the hips or touching the floor with the free foot (Fig. 1). During SLSQ each participant had to (i) stand on the platform with one foot and touch lightly the proximal edge of the reach indicator with the tip of the toes of the free foot (standby position), (ii) reach as far as possible with the free leg along each one of the eight directions for 10–sec by pushing, but not standing or

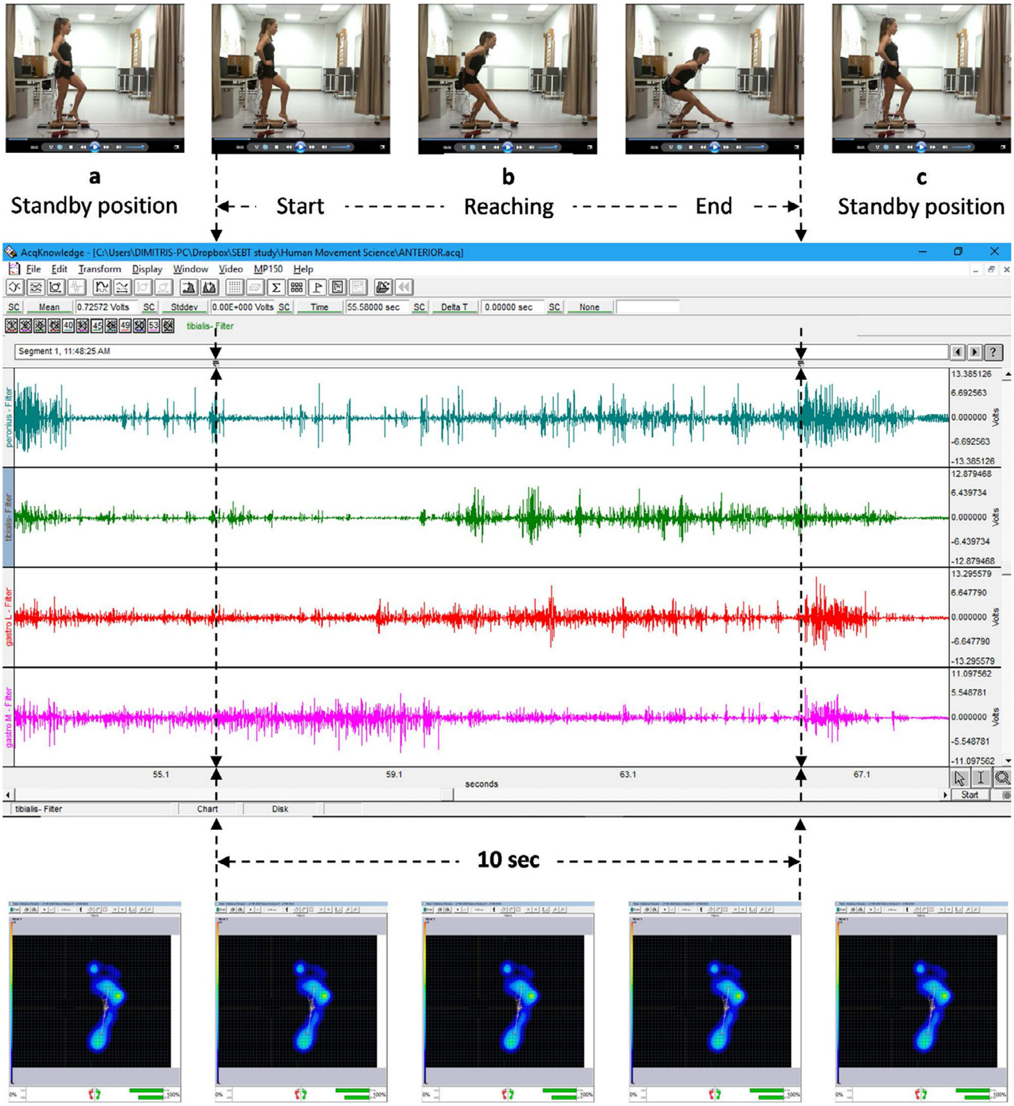

Fig. 2. Sequence of events and graphical presentation of peroneus brevis (cyan), tibialis anterior (green), medial gastrocnemius (magenta) and lateral gastrocnemius (red) filtered EMG activity (in Volts) as well as plantar pressure recordings during a 10–sec reaching in the anterior direction while performing SLSQ.

kicking the reach indicator, raising the heel or moving the stance foot and (iii) return to the standby position without removing the hands from the hips or touching the floor with the free foot (Fig. 2). Participants were informed of the time required to complete each test by the examiner, who counted loudly for 10-s using a stopwatch. All participants completed 3 practice trials for familiarization and 3 more test attempts in each one of the eight directions. There was a 2-minute break between the two tests (SLST and SLSQ) and among excursions in the different directions of SLSQ. An attempt was discarded if one of the above actions were not performed according to the examiner's instructions. In this case, an additional attempt was given. Postural control during SLST was performed prior to the assessment of postural control during SLSQ; however, the excursions at the different directions during SLSQ were performed at a random order to prevent fatigue-induced bias.

The examiner initiated the EMG and video recordings as soon as the participant was on the platform but the plantar pressure recording was started only when a participant reached the test position for SLST or initiated reaching in a direction during SLSQ. All recordings were ended when a participant return to the standby position.

Data analysis and results

To determine an adequate sample size in order to achieve statistical significance with $a = 0.05$, 80% power and effect size (f) = 0.2526 (calculated based on a partial $\eta^2 = 0.06$), *a priori* power analysis was performed using an online power analysis application (G*Power 3.1.9.2., Franz Faul, Universität Kiel, Germany). The results of the power analysis indicated a total sample size of 23 subjects.

A one-way repeated-measures analysis of variance (ANOVA) was used to compare the APd and MLd, the 95%CEA and the TTL of CoP, as well as the EMG activity of the selected ankle/foot musculature between the directions reached with SLSQ and the SLST test. Significant main effects were followed by pairwise comparisons after a Bonferroni adjustment for controlling Type I error. The statistical analyses were conducted in SPSS 25.0 (IBM Corp, Armonk, NY, USA), and level of significance was set at $p \leq 0.05$.

The accuracy in measuring the variables under investigation (posturographic-based parameters and EMG activity of the ankle musculature) in the two testing conditions (SLSQ and SLST) was estimated with the percentage coefficient of variation (%CV). The %CV was calculated based on the standard deviation of the three test attempts in each one of the testing conditions and expressed as a percent of their mean (CV = standard deviation/mean x 100). Statistical comparisons between each one of the directions reached with SLSQ and the SLST test for the %CV of all the variables measured was performed according to Forkman [8] using the MedCalc Statistical Software version 19.2.1 (MedCalc Software Ltd, Ostend, Belgium). The level of significance was set at $p \leq 0.05$.

Data analysis revealed significant differences between the directions reached with SLSQ and the SLST for the APd and MLd ($p<0.001$), the 95%CEA ($p<0.001$) and the TTL ($p<0.001$) of CoP. Significant were also the differences between the directions reached with SLSQ and the SLST for the EMG activity of the TA, PB, GM and GL ($p<0.001$). *Post hoc* analysis revealed significantly greater APd and MLd ($p<0.001$), 95%CEA ($p<0.001$) and TTL ($p<0.001$) of CoP during reaching in all directions with SLSQ compared to the SLST test. The greater CoP-based parameters recorded with SLSQ were coincided with significantly increased EMG activity of TA ($p<0.001$) and significantly decreased EMG activity of GM ($p<0.001$) compared to the SLST test. The EMG activity of PB was also increased during reaching with SLSQ compared to the SLST test but the differences were significant only with respect to the P ($p<0.05$), PL and L ($p<0.01$) direction (Figs. 3–6). *Post hoc* comparisons revealed also non-significant decreased EMG activity of GL during the majority of directions reached with SLSQ compared to the SLST test.

Comparisons of the %CV between testing conditions revealed significant lower variability for most of the posturographic and EMG data sets obtained with reaching in the majority of directions of SLSQ compared to the SLST test (see Table 1 for comparisons between each of the directions reached with SLSQ and the SLST test). The posturographic parameter with the lowest variability during SLSQ was the TTL, with%CVs ranged between $8.3 \pm 3.4\%$ – $10.8 \pm 5.0\%$, followed by the MLd ($12.2 \pm 7.0\%$ – $16.2 \pm 8.0\%$), the APd ($12.1 \pm 8.5\%$ – $21.1 \pm 10.8\%$) and the 95%CEA ($16.5 \pm 9.9\%$ – 28.3 ± 11.6) of the CoP. The corresponded %CVs calculated for the SLST test was $11.7 \pm 5.2\%$ for the TTL, $15.7 \pm 11.2\%$ for the MLd, $25.1 \pm 13.4\%$ for the APd and $28.2 \pm 16.6\%$ for the 95%CEA of the CoP.

The variability of the EMG signals for all the muscles tested were less than 18% during reaching in almost all directions of SLSQ except for the TA EMG signal, which demonstrated the greatest variability during reaching in the anterior direction ($21.0 \pm 10.1\%$). The %CV for the EMG signals recorded with the SLST test ranged between $18.9 \pm 14.5\%$ – $24.4 \pm 16.4\%$ for all the muscles tested.

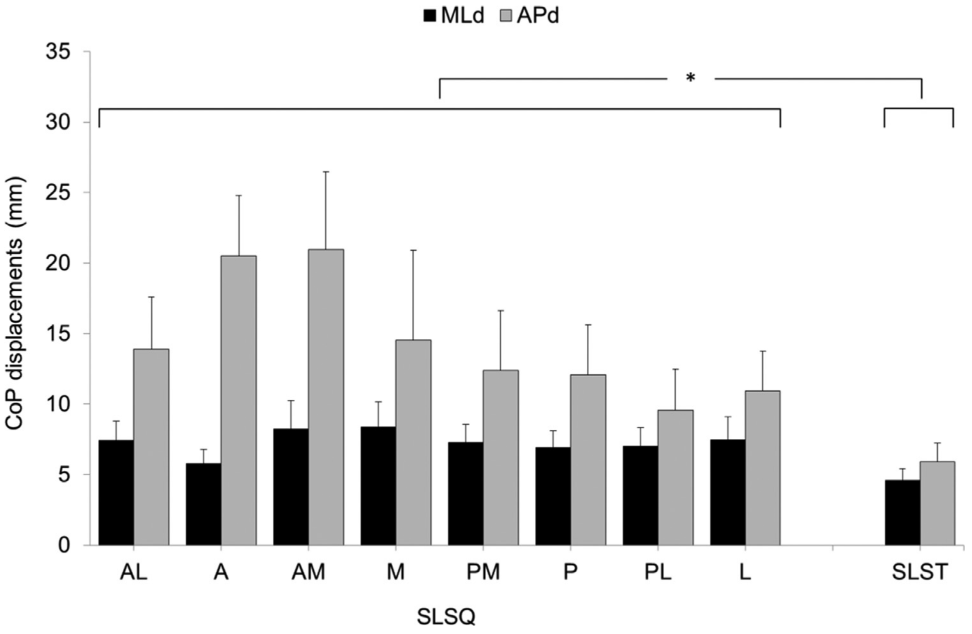

Fig. 3. Mediolateral and anteroposterior displacement (MLd, APd) of the center of pressure (CoP) during single-leg-stance (SLST) test with open eyes and during excursion in the anterolateral (AL), anterior (A), anteromedial (AM), medial (M), posteromedial (PM), posterior (P), posterolateral (PL) and lateral (L) directions while performing single-leg-squatting (SLSQ).
*significantly greater MLd and APd of CoP during reaching in all directions with SLSQ compared to the SLST test ($p<0.001$).

Additional information

Based on the findings of the proposed method, reaching in various directions with SLSQ, although is essentially a single-leg-stance-related skill [9], challenges more postural control compared to the traditional SLST test confirming its role as a test for dynamic balance assessment. Posturographic analysis revealed that all CoP-based parameters were greater with SLSQ regardless of the direction reached indicating greater body sway during this condition as oppose to the SLST test. However, the muscles of the ankle and foot that controlled the body posture in the two conditions under investigation were different. While reaching in the various directions with SMSQ required greater activation of the TA and PB, the muscles that controlled the body posture with SLST were primarily the GM and, to a certain extent, the GL. The lower variability presented by the CoP-based parameters and EMG recordings of the ankle musculature suggested also that dynamic balance testing by means of SLSQ can be assessed more accurately compared to the standard SLST test.

The dynamic nature of SLSQ has been attributed to the forward or backward inclination of the trunk, and the associated anterior or posterior shift of the center of the head, arms, and trunk mass, during reaching in the posterior-orientated or anterior-orientated directions, respectively [10]. Moreover, postural control may be compromised during SLSQ as the knee joint progressed from a close-packed (extension) to an open-packed position (flexion) in order to enable maximum excursion of the free limb. It seems that with reduced passive stability of the knee in this open-packed position, the muscles of the ankle joint were forced to become more active in order to bear and control the weight of the body. However, only the activities of the TA and PB were increased with SLSQ, as a response to increased body sway, despite the greater passive stability of the ankle that evidently achieved with the joint progressively reaching a close-packed position (dorsiflexion). One of the reasons for the increased activity in the aforementioned muscles was the increased need for dynamic stabilization of the foot. Indirect evidence have showed that the longitudinal arch, and consequently

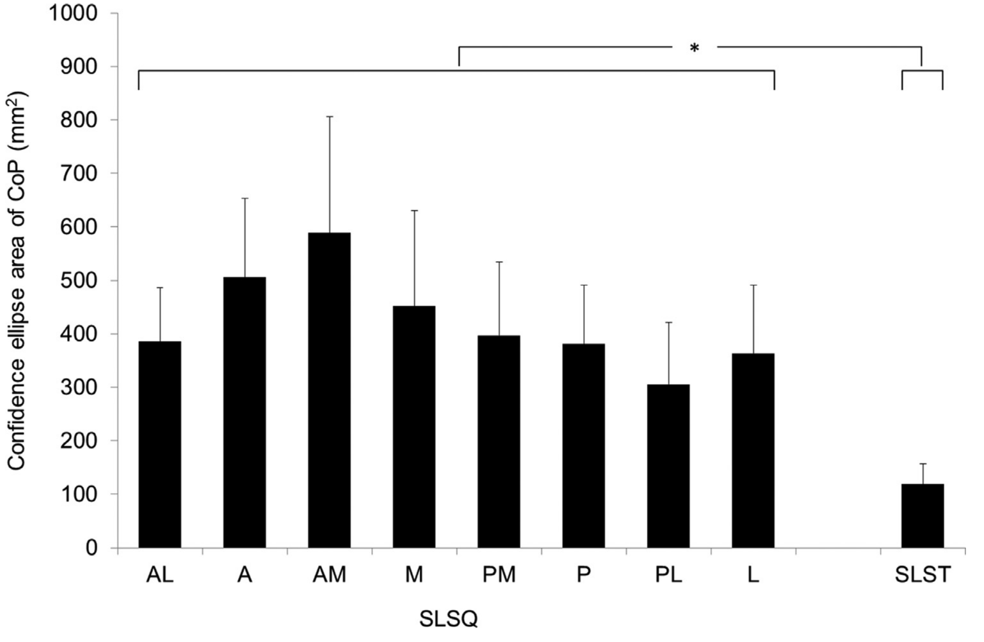

Fig. 4. Confidence ellipse area of the center of pressure (CoP) during single-leg-stance test with open eyes (SLST) and during excursion in the anterolateral (AL), anterior (A), anteromedial (AM), medial (M), posteromedial (PM), posterior (P), posterolateral (PL) and lateral (L) directions while performing single-leg-squatting (SLSQ).
*significantly greater 95% confidence ellipse area of CoP during reaching in all directions with SLSQ compared to the SLST test ($p<0.001$).

the plantar fascia of the supporting foot, is subject to different loads depending on the direction reached with the free leg during SLSQ [11]. Furthermore, the EMG activity of GM and, to a lesser extent, the GL noted with SLSQ was probably lowered due to the eccentric action of the muscles that were forced to develop in order to control the tibia as it was rolled over the foot while reaching in different directions with the free leg [12,13]. These observations are supported in part from findings of previous studies on the Star Excursion Balance Test (SEBT), a widely used test from clinicians and sport scientists in the athletic population for both assessment and rehabilitative purposes [14], which also requires SLSQ. Posturographic data gathered from certain directions of SEBT (i.e. A, PM and PL) revealed a greater area and lower velocity of CoP during excursion in the anterior direction compared to excursions in the posterior directions [15] while other authors highlighted the dominant role of the TA over the gastrocnemius muscle in controlling the ankle joint [10].

In contrast to SLSQ, the body sway induced with the STST with open eyes test was reduced, as indicated by the decreased CoP-based parameters, probably due to the greater stability provided by the knee joint and the more vertical alignment of the head-arm-trunk relative to the base of support. When the knee is fully extended (close-pack position) the stability of the joint is greater as the congruency between the articular surfaces and the tightness of the medial and lateral collateral ligaments of the knee are greater. With the center of mass of the head-arm-trunk located over the base-of-support the compression forces that are applied on the tibiofemoral joint are also increased reducing eventually body sway. In the present study body sway, in terms of the anteroposterior displacements of CoP did not exceed 1 cm, indicating a small amount of body oscillations. Similar CoP displacements of about 1–2 cm have been elicited in the two-leg upright standing posture which corresponds to body segment oscillations that they do not exceed 1–2° of joint movements [16]. Such small body sway is supposed to be controlled by the ankle strategy letting ankle plantar flexors/dorsi flexors alone to control the inverted pendulum that is the mechanical equivalent of human body's

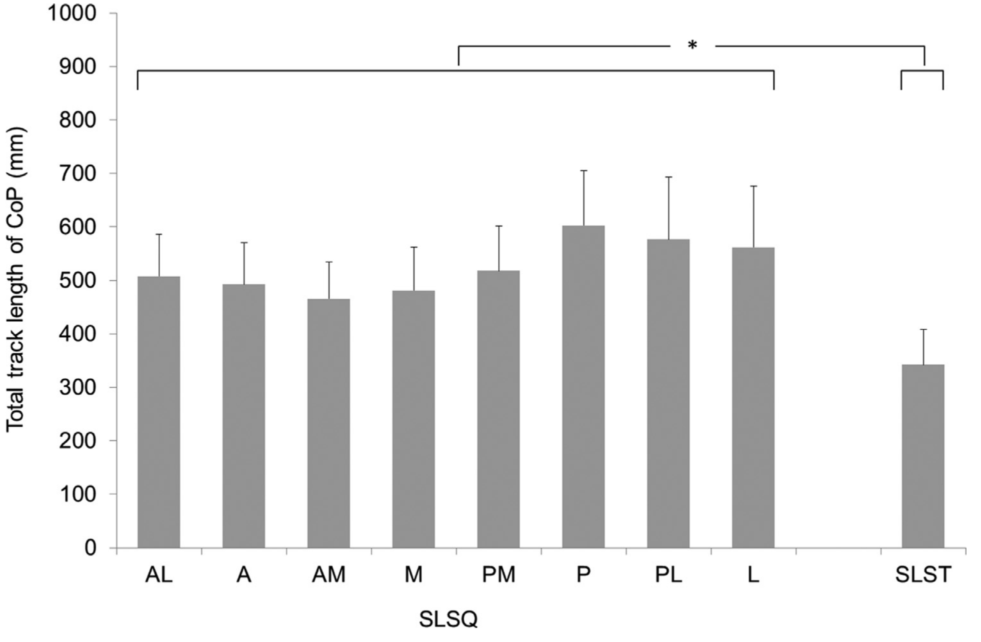

Fig. 5. Total track length of the center of pressure (CoP) during single-leg-stance test with open eyes (SLST) and during excursion in the anterolateral (AL), anterior (A), anteromedial (AM), medial (M), posteromedial (PM), posterior (P), posterolateral (PL) and lateral (L) directions while performing single-leg-squatting (SLSQ).
*significantly greater total track length of CoP during reaching in all directions with SLSQ compared to the SLST test ($p<0.001$).

postural sway in the upright standing posture. Considering that in normal stance the center of mass lies about 5-cm ahead of the ankle joint in the anterior direction and the anterior bending torque produced by the raised leg, it is not surprising why the activity of GM and, merely the GL was increased in order to control the ankle joint and prevent the body from leaning forward.

Postural control analysis based on data from multiple domains (i.e. EMG activity in conjunction with kinetic and/or kinematic analysis) has been performed mainly during two-leg upright standing on a stable or a movable platform that was able to provide anterior and posterior translations in the horizontal plane, with knees fully extended and eyes open or closed [17–20]. In one of these studies, the test was performed dynamically but essentially it was a two-leg semi-squat movement followed by an automatic rise up with the participants standing on a soft-foam, which was placed on a stable force plate while keeping both heels on the ground [20]. In another study postural control was investigated in subjects with and without ankle instability with SEBT but only during reaching with the free limb in the posteromedial direction [21]. The authors in this study placed a foot-switch under the distal phalanx of the hallux of the reach leg to track the reach event from the moment the reaching foot was lifted from the ground, to start the reaching task, to the moment the foot touched the ground along the specific direction [21]. In this way, they were able to computationally measure the reach distance and synchronize the reaching event with the kinetic, kinematic and EMG data from tibialis anterior and peroneus longus. Electromyographic data gathered from the ankle (anterior tibialis, peroneus longus, and medial gastrocnemius) and hip musculature (gluteus medius) in conjunction with plantar pressure measures was also implemented by other authors who aimed to investigate young adults with chronic ankle instability during walking [22]. Plantar pressure was measured using an in-shoe plantar system and synchronization between the plantar pressure and EMG recordings was achieved by placing heel switches to identify the initial contact of the selected limb during walking [22]. All of the above studies provided useful information; however, the methods

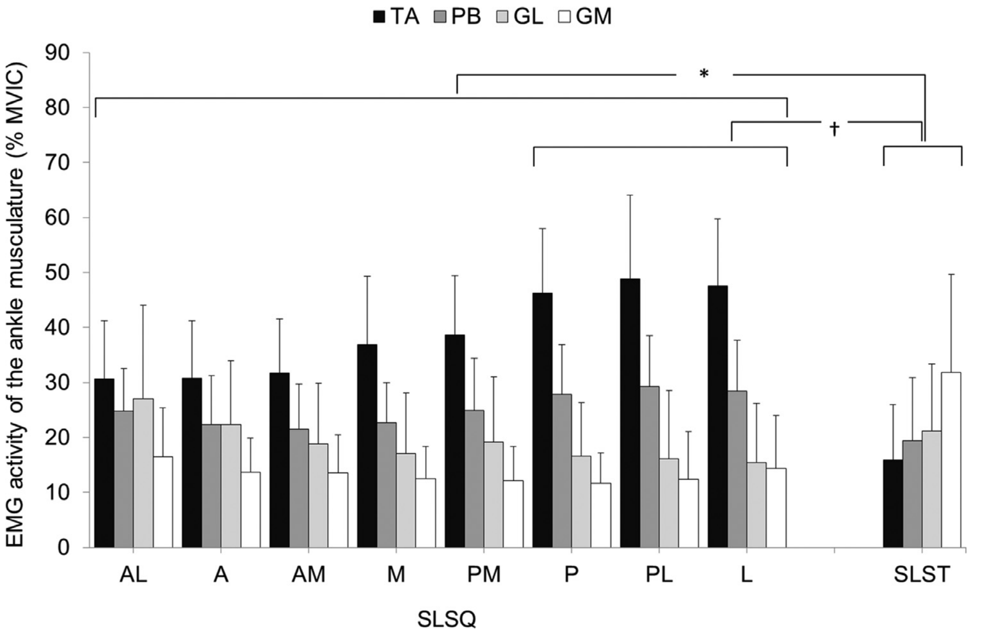

Fig. 6. Electromyographic (EMG) activity of tibialis anterior (TA), peroneus brevis (PB), lateral gastrocnemius (GL) and medial gastrocnemius (GM) during single-leg stance test with open eyes (SLST) and during excursion in the anterolateral (AL), anterior (A), anteromedial (AM), medial (M), posteromedial (PM), posterior (P), posterolateral (PL) and lateral (L) directions while performing single-leg semi-squatting (SLSQ).

*significantly higher EMG activity of TA ($p<0.001$) and lower EMG activity of GM ($p<0.002$) during reaching in all direction with SLSQ compared to the SLST test.

†significantly higher EMG activity of PB during reaching in the P ($p<0.05$), PL and L ($p<0.01$) direction with SLSQ compared to the SLST test.

used across them were circumstantial, inconsistent and incomplete as they investigated postural control under various situations and different conditions.

The repeatability and consistency of a measurement is an integral part of a methodological procedure in every aspect of health science. The %CV is an indicator of the dispersion between a set of data around its mean (variability) and as such the lower it is the greater the accuracy of a measurable variable will be. The current findings revealed that the variability of posturographic and EMG data sets recorded during the three attempts of reaching in each direction of SLSQ was lower compared to the variability of the same measurements recorded between the three attempts with the standard SLST test. These findings suggest that repeated posturographic and EMG-based measurements are recorded more consistently with the SLSQ as opposed to the SLST test. The greater consistency achieved for posturographic and EMG data sets with SLSQ could be attributed to the external attentional focus required by a participant to execute the more dynamic SLSQ compared to the standard SLST test. Attentional focus refers to the location to which an individual pays attention while performing a certain movement [23] and is more effective when someone is concentrating in a location on the outside of the body (external) [24,25]. This may have actually happened in the present study, as the proposed method required participants to focus on a location outside their body by sliding the rectangular wooden reach-indicator with the free leg in a specific direction. It has been suggested that the balance of the body under these conditions (i.e. relatively demanding motor activities with external focus) may be controlled by automatic processes through which corrective movement adjustments are performed more frequently and at a faster rate, thus minimizing errors and improve performance [25]. If, on the other hand, body balance is not challenged adequately, as when standing with one leg on a firm surface (i.e. SLST test), the automatic information processing

Table 1
Mean ± standard deviation of the percentage coefficient of variation of the three attempts performed during single-leg-standing with open eyes and the three attempts performed during reaching in different directions with single-leg semi-squatting for the posturographic-based parameters and the EMG activity of the ankle musculature.

	Posturographic-based parameters (%CV)				EMG activity (%CV)			
	APd	MLd	95%CEA	TTL	TA	PB	GL	GM
SLST	25.1 ± 13.4	15.7 ± 11.2	28.2 ± 16.6	11.7 ± 5.2	24.4 ± 16.4	20.3 ± 9.4	19.6 ± 11.0	18.9 ± 14.5
SLSQ-AL	19.4 ± 9.0	16.2 ± 8.0	22.9 ± 11.1	10.8 ± 5.0	15.7 ± 8.0‡	12.7 ± 10.2‡	13.0 ± 8.3‡	15.1 ± 11.7
SLSQ-A	12.1 ± 8.5*	15.0 ± 6.8	21.1 ± 8.1	8.8 ± 6.2	21.0 ± 10.1	11.1 ± 6.1†	14.7 ± 10.1	13.1 ± 7.9
SLSQ-AM	15.6 ± 10.6‡	15.3 ± 6.3	23.7 ± 13.5	8.5 ± 3.5	14.9 ± 7.2‡	11.2 ± 9.6†	15.3 ± 11.6	11.6 ± 8.1‡
SLSQ-M	15.0 ± 7.4‡	14.1 ± 8.8	16.5 ± 9.9†	8.8 ± 4.3	14.2 ± 10.1†	11.2 ± 6.2†	12.2 ± 6.3‡	17.9 ± 13.2
SLSQ-PM	18.4 ± 10.2	15.7 ± 6.4	24.3 ± 10.5	8.6 ± 4.7	9.7 ± 4.9*	11.3 ± 5.6†	12.8 ± 8.9‡	12.7 ± 9.2‡
SLSQ-P	17.9 ± 5.4	12.2 ± 7.0	23.1 ± 9.4	9.5 ± 4.1	12.2 ± 4.8*	12.5 ± 6.7‡	11.9 ± 10.0‡	12.3 ± 8.2‡
SLSQ-PL	21.1 ± 10.8	14.9 ± 7.7	28.3 ± 11.6	8.3 ± 3.4	10.5 ± 6.4*	9.5 ± 6.7*	8.1 ± 4.9*	9.6 ± 4.9*
SLSQ-L	19.7 ± 11.2	13.0 ± 7.0	22.9 ± 14.2	9.7 ± 5.9	12.0 ± 8.9*	9.9 ± 4.4*	7.6 ± 6.1*	8.6 ± 6.7*

%CV: Percentage coefficient of variation, CoP: Center of pressure, EMG: Electromyography, SLST: Single-leg-standing, SLSQ: single-leg semi-squatting, APd: Anteroposterior displacement, MLd: Mediolateral displacement, 95%CEA: 95% Confidence ellipse area, TTL: Total track length, TA: Tibialis anterior m., PB: Peroneus brevis m., GL: Lateral gastrocnemius m., GM: Medial gastrocnemius m., AL: Anterolateral, A: Anterior, AM: Anteromedial, M: Medial, PM: Posteromedial, P: Posterior, PL: Posterolateral and L: Lateral directions.

* $p<0.001$, †$P<0.01$ and ‡$p<0.05$ between SLTS and the direction reached with SLSQ.

may be obstructed (constrained action hypothesis) probably because the individuals' satisfaction with the ongoing motor control process discourages them to intervene even by adopting an external attentional focus. Eventually, this may result in decreased motor adjustments affecting body balance ability and movements' performance [25].

With the proposed method, an attempt was made to standardize the assessment of dynamic body balance using data from the domains of posturography and electromyography. This was mainly due to the fact that the dynamic nature of exercise and athletic performance has created the need for tests that, unlike the traditional SLST test, challenge postural control under conditions that resembles more closely the demands encountered during sporting activities. Coupling posturographic with EMG data may eventually enable sport scientists and health care providers (i) to investigate the complex mechanism that controls body posture under more dynamic conditions, (ii) to identify clinical cases that may remain undiagnosed with single-dimensional diagnostic approaches, (iii) to detect differences in postural control between individuals with anatomical deviations, musculoskeletal dysfunctions or from different disciplines (e.g. sports) and (iv) to monitor changes that may emerge as a result of a training program aiming to improve or restoring postural control for performance or rehabilitative purposes, respectively.

Declaration of Competing Interest

None of the authors have any actual or potential conflict of financial or personal competing interest.

CRediT authorship contribution statement

Dimitris G. Mandalidis: Conceptualization, Methodology, Formal analysis, Writing - review & editing, Visualization, Supervision. **Dimitris N. Karagiannakis:** Investigation, Data curation, Writing - review & editing.

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