# A new set of parameters for Computerised Dynamic Posturography

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## Abstract

The Sensory Organisation Test (SOT) of Computerised Dynamic Posturography (CDP) measures the Centre of Pressure coordinates, in order to assess upright balance function of subjects as well as the contribution of vestibular, somatosensory and visual systems. A number of subjects refer postural unbalance and have negative test. The aim of the study is to propose a new method that could improve the SOT sensitivity and increase the test's discrimination power. Principal Component Analysis (PCA) was performed in a set of 14 posturographic parameters for the six conditions of the SOT. Fifty healthy subjects (mean age 41.26±13.57 years) were analysed. Four Principal Components (PCs) that describe about the 90% of the total variation of the postural parameters were found for each condition. The variability of posturographic parameters in normal subjects has been studied and will be extended in next works to pathological subjects.

## Introduction

Bipedal upright stance is inherently unstable. A small sway deviation from a perfect upright position results in a torque due to gravity that accelerates the body further away from the upright position. To maintain upright stance, the destabilizing torque due to gravity must be countered by a corrective torque exerted by the feet against the support surface [1]. This correction is achieved by feedback mechanisms that generate an appropriate corrective torque based on body-sway motion detected primarily by visual, vestibular, and proprioceptive sensory systems [1]. Balance function involves the central integration of multiple sensory inputs; the vestibular nuclei receive information from somatosensory, visual and vestibular receptors that are drawn in the process of selecting and combining appropriate sensory information. This process is defined sensory organisation.

Visual sensory input provides the central nervous system with the position of the body in relation to other objects in its environment; relative reference frame. The visual input determines characteristics such as the velocity, surface texture or height of an object, in order to anticipate, in advance, any obstacles that could have a detrimental effect on maintaining balance. The vestibular system consists of three semi-circular canals, which act as angular accelerometers, and two otolithic organs, the utricular and saccular macula, which are gravity receptors that function as linear accelerometers to provide the principal absolute, external frame of reference of the body vertical. Vestibular sensory input provides the central nervous system with the body's linear and angular accelerations from which the position of the body, with respect to gravity, can be interpreted. This information, integrated with visual input, is also used to maintain stability of the eyes during head movements, in order to provide stable visual input; gaze control. Somatosensory input provides two different types of spatial information; an internal reference and an external reference. Proprioceptors, internal signals from within the body such as muscle spindles, provide the central nervous system with the spatial orientation and movement of a body part relative to an adjacent body segment. Exteroceptors, such as pressure (cutaneous) sensors in the feet, provide the orientation of the body with respect to the ground or support surface. The cutaneous inputs located on the bottom of the feet also provide information about the ground reaction forces of the surface.

Several methodologies have been developed to assess human postural control and the integrity of vestibulospinal function. Patients' postural sway can be analysed using force plate technologies. The force plate records the vertical forces exerted on its surface over time. The centre of vertical reaction forces (Centre of Pressure, CoP) movements provides an indirect measure of postural sway activities. Stabilometry and Computerised Dynamic Posturography (CDP) are two quantitative methods for the assessment of upright balance function [2]. Stabilometry simply analyzes the ability of the subjects in maintaining balance during unperturbed stance (spontaneous sway). Thus, stabilometry does not convey information about the motor and sensory mechanisms that may be involved in postural control, and is not specific for the vestibulospinal disorders that may produce a postural deficit [3]. Sensory Organisation Test (SOT) of CDP analyses the balance performances of a subject during six conditions in which somatosensory and visual inputs can be selectively altered. SOT analysis can help to identify the cause of instability and the patient's balance strategies [2].

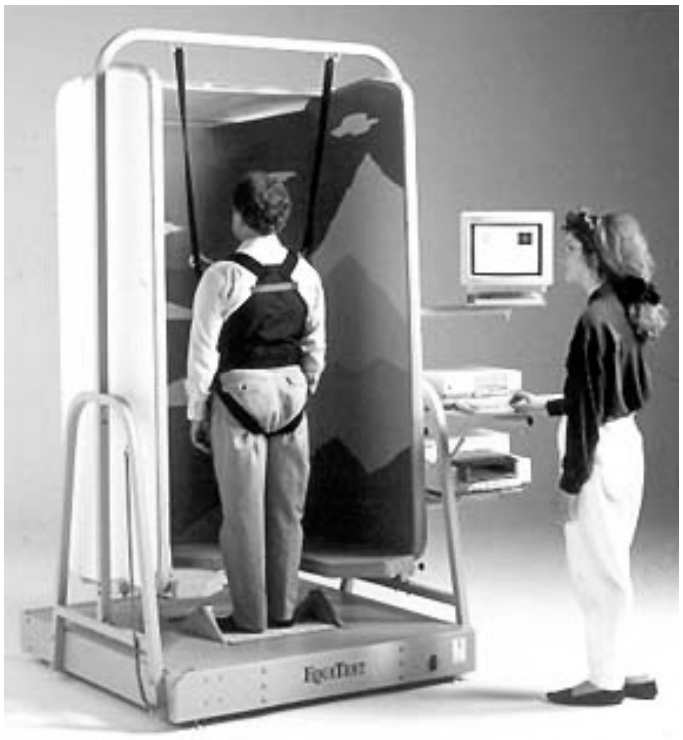
SOT is a test used for the diagnosis of vestibulospinal deficit and in the assessment of the central processes of sensory integration [2, 3]. The equilibrium scores calculated for each trial and the Composite Score (CS) of the SOT are non dimensional parameters which are generally used to describe balance function of the subject. When CS and sensory integration are normal, clinicians can obtain only information about the size of the CoP displacement. Furthermore SOT does not analyse several parameters of the CoP trajectory, in particular, frequencies measures and data velocity and principal direction of CoP trajectory are not described. SOT test has a high positive predictive value in the evaluation of true positive subjects and is a useful instrument for the outcome evaluation of balance function rehabilitation [4]. There are some studies that have tried to find more valid measures of stability [5]. Stabilometry studies the Centre of Pressure (CoP) displacement during a normal stance trial, allowing the calculation of several different parameters. Rocchi et al. [6] identified those features of the CoP trajectory that are most sensitive to postural performance through Principal Component Analysis (PCA) in one static condition.

In this report we extend the above results to six different conditions (SOT) and propose a different procedure to describe the test results. We propose a new analysis that could reduce the number of false negative subjects in the SOT and improve its sensitivity and negative predictive value. The purpose is to select a new set of parameters from 14 starting parameters (Summary Statistical Score) calculated by the coordinates of the CoP obtained during the six conditions of SOT. The future development of this study will aim to increase the sensitivity of SOT test in the discrimination of balance pathologies, even when SOT scores are normal in patients with a sub-clinical balance dysfunction. This new procedure could be used both in clinical practice and research.

# Experimental set-up.

Fifty healthy volunteer adults (20 males and 30 females) without musculoskeletal and neurological diseases were entered on the study at ENT Rehabilitation Unit, San Raffaele Pisana Scientific Institute Tosinvest Sanità. The mean age was 41.26 years (SD 13.57 years, range 21-75 years).

The experimental set-up consisted of six conditions of the SOT. During the SOT the somatosensory and visual environments were systematically altered and the subjects' responses were recorded and measured. The force plate and visual surround were "sway referenced" so that they moved to follow the anterior-posterior sway of the subject (Fig.1, Table1). SOT measures three 20 seconds trials for every condition.



The equilibrium scores (C1-C6) were calculated, for each trial, by comparing the angular difference between the patient's calculated maximum anterior to posterior CoG displacements to a theoretical maximum displacement of approximately 12.5° [7]; the equilibrium scores do not account for medio-lateral CoG displacement. The Composite Score (CS) was calculated by independently averaging the scores for Condition 1 and 2, adding these two scores to the equilibrium score from each trial of Conditions 3, 4, 5 and 6 and dividing this sum by the total number of the trials [7]. The result is expressed as a percentage between 0 and 100. Scores approaching 0 indicate sway amplitudes approaching the limits of stability with a value of 100 indicating perfect stability. A score of zero indicates that the patient "fell" on that trial [7].

Fig.1 Neurocom Equitest.

The coordinates of the CoP were registered by the force plates at 100Hz. Data were then filtered at 8Hz with a $30^{th}$-order low-pass FIR digital filter and down-sampled at 20Hz [6].
From the temporal series 14 different parameters, known as "Summary Statistical Score", were calculated [6]. These parameters may be divided in three groups that describe three characteristics of the CoP: trajectory measures, frequency domain measures (range 0.15-5 Hz) [6] and area measures (Table 2). The frequency domain measures are based on Power Spectral Density (PSD) which describes how a signal or time series power is distributed with frequency.

The influence of several biomechanical factors on the posturographic parameters was taken into account according to the reccommendations present in the literature [8 - 11].

After the normalisation for each of the six SOT conditions, the posturographic parameters were analysed through Principal Component Analysis (PCA). For the PCA the correlation matrix was used instead of the covariance matrix, since parameters were different both in values and in variance [6, 11]. The PCA is a method used to reduce the complexity of a data set. The reduction is obtained through a determined number of new variables that are linear combination of the old ones (Principal Components (PCs)).

# Results

Through PCA we obtained a set of 14 new parameters, for every condition, named PCs. In Table 3, 4 the coefficients of PCs for each experimental condition are listed.

### *Fixed force plate conditions (Condition 1, Condition 2 and Condition 3)*

In Condition 1, the first four PCs described 90% of the total variance of the original set of 14 posturographic parameters. **Table1**. SOT equilibrium conditions and sensory alteration

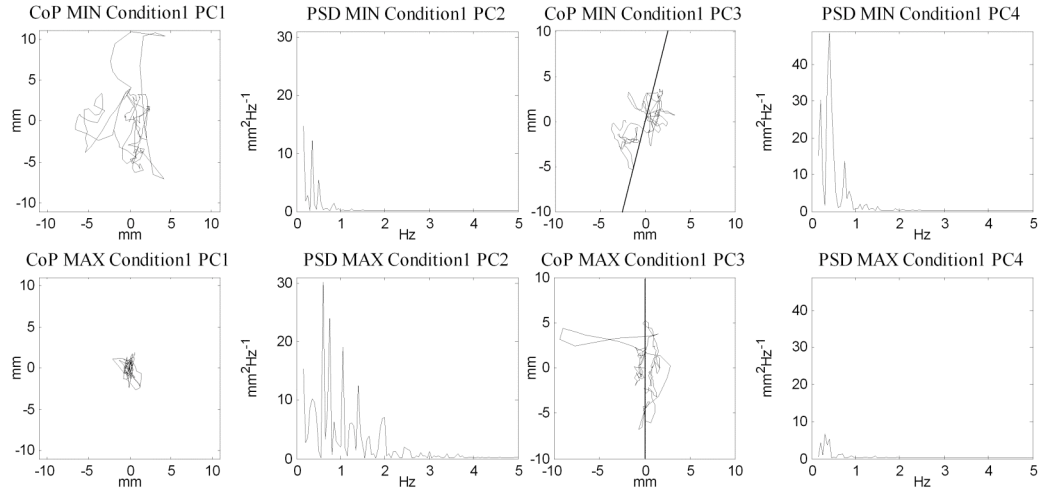
| Condition | Sensory alteration | | | Effect on sensory feedback |
|---|---|---|---|---|
| | Surface | Eyes | Visual Surround | |
| 1 | Fixed | Open | Fixed | Somatosensory = Normal<br>Vision = Normal<br>Vestibular = Normal |
| 2 | Fixed | Closed | Fixed | Somatosensory = Normal<br>Vision = Absent<br>Vestibular = Normal |
| 3 | Fixed | Open | Sway-referenced | Somatosensory = Normal<br>Vision = Altered<br>Vestibular = Normal |
| 4 | Sway-referenced | Open | Fixed | Somatosensory = Altered<br>Vision = Normal<br>Vestibular = Normal |
| 5 | Sway-referenced | Closed | Fixed | Somatosensory = Altered<br>Vision = Absent<br>Vestibular = Normal |
| 6 | Sway-referenced | Open | Sway-referenced | Somatosensory = Altered<br>Vision = Altered<br>Vestibular = Normal |

**Table 2** Posturographic parameters: acronym and short description.

| Acronym | Description |
|---|---|
| Trajectory measures of CoP | |
| MD [mm] | Mean Distance from the centre of the CoP path |
| RMS [mm] | Root Mean Square of CoP time series |
| RANGE [mm] | Range of CoP displacement |
| MV [mm $s^{-1}$] | Mean Velocity ($SP^{*}/T^{**}$) of CoP displacement |
| MF [Hz] | Mean Frequency ($SP^{*}/(2\pi$ MD $T^{**})$) calculated as the number of loops, per seconds, that have to be run by CoP to cover a total path equal to SP |
| Frequency domain measures | |
| TP [$mm^2$] | Total Power, total spectral power |
| f50 [Hz] | Median frequency, frequency below which 50% of TP is present |
| f95 [Hz] | 95% Power Frequency, frequency below which 50% of TP is present |
| CF [Hz] | Centroidal Frequency, at which spectral mass is concentrated |
| FD | Frequency Dispersion, unitless measure of the variability of frequency content of the Power Spectral Density (PSD) (zero for a pure sinusoid, increase with spectral bandwidth to one) |
| Area measures | |
| AD [deg] | Angular Deviation of sway from anterior-posterior direction |
| CCA [$mm^2$] | Confidence Circumference Area at 95% |
| CEA [$mm^2$] | Confidence Ellipse Area at 95% |
| SA [$mm^2 s^{-1}$] | Sway Area calculated as area included in CoP displacement per unit of time |

$^{*}$SP [mm] Sway Path,
$^{**}$T [s] trial duration total length of CoP path

Fig.2 Condition 1: CoP trajectories and PSD of two subjects for every PC selected. The two subjects are identified by the minor (MIN) and the maximum (MAX) coordinate along the corresponding PC: a) PC1; b) PC2; c) PC3; d) PC4.




PC1 was determined principally by parameters that describe the width of oscillations (trajectory and area measures). Fig.2a illustrates this interpretation, showing the differences between the subjects at the extreme limits of PC1. Particularly, PC1 was highly correlated (|r|>0.90) with a group of postural parameters that describe the size of the CoP path (Table 3).
PC2, instead, was determined principally by parameters that describe the morphology of the PSD. Fig.2b shows the PSD of the CoP trajectories of the subjects at the extreme limits of this PC, with evident spectral differences. PC2 was highly correlated (|r|>0.81) with three measures in the frequency domain. PC2 was even correlated (r = 0.63) with MV and MF.
PC3 was highly correlated (r = -0.95) with only one posturographic parameter: AD. Then PC3 described the principal direction of the CoP trajectory. Fig.2c confirms this hypothesis underlining the differences in the CoP direction along the two extreme limits of this PC.
PC4 was correlated (r=-0.54) exclusively with the parameter FD. Then PC4 described variability of frequency content of the Power Spectral Density (PSD). Fig.2d shows the spectral differences between the two trials at the extreme limits of PC4 dimension.
In Condition 2 and Condition 3 we obtained similar results to Condition 1 (Table 3)

### *Sway force plate conditions (Condition 4, Condition 5 and Condition 6)*

In Condition 4 four PCs explained the 89% of the total variation of the postural parameters (Table 4). PC1 was correlated principally with parameters that describe the width of oscillations. Nevertheless, in this condition, PC1 was correlated even with all the others posturographic parameter except AD.
PC2, instead, was correlated principally with parameters that describe the morphology of the Power Spectral Density (PSD). But, in this condition, an highly correlated parameter was MV (r = 0.73); moreover there was a correlation of PC2 even with two area measures (CEA and SA) and with MF.
PC3 was correlated (r = 0.54) with only one posturographic parameter: AD.
PC4 was correlated exclusively with AD and MF (r = -0.71, r = 0.49).
In Condition 5 and Condition 6 we obtained similar results to Condition 4 (Table 4) except for PC4 that was correlated with FD.
In Conditions 4 and 6, the fifth PC needed in order to account the 90% of the total variance are mainly correlated with f95 and FD.

**Table 3** Conditions 1, 2 and 3: coefficients of the Principal Components (PCs) and correlation coefficients between parameters and corresponding PC. Only values of |r|>0.4 are shown in brackets.

| | | Trajectory measures | | | | | | Frequency measures | | | | Area measures | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | MD | RMS | RANGE | MV | MF | TP | f50 | f95 | CF | FD | AD | CCA | CEA | SA |
| Condition 1 | PC1 (50%) | -0.37 (-0.97) | -0.37 (-0.98) | -0.35 (-0.92) | -0.24 (-0.63) | 0.21 (0.55) | -0.33 (-0.87) | 0.12 | 0.08 | 0.11 | -0.09 | -0.05 | -0.36 (-0.96) | -0.34 (-0.91) | -0.32 (-0.84) |
| | PC2 (77%) | 0.05 | 0.03 | 0.04 | 0.34 (0.67) | 0.32 (0.63) | 0.00 | 0.41 (0.81) | 0.43 (0.84) | 0.46 (0.90) | -0.38 (-0.74) | 0.02 | 0.03 | 0.10 | 0.22 (0.43) |
| | PC3 (85%) | -0.04 | -0.02 | 0.09 | 0.06 | 0.11 | 0.06 | 0.06 | -0.22 | -0.14 | -0.22 | -0.92 (-0.95) | 0.03 | -0.01 | 0.05 |
| | PC4 (90%) | -0.05 | -0.06 | -0.02 | 0.18 | 0.27 | -0.07 | -0.44 | 0.35 | 0.22 | 0.65 (-0.54) | -0.25 | -0.07 | 0.02 | 0.18 |
| Condition 2 | PC1 (53%) | -0.33 (-0.91) | -0.35 (-0.96) | -0.35 (-0.95) | -0.26 (-0.72) | 0.07 | -0.34 (-0.94) | 0.15 (0.42) | 0.14 | 0.15 (0.42) | -0.15 (-0.42) | -0.08 | -0.36 (-0.98) | -0.34 (-0.93) | -0.33 (-0.91) |
| | PC2 (82%) | 0.03 | 0.04 | 0.09 | 0.32 (0.63) | 0.44 (0.88) | 0.09 | 0.41 (0.82) | 0.40 (0.80) | 0.42 (0.85) | -0.33 (-0.65) | -0.16 | 0.07 | 0.11 | 0.15 |
| | PC3 (88%) | 0.00 | -0.02 | -0.05 | -0.05 | -0.07 | -0.04 | 0.08 | 0.18 | 0.15 | -0.08 | 0.95 (0.91) | 0.01 | 0.07 | 0.06 |
| | PC4 (93%) | 0.21 | 0.15 | 0.08 | 0.00 | -0.26 | -0.08 | 0.37 | -0.37 | -0.25 | -0.71 (-0.60) | 0.02 | -0.01 | -0.08 | -0.11 |
| Condition 3 | PC1 (50%) | -0.36 (-0.96) | -0.37 (-0.97) | -0.35 (-0.94) | -0.18 (-0.48) | 0.21 (0.55) | -0.33 (0.51) | 0.19 | 0.15 (0.44) | 0.17 (-0.48) | -0.18 | -0.05 (-0.84) | -0.35 (-0.76) | -0.32 (-0.96) | -0.29 (-0.97) |
| | PC2 (80%) | 0.08 | 0.07 | 0.09 | 0.38 (0.79) | 0.35 (0.72) | 0.06 (0.75) | 0.37 (0.78) | 0.38 (0.85) | 0.41 (-0.73) | -0.35 | -0.15 | 0.07 (0.53) | 0.18 | 0.26 |
| | PC3 (87%) | -0.03 | -0.07 | -0.12 | 0.10 | 0.05 | -0.07 | -0.01 | 0.08 | 0.04 | 0.00 | 0.93 (-0.89) | -0.12 | 0.23 | 0.13 |
| | PC4 (91%) | 0.06 | 0.07 | 0.10 | -0.12 | -0.11 | 0.33 | 0.48 | -0.37 | -0.14 | -0.55 (-0.41) | 0.20 | 0.13 | -0.17 | -0.28 |

**Table 4** Conditions 4, 5 and 6: coefficients of the Principal Components (PCs) and correlation coefficients between parameters and corresponding PC. Only values of |r|>0.4 are shown in brackets.

| | | Trajectory measures | | | | | Frequency measures | | | | | Area measures | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | MD | RMS | RANGE | MV | MF | TP | f50 | f95 | CF | FD | AD | CCA | CEA | SA |
| Condition 4 | PC1 (48%) | -0.33 (-0.87) | -0.36 (-0.93) | -0.36 (-0.94) | -0.18 (-0.47) | 0.21 (0.54) | -0.33 (-0.87) | 0.19 (0.50) | 0.20 (0.52) | 0.22 (0.56) | -0.18 (-0.46) | 0.00 | -0.36 (-0.93) | -0.30 (-0.78) | -0.27 (-0.70) |
| | PC2 (73%) | 0.11 | 0.08 | 0.10 | 0.39 (0.73) | 0.29 (0.55) | 0.06 | 0.38 (0.70) | 0.34 (0.63) | 0.39 (0.74) | -0.39 (-0.73) | 0.18 | 0.06 | 0.22 (0.42) | 0.30 (0.55) |
| | PC3 (82%) | -0.34 | -0.29 | -0.01 | 0.21 | 0.30 | 0.07 | -0.26 | -0.20 | -0.23 | 0.17 | 0.50 (0.54) | -0.27 | 0.22 | 0.31 |
| | PC4 (89%) | -0.17 | -0.09 | 0.11 | 0.34 | 0.48 (0.49) | 0.27 | -0.04 | -0.16 | -0.07 | 0.02 | -0.69 (-0.71) | -0.02 | -0.14 | -0.03 |
| Condition 5 | PC1 (53%) | -0.35 (-0.96) | -0.36 (-0.98) | -0.34 (-0.92) | -0.19 (-0.53) | 0.20 (0.56) | -0.33 (-0.90) | 0.20 (0.54) | 0.16 (0.45) | 0.18 (0.49) | -0.17 (-0.47) | -0.05 | -0.35 (-0.96) | -0.32 (-0.88) | -0.29 (-0.81) |
| | PC2 (82%) | 0.07 | 0.07 | 0.14 | 0.39 (0.78) | 0.35 (0.71) | 0.13 | 0.35 (0.70) | 0.38 (0.76) | 0.40 (0.80) | -0.34 (-0.68) | -0.23 (-0.46) | 0.07 | 0.12 | 0.24 (0.49) |
| | PC3 (88%) | 0.06 | 0.02 | -0.07 | -0.01 | -0.04 | -0.12 | 0.21 | 0.11 | 0.11 | -0.12 | 0.92 (0.86) | -0.02 | 0.15 | 0.13 |
| | PC4 (92%) | -0.02 | -0.03 | 0.02 | -0.17 | -0.18 | -0.04 | 0.39 | -0.46 | -0.31 | -0.63 (-0.48) | -0.14 | -0.06 | 0.22 | 0.12 |
| Condition 6 | PC1 (54%) | -0.32 (-0.88) | -0.34 (-0.94) | -0.33 (-0.92) | -0.21 (-0.59) | 0.20 (0.56) | -0.30 (-0.82) | 0.25 (0.68) | 0.21 (0.57) | 0.23 (0.62) | -0.24 (-0.66) | -0.09 | -0.33 (-0.91) | -0.30 (-0.82) | -0.28 (-0.78) |
| | PC2 (75%) | 0.06 | 0.09 | 0.13 | 0.39 (0.66) | 0.33 (0.57) | 0.09 | 0.34 (0.58) | 0.37 (0.63) | 0.42 (0.71) | -0.33 (-0.56) | 0.07 | 0.12 | 0.23 | 0.31 (0.52) |
| | PC3 (82%) | -0.16 | -0.08 | 0.08 | 0.12 | 0.13 | -0.18 | -0.11 | -0.15 | -0.08 | -0.03 | 0.91 (0.92) | -0.16 | -0.02 | 0.04 |
| | PC4 (88%) | -0.24 | -0.24 | 0.10 | 0.34 | 0.62 | 0.28 | -0.30 | -0.14 (-0.44) | -0.13 | 0.27 (-0.42) | -0.25 | -0.18 | -0.06 | 0.00 |

Only in Condition 6 four posturographic parameters over 14 were correlated (coefficient of determination $r^2 \geq 0.25$) with the age of the subjects: RANGE ($r^2$=0.27), MV ($r^2$=0.27), CEA ($r^2$=0.25), SA ($r^2$=0.28). In all the other conditions there were no significant correlations between the posturographic parameters and the regressors chosen.

### *The main four PCs along the six conditions of SOT*

Tables 3, 4 show the differences between the first three conditions, with fixed force plate and the last three conditions, with sway force plate.
The figures shows, in particular, the differences between two groups of conditions for PC1: PC1, in the conditions with fixed force plate, was described principally by parameters correlated with the width of oscillation, while in the sway force plate conditions this PC was described even by frequency parameters.

## Conclusive Remarks.

In this study we analysed the values of 14 posturographic parameters in six different conditions of the SOT, in order to identify the minimum number of parameters to accurately describe the subjects' oscillations.

The posturographic parameters were not correlated with biological factors except for Condition 6 where age influenced four parameters. Older subjects had a lower response in this condition, probably because aging affects on the Central Nervous System reducing the capacity to distinguish an erroneous visual input. The literature reports that visual impairment in elderly subjects is strongly associated with an elevated risk of falling and a deterioration of postural control [12].
PCA suggests that, in order to account enough of the total variance of the posturographic parameters, at least four PCs are necessary for every one of the six conditions.
In the condition with fixed force plate and visual reference (Condition 1) we confirmed Rocchi et al. [6] results in a shorter acquisition time period (our parameters were recorded in a period of 20s instead of 60s). This condition is comparable with a standard stabilometric trial.
The results showed the high variability of normal responses, even when subjects had similar equilibrium scores.
The SOT equilibrium scores are not sufficient to describe the CoP displacement at all. At present, tests of balance control have not been fully developed to distinguish between the effects of different pathologies in CNS areas or between a CNS versus biomechanical/musculoskeletal anomaly [13]. For example we have noted that patients with CNS pathologies, for example Parkinson's disease, which influence balance function, could have a normal SOT response [14, 15].
Our study suggests a feature selection procedure to choice dynamic posturographic parameters that could improve the diagnostic power of SOT. Further study is warranted to clarify the utility of this analysis in the assessment of postural strategies used by pathological population.

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