Department of Veterans Affairs

Journal of Rehabilitation Research and Development Vol. 32 No. 3, October 1995
Pages 227-235

Phase plane analysis of stability in quiet standing

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Abstract—We analyzed the standing balance control of 11 healthy subjects and 15 subjects with bilateral vestibular hypofunction (BVH) using phase plane (velocity versus displacement) plots. We hypothesized that maintaining postural stability requires control of both the position and momentum of the center of gravity (CG) and infer that it is advantageous to use both velocity and displacement data to characterize balance control. Phase plane plots provide insight into this dynamic aspect of balance control. We evaluated phase plane plots based on whole body CG and center of pressure (CoP). We varied stability by altering the base of support and visual information. Three different foot placements were used: feet wide apart, feet together, and semitandem stance. Feet together standing was performed with eyes open and with eyes closed. The phase plane plots show changes in stability as base of support is altered or visual input is removed and reveal stability differences between the control and BVH groups. The root mean square variance of velocity and displacement was used to quantify the phase plane information. This parameter showed significant differences between activities and between groups. We conclude that phase plane plots that combine displacement and velocity information are more useful in characterizing balance control than displacement or velocity alone.

Key words: *balance, center of gravity, center of pressure, force plates, phase plane, posture, vestibular.*

This material is based on work supported by the Whitaker Foundation and the National Institute on Disability and Rehabilitation Research.
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INTRODUCTION

Deficits of posture and balance control can severely limit activities of daily living. Such deficits also can lead to falls, a major source of morbidity and mortality in the elderly population (1,2). Many sensory and motor system pathologies adversely affect balance control, including balance impairment associated with vestibular system pathologies. Vestibular physical therapy treatments have been developed to improve the function and quality of life of persons with vestibular pathologies such as bilateral vestibular hypofunction (BVH). Objective measures of balance control are needed to assess the effectiveness of these treatments (3,4). In addition, BVH provides a model of balance impairment where the sensory deficit is quite well characterized. Defining the relationship between the sensory system pathology and resulting functional impairment will permit improved analytical and conceptual models of the balance control system and provide insight into the less understood forms of balance impairment.

Balance testing is commonly done using force plates and some measure of center of pressure (CoP) movement called postural sway (5-9). Several different parameters are used to quantify postural sway: linear measures, such as mean sway path (10-12), area measures, such as sway area (9,11-15), and velocity measures, such as mean sway velocity (5,6). We hypothesize that maintaining postural stability requires not only control of the body center of gravity (CG) position but also control of its momentum. We expect, therefore, that measures that incorporate both position and velocity of the CG or

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CoP will be more useful in characterizing balance control than displacement measures alone.

A phase plane plot is developed by plotting the time derivative of a parameter against that parameter. A phase plane plot with CG velocity as the ordinate and CG displacement as the abscissa characterizes both CG displacements and CG velocity or momentum. Such plots can provide insight into both the static and dynamic aspects of balance control.

CoP movement is assumed to reflect CG movement, but this is not strictly true (16). We have explored the relationship between CoP and CG kinematics and confirmed that a reasonable approximation of CG kinematics can be derived from measurements of CoP displacement if the standing posture is quasi-static, such as quiet standing in healthy controls (17). While CG kinematics are of primary interest on theoretical grounds, CoP displacements are more readily and economically measured, accounting for their widespread use. Only a force plate is required to measure CoP movement, while a kinematic data acquisition system and a whole body model are required to obtain CG kinematics (18). Because CoP measures are so prevalent in balance control research and are widely used clinically for both diagnosis and treatment, we also present here phase plane plots based on CoP displacements.

METHODS

We estimated the body CG displacements using whole body kinematic data acquired with a four-camera SELSPOT II™/TRACK® kinematic data acquisition system. The kinematic data and subject-specific anthropometric data were incorporated into our 11-segment whole body model (18) to estimate the body CG kinematics. The subjects stood on two force plates in the approximate center of our viewing volume. Their sagittal planes were aligned approximately with our laboratory global X and Y (vertical) axes. The CG kinematics were expressed as displacements from the initial position in the laboratory global coordinate system. Anterior/posterior displacements correspond to movements along the global X axis: lateral displacements correspond to movements along the global Z axis.

The CoP was measured using two Kistler™ force plates. The subjects stood with one foot on each force plate to permit individual ground reaction forces and centers of pressure to be measured. This information was needed for detailed analysis of trials in which the subject had to take a step to maintain balance control. The combined CoP was calculated from the individual force plate CoPs and the known force plate locations and orientations. CoP displacements were also measured in the laboratory global coordinate system using the same convention used for CG displacement. Force plate data were obtained at 153 Hz in synchrony with the kinematic data.

Data sets were 7 seconds long. We desired to compare force plate and kinematic data directly and 7 seconds was the longest whole body kinematic data set that could be obtained at the time of this study. Derivatives were estimated using a fifth-order Lagrangian estimator. The middle 6 seconds of data were used for analysis to avoid startup transients in the derivative estimates.

To compare the phase plane plots quantitatively, we used a set of unitless parameters to characterize the size of the anterior/posterior (AP) and lateral (Lat) phase plane distributions. The parameters were based on the root mean square variance of the position and velocity components. For AP movement, the parameter was calculated using Equation 1a. For lateral movement the parameter was given by Equation 1b.

$$\sigma_{AP_r} = \sqrt{\sigma_{AP_d}^2 + \sigma_{AP_v}^2} \qquad [1a]$$

$$\sigma_{Lat_r} = \sqrt{\sigma_{Lat_d}^2 + \sigma_{Lat_v}^2} \qquad [1b]$$

Where:

σ_{AP_r} and σ_{Lat_r} are the directional stability parameters.

σ_{AP_d} and σ_{Lat_d} are the standard deviations of the displacements.

and

σ_{AP_v} and σ_{Lat_v} are the standard deviations of the velocities.

Directional parameters were calculated for each phase plane plot, that is, for CG, CoP and TF displacements and velocities. A combined stability parameter was then calculated using Equation 1c.

$$\sigma_r = \sqrt{\sigma_{AP_r}^2 + \sigma_{Lat_r}^2} \quad [1c]$$

Analysis of variance (ANOVA) was used to determine whether the parameters were significantly related to group (control versus BVH) and test conditions.

The subjects were told to stand as still as possible. The base of support was varied by controlling foot placement. The wide base of support (FW: feet wide, the baseline measure) was obtained by placing the feet parallel and approximately 30 cm apart at the midheel; the eyes were open. The narrow base of support was obtained by placing the feet side by side with a separation of approximately 1 cm; in this condition, the subjects were tested both with eyes open (EO) and with eyes closed (EC). For semitandem stance (ST) the feet were 1 cm apart, with the heel of the forward (dominant) foot even with the toe tip of the hind foot. Foot dominance was determined by asking the subjects to pretend to kick a ball. In all cases, the feet were parallel to each other and to the sagittal plane.

Eleven non-BVH control subjects and 15 subjects with BVH were evaluated and compared. The control subjects were in good general health with no neurological or orthopedic conditions that would affect balance control. The BVH patients were diagnosed based on testing conducted in the Jenks Vestibular Laboratory at the Massachusetts Eye and Ear Infirmary that included sinusoidal vertical axis rotational (SVAR) tests showing vestibulo-ocular reflex (VOR) gains of ≥ 3 SDs below normal. The BVH subjects had no other condition that might affect balance control. Informed consent was obtained from all subjects. Subject descriptive parameters are presented in **Table 1.**

Pearson correlation coefficients were used to evaluate the relationship between stability parameters σ_r for repeat tests within a session and the relationship between AP and lateral parameters. Two-factor repeated measures ANOVA was used to assess the between group and between conditions discriminating power of the combined stability parameters. For each combined stability parameter, one-way repeated measures ANOVA was used to access the between-group discrimination for each test condition and the between-condition discriminating power for each group. The level of significance was set at 0.05.

RESULTS

Phase Plane Plot Comparison

Figures 1a and **2a** show a set of lateral CG and lateral CoP phase plane plots representing seven standing trials from a test session of a typical control subject. The seven plots in **Figure 1a** show the lateral CG velocity plotted against the lateral CG displacement. In this analysis, the initial CG position was taken to be zero and all subsequent data points are displacements from that initial position. Lateral CoP kinematics for the same seven standing trials are shown in **Figure 2a.**

Figures 1b and **2b** are the corresponding plots for a typical BVH subject that provide a clear pictorial indication of the difference in stability between the normal and BVH subject in all conditions except the FW baseline. The larger areas shown in these plots indicate the greater variability in both position and velocity for the BVH subject. The second ST trial **(Figure 2b/6)** is of particular interest as it shows the effect of a transient loss of

Table 1.
Subject parameters.

	N	Sex	Age (yr)	Height (m)	Weight (kg)	BMI (kg/m2)
Control Mean	11	7M 4F	50.25	1.71	69.17	23.40
Control SD			22.63	0.09	11.29	2.09
BVH Mean	15	4M 11F	66.01	1.68	65.54	23.40
BVH SD			15.72	0.11	11.50	3.46

BVH = bilateral vestibular hypofunction; BMI = body mass index.

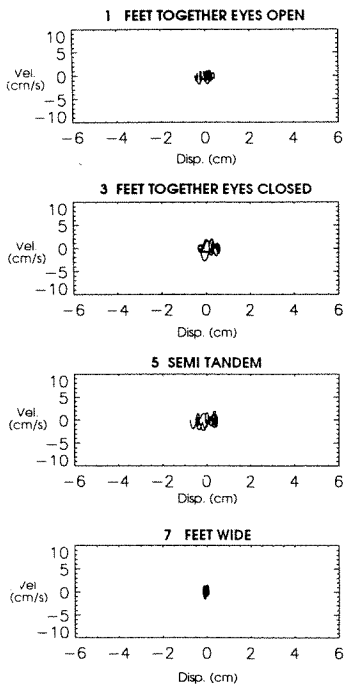

Figure 1a.
Lateral CG Phase Plane Plots for two sets of seven standing posture control trials of the typical control subject.

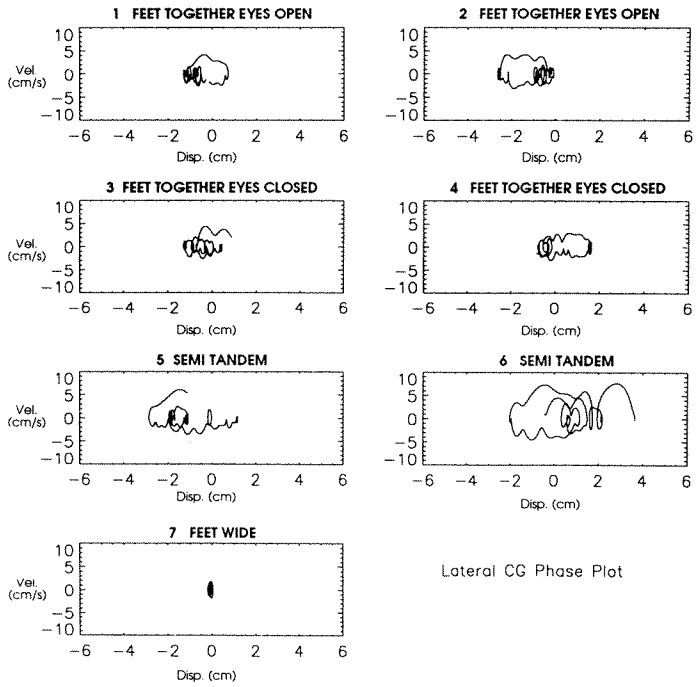

Figure 1b.
Lateral CG Phase Plane Plots for two sets of seven standing posture control trials of the typical BVH subject.

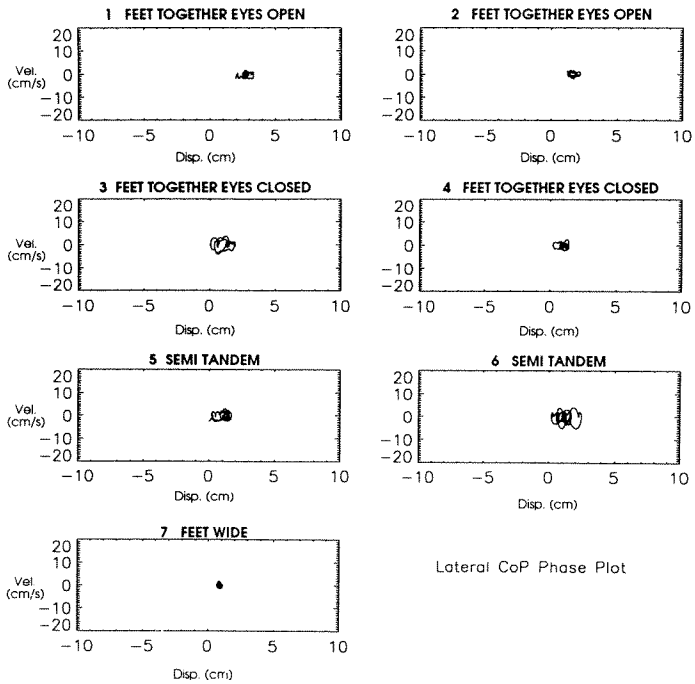

Figure 2a.
Lateral CoP Phase Plane Plots for two sets of seven standing posture control trials of the control subject in Figure 1a.

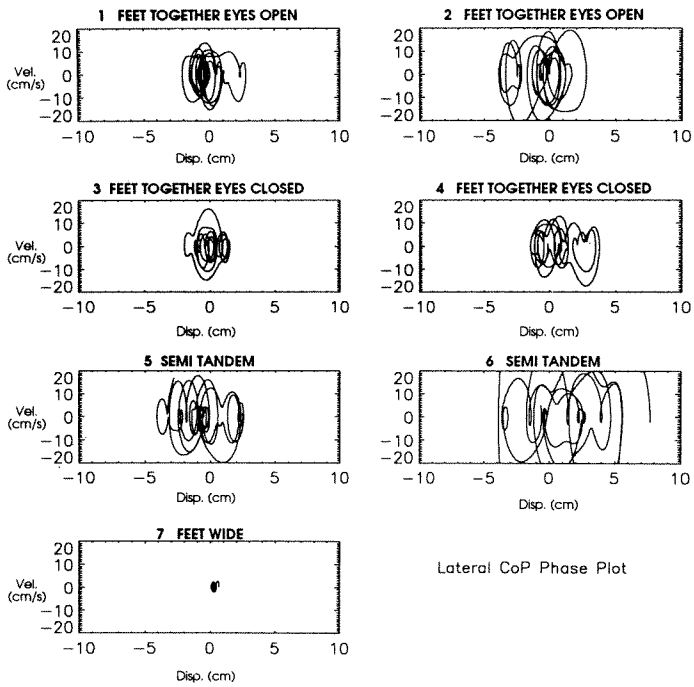

Figure 2b.
Lateral CoP Phase Plane Plots for two sets of seven standing posture control trials of the BVH subject in Figure 1b.

balance control: the subject was unable to stand quietly and had to take a small step to recover. Note that such trials were excluded from the statistical analysis described below.

Comparing the plots within a set provides an indication of the relative stability of the different conditions. The small pattern of the FW condition shows its relative stability. The larger patterns of the EO condition indicate the lesser stability of this condition, and the ST stance is less stable still. The effect of altering visual input may be accessed by comparing the EO and EC trials. Postural stability is somewhat less for EC than for the EO condition with the same base of support.

Figure 3 shows the AP CG phase plane plots for the data set of the subject whose lateral CG phase plane plots are shown in **Figure 1b.** Manipulating the base of support had a similar effect on the AP and the lateral phase plane plots for both CG and CoP. Similarly, removing vision affected both AP and lateral phase plane plots.

Stability Parameter Analyses

The Pearson correlations for the AP and lateral parameters are quite high. The correlation for AP and lateral CG parameters was 0.8807 and the correlation for AP and lateral CoP parameters was 0.9316. The high correlation indicates that AP and lateral balance control are closely linked. The combined stability parameter σ_r, the root mean square of the AP and lateral stability parameters, was used for statistical comparison.

For each session, repeat trials were obtained for EO, EC, and ST conditions. The correlations between the first and second trial stability parameters σ_r are shown in **Table 2.** Except for CGAP, these values were reasonably well correlated for the healthy control subjects. For the BVH group, the stability parameters σ_r were poorly correlated. This is not a training effect, as the subjects practiced the stance before data were collected and the second trial was not consistently better than the first. In fact, there was a tendency for the BVH subjects to do worse on the second trial. For those conditions with repeat trials, the one with the best (lowest absolute value) stability parameter was used for statistical comparison as this represented the subject's best performance.

The mean and standard deviation of σ_r for each condition and group are shown in **Figures 4a** and **4b.** Both the CG and CoP parameters increase, indicating less stability, as the condition changes from FW to EO to EC to ST. The increase is more pronounced for the BVH group, as expected. The CoP and CG parameters are similar to each other for each of the different conditions and groups. The CoP values are slightly larger for each condition and group. This is consistent with our previous observation that the CG kinematics approximates a smoothed version of the CoP kinematics (17).

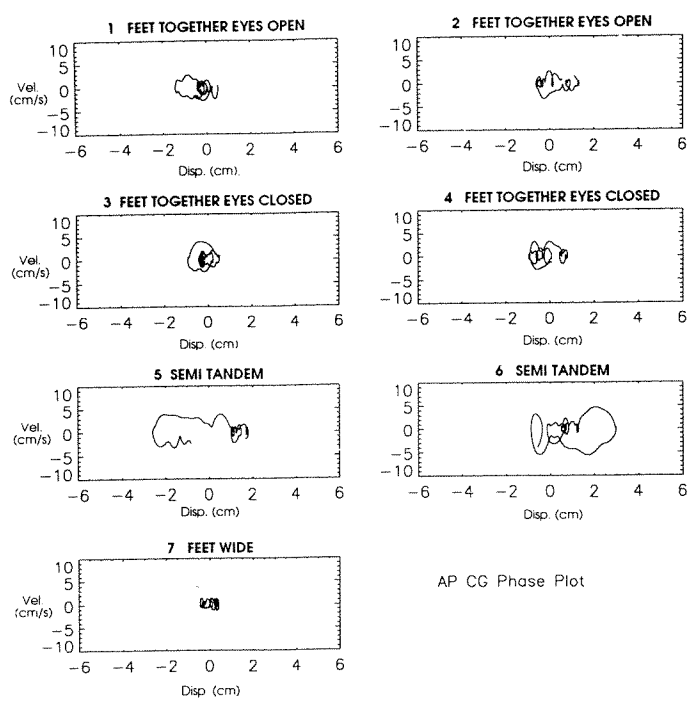

Figure 3.
AP CG Phase Plane Plots for the BVH subject, the same as shown in Figure 1b.

Between-Group Differences

The combined CG and CoP variables showed statistically significant differences between the BVH

Table 2.
Pearson correlation coefficient: Trial 1 and Trial 2.

	CGL	CGAP	COPL	COPAP
BVH	0.4990	0.4234	0.3395	0.3926
Control	0.7459	0.5028	0.9134	0.7827

CGL = lateral center of gravity; COPL = lateral center of pressure; CGAP = anterior posterior center of gravity; COPAP = anterior posterior center of pressure; BVH = bilateral vestibular hypofunction.

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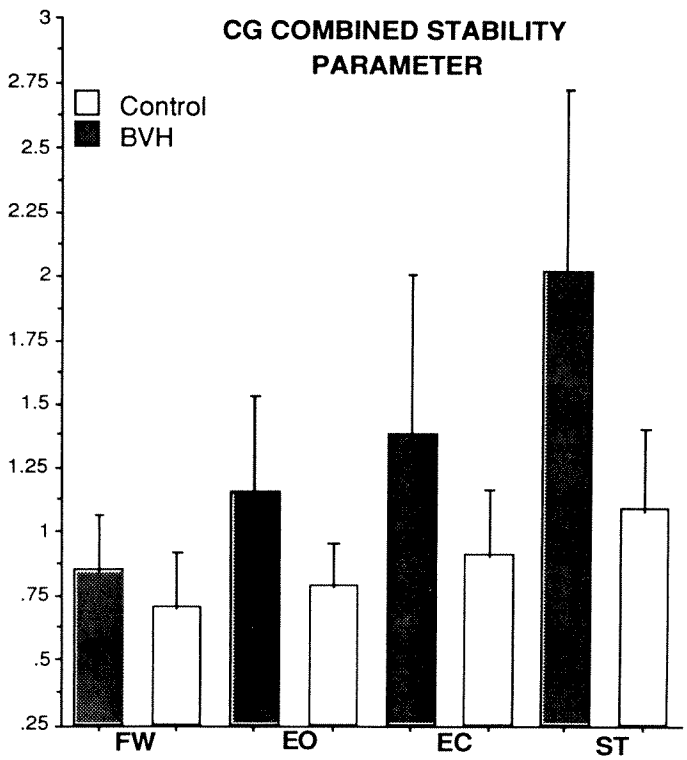

Figure 4a.
Mean and standard deviation of the CG stability parameter σ_r, the root mean square variance of Ap and lateral position and velocity, for all four test conditions for the control and BVH groups.

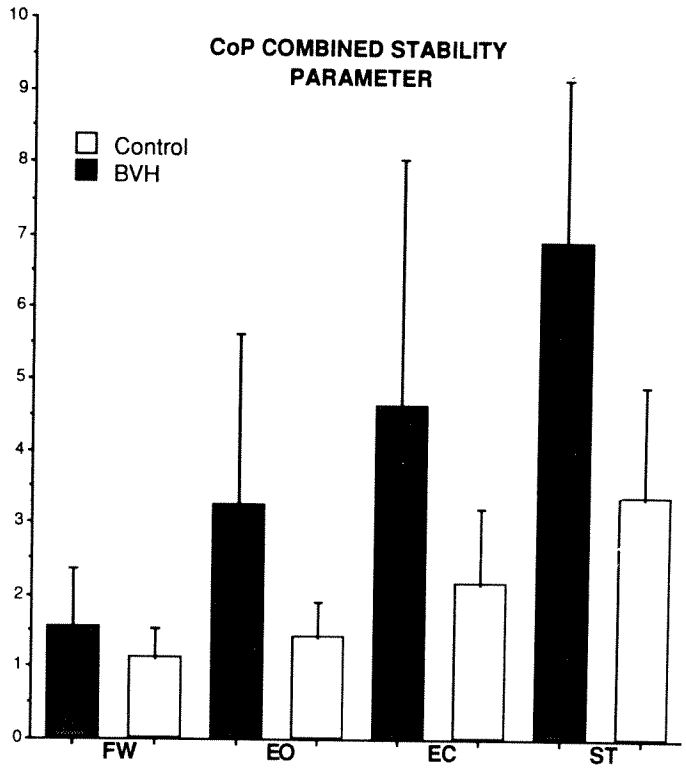

Figure 4b.
Mean and standard deviation of the CoP stability parameter σ_r, the root mean square variance of Ap and lateral position and velocity, for all four test conditions for the control and BVH groups.

and control groups (**Table 3**) over all conditions using a 2-factor repeated measures multivariate ANOVA. A repeated measures ANOVA was used to evaluate the group discriminating power of each test condition. The stable FW condition did not discriminate well between groups. The ST condition provided the best between-group discrimination. The EO and EC conditions also discriminated between groups, but the level of statistical significance was less.

We also examined the discriminating power of parameters based on displacement or velocity information alone. Stability parameters based on AP CoP displacement and velocity and lateral CoP velocity yielded statistically significant differences in between-group variances ($p=0.008$, 0.048, and 0.0057, respectively). Stability parameters based on lateral CoP displacement, AP and lateral CG displacement, and velocity did not discriminate between groups at the $p<0.05$ level.

Table 3.
Combined stability parameter (σ_r) for CG and CoP to compare between control and BVH group differences.

Condition	Significance (Pr>F) of Combined Parameter Between Group ANOVA CG	CoP
Combined	0.0007*°°	0.0042*°°
FW	0.1007	0.1141
EO	0.0052*°°	0.0211*
EC	0.0302*	0.0295*
ST	0.0007*°°	0.0003*°°

The p values for the ANOVA are shown. Statistically significant differences ($p<0.05$) are identified by a *, $p<0.01$ is identified by °°. FW = feet 30 cm apart; EO = feet together, eyes open; EC = feet together, eyes closed; ST = feet in semitandem position; CG = center of gravity; CoP = center of pressure.

Between-Condition Differences

The 2-factor repeated measures multivariate ANOVA showed that the variances of the combined

CG and CoP parameters were a significant function of the test condition for the combined control and BVH group data. Repeated measures ANOVA was used to determine which conditions produced significant differences in the variables; the results are summarized in **Table 4.** The control group showed a marginally significant difference between the EO and EC conditions for the CG parameter with a significant difference for the CoP parameter. The FW and EO conditions were not significantly different for the CG parameter and were marginally different for CoP parameter. For the control group, the other conditions were significantly different. The ST stance was significantly different from both the FW and EO stances.

The results for the BVH group were similar, but between-condition differences tended to be more significant. The BVH group showed a significant difference between the EO and EC conditions for both the CG and CoP parameters. In contrast to the controls, the FW and EO conditions were also significantly different for both the CoP and CG parameters. Again, ST stance differed from both the FW and EO conditions at very high levels of significance.

DISCUSSION

Most prior posturography studies focus on CG or CoP displacement, assuming those CG excursions near the perimeter of the base of support yield instability (19–26). Phase plane plots provide a pictorial and a quantitative measure of stability in quiet standing. These data suggest that the CG and CoP phase plane plots are useful in studying and quantifying relative postural stability. CoP phase plane plots, which are easier to obtain, are as informative as CG phase plane plots for these patients and conditions. The sensitivity of postural stability to base of support alterations is readily apparent.

One limitation of these plots is that relatively stable and unstable states both occupy the same phase space. In **Figure 2b,** for example, the subject is clearly less stable in ST stance than in FW stance. However, the phase plane plots for both conditions are centered at the same location in the two dimensional state space. As stability degrades, the bounds of the occupied space expand, but there is no sharply defined boundary between stability conditions. A state space mapping, in which different stability conditions occupied distinct regions is highly desirable. This state space may well be more than two dimensional.

When a simple parameter that combines AP and lateral position and velocity information is used, differences in lateral stability due to foot placement are apparent and can be easily quantified. The ST stance was significantly different from both the FW and feet together conditions for both groups, with this difference being more significant for the BVH group. ST stance provides the same lateral base of support width as feet together stance and provides a longer AP base of support than

Table 4.
Combined stability parameter (σ_r) for CG and CoP for the BVH and control subjects to compare the effect of activity conditions.

	Significance (pr>F) of Between Conditions ANOVA			
	CG-BVH	CG-Control	CoP-BVH	CoP-Control
Combined	0.0001*°°	0.0001*°°	0.0001*°°	0.0001*°°
FW-EO	0.0025*°°	0.0869	0.0036*°°	0.0435*
FW-ST	0.0004*°°	0.0009*°°	0.0001*°°	0.0002*°°
EO-EC	0.0374*	0.0474*	0.0277*	0.0043*°°
EO-ST	0.0011*°°	0.0024*°°	0.0001*°°	0.0003*°°

The p values for the ANOVA are shown. Statistically significant differences ($p<0.05$) are identified by a *, $p<0.01$ is identified by °°
FW = feet 30 cm apart; EO = feet together, eyes open; EC = feet together, eyes closed; ST = feet in semitandem position; CG = center of gravity; CoP = center of pressure.

either the FW or feet together conditions. Load bearing tends to be concentrated heavily on the hind leg and this may contribute to the instability of this position.

The effect of removing visual information is also measurable but less significant. The EO–EC difference was approximately the same for the BVH and control groups. The BVH group was expected to be especially dependent on visual information. The feet together condition did not stress balance control severely or induce severe dynamics. Hence, proprioceptive information may be adequate for balance control without either vestibular or visual information. It should be noted that one of the BVH subjects was not able to perform the EC task at all and several of the subjects were only successful for one trial out of two. The stability parameter σ_r was calculated based on successful trials only and may not completely reflect the difficulty that BVH subjects had with the EC condition.

The CG- and CoP-based phase plane plots provided very similar between-group discriminations. This suggests that phase plane studies using force plates only may be useful. For this particular analysis, estimation of the CG using whole body kinematics does not appear to add significantly to our knowledge. Velocity information alone and in combination with displacement information discriminated between groups more effectively than displacement information. CG or CoP position, which is often examined, did not discriminate between groups. Because the combined stability parameters measure both the displacement and velocity, they might be expected to be more robust measures over a range of pathologies.

We did not use mean sway path, mean sway area, or mean sway velocity to quantify CG or CoP movement. We did examine measures of the variability of CG and CoP positions during our trials. However, as our trials were only 7 seconds long, and the CoP variables are usually calculated for much longer data sets, the values would not be directly comparable. Technical modifications to our data acquisition and processing systems now permit us to obtain data sets of longer duration. In the future, we plan to determine if quiet standing for extended periods, 20 to 30 seconds, is really a stationary process. We will compare phase plane parameters for longer trials to those determined from 7-second trials. We will also explore the correlation between phase plane based parameters and the more classic posturography parameters.

Further work is needed to determine if the analysis is useful for discriminating between balance impairment due to vestibular dysfunction and balance impairment due to other causes, such as Parkinson's disease. The ability to differentiate between different levels of vestibular dysfunction also needs to be determined. The patient population in this study was comparatively small.

The effect of age also needs to be addressed with comparisons of young and old normal subjects and comparisons of age-matched patient and control populations. This was not possible with our initial data, but we are currently expanding our database.

CONCLUSION

The usefulness of the phase plane analysis for quantifying balance impairment has been demonstrated. These data suggest that including combined displacement and velocity parameters in a phase plane analysis, clearly discriminates balance-impaired from non-impaired subjects. Whole body CG and CoP data discriminate equally well between normal controls and subjects with vestibular pathology. We conclude that combined displacement and velocity data are useful in studies of standing balance. The fact that the combined parameter and the velocity parameters were both highly discriminatory between balance-impaired and control subjects, while displacement-only parameters were not, supports our hypothesis that control of momentum is important even in such an apparently static activity as standing.

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