Center-of-Pressure Parameters Used in the Assessment of Postural Control

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Objective: To define the numerous center-of-pressure derivatives used in the assessment of postural control and discuss what value each might provide in the assessment of balance. *Data Sources:* MEDLINE and SPORTDiscus were searched with the terms *balance, postural control, postural sway,* and *center of pressure*. The remaining citations were collected from references of similar papers. A total of 67 references were studied. *Conclusions:* Understanding what is represented by each parameter used to assess postural control is crucial. At the present time the literature has failed to demonstrate how the variables reflect changes made by the postural-control system. Until it can be shown that the center of pressure and its derivatives actually reveal changes in the postural-control system, the value of using these measures to assess deficits in postural control is minimized. *Key Words:* forceplate, center of pressure, balance

Maintaining body equilibrium, which is thought by most to be an effortless task, is actually a complex process involving the coordinated activities of multiple sensory, motor, and biomechanical components.[1] Because the design of the human body is inherently unstable, a postural-control system is required in order to preserve an upright stance. This system tends to degenerate with age[2-6] and is also affected by multiple neurological disorders,[3,7-13] as well as musculoskeletal[14-20] and head injuries.[11,21-23] Impairment of the postural-control system has undergone much investigation in hopes that medical professionals can create effective rehabilitation protocols to reverse or improve the damage caused by the various pathologies.

Since the early 1970s, force platforms have been used to acquire quantitative measures and analyses of postural control. A force platform is a technical apparatus that provides an indirect assessment of changes in postural sway by recording the ground-reaction forces projected from the body.[4,24] The center of pressure (COP) is calculated from these ground-reaction forces. It reflects the trajectory of the center of mass and the amount of torque applied at the support surface to control body-mass acceleration.[12] Various parameters including mean sway amplitude, maximum sway am-

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plitude, minimum sway amplitude, peak-to-peak amplitude, sway path, sway velocity, root-mean-square (RMS) amplitude, and RMS velocity have been derived from COP data in order to quantify alterations in balance. Spectral- and time-frequency analyses are techniques that quantify postural control in terms of frequency and have also been used to assess changes in postural control.[16,25-34] Center of gravity (COG) is a variable analyzed in the evaluation of postural sway, but this measure cannot be directly obtained from a force platform.[6,12]

With the numerous parameters available to quantify postural control, the question of which measure to use often arises. Selection of a parameter is a controversial topic in the literature, because conflicting opinions exist as to which measures are most sensitive to the changes occurring while one is standing upright. In addition, how the changes seen in the various parameters reflect alterations made by the postural-control system remains unclear. Therefore, the purpose of this article is to review the COP variables used to quantify postural control and discuss what value each might provide in the assessment of balance.

Basic Definitions

The terms defined in this section are used throughout the article. Understanding what each term represents is important when discussing the various parameters used to assess postural control.

Balance. Balance is a generic term describing the dynamics of body posture to prevent falling.[35] It is the ability of the body to maintain the center of gravity within the limits of stability as determined by the base of support.[36]

Postural Control. Postural control is the task of controlling the body's position in space for the dual purposes of stability and orientation.[37]

Postural Sway. Postural sway refers to changes in the center of gravity (COG). This term should not be used to represent changes in the center of pressure (COP).[6]

Postural-Control System. The postural-control system involves a complex interaction between musculoskeletal and neural systems (see Figure 1). It has 2 primary functions: first, to ensure that balance is maintained, and second, to fix the orientation and position of body segments, which serve as a reference frame, in order for accurate perception and action to take place with respect to the external environment.[38]

COG vs COP

Researchers and clinicians attempting to quantify adjustments made in the postural-control system have focused on the movement of 2 variables: the COP and the COG. Oftentimes, these terms are thought to be synonymous with one another, but this is not the case. The human body has a given
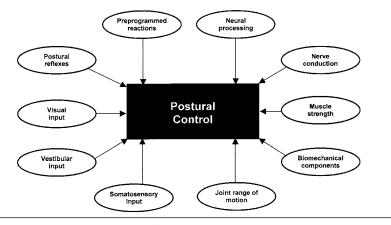
Figure 1   General representation of the postural-control system.

mass, and the vertical position of the center of this mass from the ground, or the center of gravity, changes according to alterations in the positions and movements of the body segments.[6,12] The COG is considered to be a passive variable that is guided by the postural-control system.[6] The COP, on the other hand, is the center of the distribution of the total force applied to the supporting surface.[6,13] It represents the weighted average of all pressures created from the area in contact with the support surface.[12] The movement of the COP varies depending on the movement of the COG, and it also depends on the projection of the muscle forces required to control or produce the movements. Although people are not consciously aware of the positions of the COP and the COG, they are cognizant of their limits. When the limits are exceeded, one must take a step to reestablish the base of support below the COG or one will fall.[1] COP movement will always be somewhat greater than COG movement in order to maintain balance when changes in the COG occur. For example, when a posterior shift in the COG is detected by the central nervous system, a reflexive contraction of the dorsiflexors will occur, moving the COP posterior to the COG in an attempt to regain balance.

Although both COG and COP are important in the assessment of balance, COP and its derivatives are by far the most frequent dependent variables used in research, and they are therefore the focus of this article.
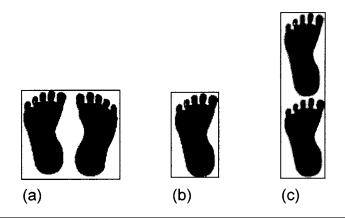
Base of Support

Before discussing the various parameters employed to assess postural control, it will be helpful to briefly review the support stances used in the literature and how they can affect the variables used to measure balance.

Most research evaluating postural control has recorded the net COP during a double-legged stance. The COP obtained when both feet are in

contact with a single force platform has been termed the net COP.[6,12,13] The net COP will be found between the left and right feet, depending on how much weight each foot absorbs. In order to obtain the COP located under each foot, 2 force platforms are needed.

The double-legged stance provides the widest base of support when compared with the other stances that we discuss later in this section (Figure 2). Over two thirds of our body's weight, however, is balanced two thirds of our body's height above the ground over our legs.[6] This places great demands on the postural-control system just to maintain balance under this normal stance condition.

The single-legged stance allows for the assessment of balance under conditions that introduce additional challenges to the postural-control system. This stance reduces the base of support and requires the postural-control system to make more adjustments in order to prevent a fall. In addition to further challenging the postural-control system, this stance also allows a subject to act as his or her own control when the clinician or researcher wishes to compare the steadiness between 2 legs. Several studies[13,24,39,40] have shown that COP does not differ between dominant and nondominant limbs. The evaluator must be cautious, however, when comparing an injured with an uninjured limb. A bilateral change might occur with injury, making the comparison of these limbs invalid.

Single-legged-stance testing not only introduces a challenge to the postural-control system but also presents a challenge to the clinician or

Figure 2 Variations in the base of support (BOS): (a) Double-legged stance, (b) single-legged stance, and (c) tandem stance. With stance (a) the medial/lateral (M/L) BOS is twice as large as with stances (b) and (c). In the tandem stance the anterior/posterior (A/P) BOS is larger than in stance (a) and (b). Stance (b) has the smallest BOS in both the A/P and M/L directions.

researcher. Many subjects encounter problems standing on 1 leg for any period of time, especially when an additional sensory system that functions to maintain balance is hindered (ie, reducing visual input by closing the eyes). The evaluator must determine whether a touchdown by the nonstance leg should be ignored or whether the trial containing the touchdown should be eliminated and repeated. In order to eliminate touchdowns, Goldie[41] has suggested shortening the trial duration to 5 seconds. Although this might eliminate touchdowns, this trial duration is not appropriate for all methods of analysis. Some clinicians have incorporated safety harnesses into testing in order to minimize touchdowns. This is an effective method of reducing touchdowns, but the harness might influence the postural-control system by providing an additional sensory input. In our laboratory, we find that orienting the subject to the surroundings before testing and providing a rail on either side of the force platform provide a sense of safety for the subject and tend to minimize touchdowns.

It has been argued that eliminating touchdowns from the data might remove a component of what the clinician is attempting to measure—changes in postural stability. An increased number of touchdowns might indicate a decrease in postural control. Instead of eliminating touchdowns, some evaluators have incorporated them into the study design as a dependent measure. If this approach is taken, subjects should be instructed to touch down off of the force platform so as not to interfere with the COP measure. Counting the number of touchdowns in a trial might provide another measure for evaluating postural control.

The tandem stance has also been used to challenge the postural-control system. This stance requires the subject to stand heel to toe. Foot position, dominant forward/nondominant behind or vice versa, did not create a change in the mean anterior/posterior (A/P) or medial/lateral (M/L) COP for this stance.[24] The tandem stance can be a valuable alternative to the single-legged stance when one is trying to place additional demands on the postural-control system, especially in the frontal plane. As stated previously, subjects experience difficulty when attempting to stand on 1 leg for an extended period of time. The tandem stance places extra stress on the postural-control system by narrowing the base of support but might allow subjects to stand for a longer trial duration. The clinician must be aware that the size of the force platform influences whether this stance can be used. Some subjects' feet, when placed in this stance, might exceed the length of the force platform.

The clinician or researcher must realize that double- and single-legged stances, as well as the tandem stance, are different from one another. Results obtained when subjects are maintaining one of these stances might not be applicable when they are maintaining another.

Maximum, Minimum, Peak-to-Peak, and Mean Amplitude

The maximum amplitude is the maximum absolute displacement of the COP from its mean, whereas minimum amplitude is the minimum displacement of the COP from its average point. An increase in either the maximum[42] or the minimum amplitude suggests a decreased ability to sustain an upright stance, and a decrease in either of these variables is thought to represent an increased ability by the postural-control system to maintain balance.

These parameters are 1-dimensional, allowing for the assessment of postural control in both A/P and M/L directions, but how accurately they reflect balance is questionable. The maximum and minimum amplitudes are single data points used to represent an entire trial of data. As many as 2500 data points can be collected for a single trial, and minimum or maximum amplitude only requires 1 of these points to be examined. This single data point is then expected to accurately quantify a change in postural control.

The maximum and minimum amplitude values are likely to show great variance between trials and between subjects. It is possible that the maximum and minimum amplitudes misrepresent increases and decreases in postural control because of the high variability of any maximum or minimum value. For example, a small perturbation in the environment (eg, a noise) that influences the postural-control system and causes a loss balance for a split second can create a larger than normal maximum amplitude.

Peak-to-peak amplitude represents the difference between the maximum and minimum amplitudes of COP.[5] Similar to the maximum and minimum amplitude values, peak-to-peak amplitude uses 2 data points that are thought to represent the changes occurring in an entire trial of data. The problems with this measure are similar to those noted for the maximum and minimum amplitude values. Two data points cannot be expected to represent all changes occurring in a data sample. Maximum and minimum amplitude values, along with peak-to-peak amplitude, are likely to cause a misinterpretation of alterations in balance and should not be used to evaluate postural control.

Mean amplitude of COP is an average value over all data points collected in a trial and is a more representative measure of postural control. Increased values in mean COP amplitude suggest decreased postural control, whereas a decrease is thought to represent increased postural stability.[7,13,21,43,44] Like the variables previously described, mean COP allows for the assessment of postural equilibrium in the A/P and M/L directions. Although all data points are included in the analysis, this statistic still has flaws. Again, imagine when sampling a trial of data that a noise occurs. This noise might cause an abnormal increase in the COP for a moment. Although this change is not as likely as maximum amplitude is to mis-represent a trial of data, because all of the data points collected in a trial are included, there is still a possibility for error. One way to prevent this error might be to take the
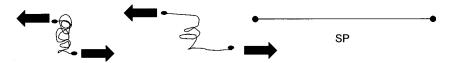
average of multiple trials.

Mean amplitude is the average COP amplitude. It has demonstrated to be reliable for individual subjects during a double-legged stance between trials (intraclass correlation coefficient = .70–.90).[13] An issue that must be addressed when considering the mean amplitude as a valid measure of postural control is how this value is calculated. From what point is the mean value actually analyzed? Is it from the center of the force platform, or does it depend on the placement of the foot or feet on the forceplate? Consider for a moment that the mean is determined from the center of the force platform, and the feet are not aligned centrally on the forceplate, where the x- and y-axes meet. The mean calculated would not be accurately represented, and this parameter might show the COP to be more A/P and/or M/L, depending on the location of the feet or foot on the platform. Let us take this scenario a step further and say that the foot position was not standardized between trials. An alteration in foot placement from the initial position would change the mean amplitude and would misrepresent a change in the data analyzed.

Mean COP has been shown to fluctuate with differing degrees of stance width, stance length, and foot angle.[44] The position of the feet or foot on the measuring device is often not standardized within a subject or between subjects, nor is it reported. This variable must be controlled when collecting data, and an educated reader must be aware that reports in the literature on research that did not control for a change in foot position might present data that misrepresent differences in mean COP amplitude.

Total Excursion of the COP and COP Velocity

Total excursion (TE) of the COP is defined as the total distance traveled by the COP over the course of the trial duration (Figure 3). TE is often referred to as sway path, but this is not an accurate description because the COP does not directly represent changes in postural sway. TE can be calculated by summing the actual distance between successive COP locations.[9] Hufschmidt et al[9] provide a comprehensive explanation of the calculation of TE.

In order to use the TE of the COP to assess postural control, an understanding of what increases and decreases in this value represent is crucial.

Figure 3   Length of a center-of-pressure (COP) excursion. The squiggly line represents a single COP trial. The straight line represents the sway path, which will be the same length as the COP trial if one were able to pull it apart.

The literature suggests that increases in TE represent a decreased ability by the postural-control system to maintain balance.[44-47] This interpretation can be argued, however. It is quite possible to see a large TE during a stable stance or to have a small TE representing an unstable stance. A large TE might simply suggest that the COP needs to make sizeable excursions or several small excursions to produce a steady posture.

The length of the path traveled by the COP does not provide the clinician or researcher with much useful information. Why is it important to know the length of the COP traveled? It has yet to be demonstrated how total COP excursion represents changes by the postural-control system. Until such a conclusion can be made, the usefulness of TE to quantify changes in postural control is minimized.

COP velocity represents the total distance traveled by the COP over time. This parameter is determined by dividing TE by the trial duration. COP velocity has been shown to be reliable between sessions when a double-legged stance is used ($R = .84$).[43]

Numerous researchers and clinicians[2,7,47-52] have used COP velocity to assess changes in COP. An increase in COP velocity is thought to represent a decreased ability to control posture, whereas a decrease in the velocity represents an increase in the ability to maintain an upright stance.[2,7,15,17,43,46,53] Like the other parameters used in the assessment of postural control, COP velocity's usefulness is questionable. Again, how this variable is represented in most of the literature might not be accurate. For example, the COP velocity in a group of control subjects who had an intact anterior cruciate ligament (ACL) was greater than in subjects who had a complete rupture of the ACL.[15] If the preceding definition always proved to be correct, one would think that the control group would have a lower COP velocity than the ACL-deficient subjects. The higher velocity in the control group might represent the generation of a normal active sway to find a stable solution to the postural challenge.

The information that is provided by the TE of the COP and COP velocity is inadequate to explain the complete nature of postural control. These measures are 2-dimensional, representing a combination of A/P and M/L COP movement. As a result, it is possible to miss important directional information. For example, the frequency of A/P movement seems to increase in patients with cerebellar lesions.[2,7] Jarnlo and Thorngren[20] reported that patients who had suffered hip fractures showed an increased mean COP in the sagittal plane. If the TE of the COP and/or COP velocity had been used to evaluate changes in postural control that appeared as a result of these pathologies, the directional differences detected might have been overlooked. To discover changes that emerge, it is therefore imperative to evaluate the directional components of postural control. The use of TE and COP velocity as lone measures to address changes in postural control is not warranted.

Root-Mean-Square Amplitude and Velocity

Root-mean-square (RMS) amplitude represents the standard deviation of the displacement of the COP. This parameter measures the average absolute displacement around the mean COP and has been employed by numerous researchers.[3,5,11,54,55] RMS velocity has been defined as the distribution of COP displacements over time.[2,5,54,55] A decrease in both RMS amplitude and RMS velocity represents an increased ability to preserve an upright stance. An increased value for either variable suggests a decreased ability to maintain postural control.[5]

It has been suggested that RMS amplitude and velocity are reliable measures to evaluate postural equilibrium.[5,43] Geurts et al[5] report that RMS amplitude (coefficient of variance = 31.75%) and velocity (coefficient of variance = 26.75%) show sufficient intrasubject consistency over a 5-week period.[5] In addition, intersession reliability was implied to be high in both the A/P ($R = .86$) and M/L ($R = .81$) directions during a double-legged-stance condition.[43] No intraclass correlation coefficients were given to support this reliability, however, and therefore the reliability is inconclusive.

RMS amplitude and velocity have been demonstrated to be sensitive to altered proprioception[54] and to visual deprivation.[5,54] Both measures were able to identify changes in the A/P direction in stroke victims with impaired proprioception.[54]

A moderate correlation has been shown between RMS amplitude and velocity under an eyes-open condition in the frontal ($r = .52$) and sagittal ($r = .74$) planes. During the eye-closed condition, the correlation between the 2 variables decreased ($r = .48$) in the frontal plane while it increased ($r = .80$) in the sagittal plane.[5] There was not a high correlation between these 2 variables, which suggests that RMS amplitude and velocity measure different aspects of the postural-control system.

Although variations seen in these variables can be used to identify changes in postural control, it is not known what adjustments are made in the postural-control system in order for these differences to be detected. For either variable to be of value in the evaluation of postural control, further information is needed.

Spectral (Frequency) Analysis

A component necessary to understand the postural-control system is the relative contribution that each of the 3 sensory systems and their interactions provide in order to maintain an upright stance. The ability to identify a frequency range in which each sensory system works and the power contained within this range would allow an estimate to be made as to which system or systems are the most important for different tasks. Since the introduction of

power spectral-density analysis in 1968 by Bensel and Dzendolet,[56] several researchers have attempted to fill the void in the literature regarding this topic, but these attempts have not been very fruitful.

Many clinicians have attempted to define the frequency range in which the visual, vestibular, and somatosensory systems operate in order to maintain upright stance. The conclusions drawn from these studies vary. Nashner[57] suggested that the visual system operates below 0.1 Hz, whereas Mauritz et al[58] concluded that it functions below 1.0 Hz, and Dichgans and Brandt[59] found it to function below 1.2 Hz. With regard to the vestibular system, Nashner[60] hypothesized that the semicircular channels sense sway at above 0.1 Hz, and the otoliths detect change below this frequency. The somatosensory system might operate somewhere between 0.3 and 1.2 Hz.[30] A definite frequency range under which each system is functioning has still not been defined in the literature. It is likely that the frequency ranges stated are inaccurate because inadequate sampling parameters were used to acquire data.

Analysis of the frequency spectrum has potential as a useful technique for measuring balance ability. The ability to determine which sensory system is functioning at a given point in time and whether the reliance on each sensory system changes with different tasks would be valuable information for the clinician to have. The research examining this method of analysis, however, does not present definitive results as to where each sensory system is functioning. Further research must be conducted if spectral analysis is to provide the clinician with information that will aid in the rehabilitation of diseased or damaged postural-control systems.

Time-Frequency Analysis

Although many clinicians have examined the frequency characteristics of postural control, few have focused on the time-invariant properties of the COP signal. In other words, the COP is not static and will change over the duration of a sample. Recently, the COP has been shown to change over time,[27,61-63] and a new method of analysis has been developed to detect the time-varying frequency changes.

Time-frequency analysis is capable of detecting what frequencies existed in a signal, in addition to when they occurred and how they might be changing over time. With this new method of analysis, it has been shown that normal subjects are able to adapt to constant frequency perturbation, whereas patients with vestibular disorders cannot.[27] Time-frequency analysis allowed for the detection of when the adaptation occurred, and this would not have been detected if conventional frequency analysis had been used.

Time-frequency analysis allows the 3 sensory systems to be examined individually. This enables the clinician to examine how the visual, vestibular, and somatosensory systems react and adapt to different perturbations or

various pathological conditions. Because this method of analysis is relatively new, more research needs to be conducted in order to gain a full understanding of how it will help clinicians evaluate and rehabilitate postural deficits. Because of the inability of spectral analysis to detect the variations in frequency that occur over time, time-frequency analysis should be used in addition to spectral analysis to guarantee that all the changes that occur within a signal are detected.

Clinical Applications and Recommendations

The primary purposes of assessing balance in the clinical setting are to determine (1) whether a balance deficit exists, (2) whether treatment is needed, (3) the underlying cause or causes of the balance impairment, and (4) what treatment will be effective in reestablishing normal control of posture.[36] It should be apparent that creating an effective rehabilitation protocol to correct a balance deficit will be difficult without understanding the cause of the postural impairment. Being able to create a rehabilitation program to regain postural equilibrium (purpose 4) relies on understanding the origin of the deficit (purpose 3).

Research supports the fact that the various COP parameters can be used to detect balance impairments associated with neurological disorders[3,7-13] and musculoskeletal pathologies.[14-20] Once one has used these parameters to identify a deficit, one then knows that treatment is needed, accomplishing purposes 1 and 2 depending on the parameters chosen. We recommend that clinicians choose a variable capable of detecting changes in the A/P and M/L (mean COP, RMS amplitude, and RMS velocity) directions so that postural impairments will not be missed.

Because COP variables can be used to detect balance deficits associated with pathological conditions, a logical clinical application of the parameters would be to diagnose disease and injury. Postural-control assessment is rarely used, however, to diagnose pathologies; this information is obtained from the clinical examination. In addition, using postural assessment as a tool to diagnose specific pathologies would not be effective. Patients with different diagnoses might have similar postural impairments resulting in similar changes in the COP; furthermore, patients with the same pathologies might reveal different changes in the COP.

The current literature fails to provide justification for using COP variables to identify the cause or causes of postural deficits. There is a lack of physiological evidence illustrating why alterations occur in the various COP parameters. Without this critical information, COP variables provide little assistance to the clinician in designing effective rehabilitation programs for reestablishing normal control of posture. The frequency measures of COP might provide insight into the underlying causes of the balance deficits. These procedures examine the 3 sensory systems that function to maintain

postural control. The capability to detect changes in a specific system that result in balance deficits would help us begin to understand what causes balance deficits, thereby increasing the chance of creating a successful rehabilitation protocol. Further research must be conducted to determine the physiological changes occurring in the postural-control system when alterations in COP variables are detected.

COP parameters are inadequate to address all the purposes of clinical balance assessment. A more complex approach to evaluating balance impairments must be used to sufficiently interpret alterations in postural control. For comprehensive reviews on the clinical assessment of balance, refer to reviews by Horak[36] and Guskiewicz.[64]

Conclusions

Various parameters that quantify postural control have been reviewed. There is currently no consensus in the literature as to which variable most accurately represents changes seen in postural control. Although changes in these variables enable us to detect changes in postural control, we still do not know which aspect of posture each parameter represents. COP variability is thought to measure a central postural-control mechanism,[13] in which changes in velocity measures might represent the strategy the body adapts to maintain postural stability.[65] Understanding what each parameter represents is crucial—until we know what we are measuring with each variable, we cannot know which parameter to choose. Further research is needed in order to identify what aspects of posture the different parameters represent. In addition, we need to focus on which variable or variables provide the greatest reliability and validity, under different stance conditions, for the clinical quantification of balance.

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