



## A CRITICAL REVIEW OF POSITION- AND VELOCITY-BASED CONCEPTS OF POSTURAL CONTROL DURING UPRIGHT STANCE

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### ABSTRACT

**Purpose.** Postural control during quiet standing has been modeled by concepts using kinematic variables estimated from center of pressure (COP) signals. The concept of position-based postural control has had particular ramifications in the literature, although a more recent concept of velocity-based control has been proposed as being more relevant. **Methods.** This study reviews the literature investigating these concepts and their respective quantitative methods alongside current supporting evidence and criticisms. **Results.** The position-based control concept suggests the existence of two control loops that alternate whenever certain thresholds are exceeded. Such a theory is supported by studies describing the time delay between the skeletal muscle activation and CoP displacement. However, this concept has been criticized to be the result of statistical artifacts due to it not being adapted to the analysis of bounded time series. Conversely, the velocity-based control concept claims that velocity is the most relevant kinematic variable for postural control. Such a theory suggests that postural adjustments are executed to change the trajectory of the CoP whenever the velocity crosses a threshold. Both theories have their major methodological limitations, while interpretation of data from the position-based concept is difficult, velocity-based thresholds are empirical and still need verification in different motor tasks and populations. **Conclusions.** Given the observed similarities and mutual exclusivity of both concepts, there is a need for the development of methods that can quantitatively analyze stabilometric signals while simultaneously considering both kinematic variables.

**Key words:** biomechanics, postural balance, rehabilitation

### Introduction

Postural control is an important factor of the motor system when performing activities of daily living. Information from the vestibular, visual, and somatosensory systems is integrated to generate postural adjustments appropriate for a given motor task. Each of these systems contributes to postural control by providing kinematic feedback on position, velocity, and acceleration variables, either linear or angular. The primary aim of the postural control system during upright standing is to counteract gravity and inertial forces acting on the body's segments, represented by the body's center of mass (CoM), so as to maintain the CoM within the base of support (BoS) and avoid falling [1–3]. Although the trajectory of the center of pressure (CoP) – the point of application of the body's ground reaction force vector [1] – is totally independent of CoM displacement in the anteroposterior (AP) and mediolateral (ML) directions, CoP is usually interpreted as the neuromuscular response of the body to maintain balance. For these reasons, both univariate and bivariate CoP time series (stabilograms and statokinesigrams, respectively) obtained from force platforms are used to assess postural stability during quiet stance. Several theories alongside a wide array of methodological approaches have been designed to explain the

relationship between postural control mechanisms and CoP time series variables.

Among several published models, Collins and De Luca's proposition [4, 5] has had particular wide ramifications and been the subject of extensive research [2, 6]. In this model, postural adjustments related to upright stance were theorized to be accounted by the kinematic variable CoP *position* [4, 5]. More recently, Delignières et al. [7] proposed a new concept suggesting that CoP *velocity* is more relevant in explaining postural control. As both concepts have been used in the study of human movement science, researchers and clinicians ought to have a critical understanding of both theories in the planning of future studies and in assessing rehabilitation of patients with poor postural balance. Therefore, this study: 1) reviews the concepts and quantitative methods analyzing CoP signals in relation to position- and the velocity-based control of upright stance, and 2) discusses the similarities and dissimilarities of both concepts as well as supporting evidence and current criticism. Perspectives for the quantitative analysis of stabilometric signals and the need for the development of new quantitative analysis methods including both CoP position and velocity variables are also put forward.

The concept of position-based postural control

This concept theorizes that undisturbed erect stance is stabilized by two control loops, namely the 'open-loop' and 'closed-loop' [4, 5]. On the one hand, the open-loop

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is characterized by commands descending to different postural muscles so that upright stance is maintained by ‘muscle stiffness’. On the other hand, the closed-loop is characterized by the use of feedback information to generate motor responses as a reaction to postural disturbances, where postural correction is thusly mediated by compensatory muscular responses. Loops are switched whenever the univariate (AP or ML) or bivariate CoP position reaches a given threshold. Within the context of position-based control, a threshold is defined as some systematic criterion, if exceeded, activates corrective feedback mechanisms. Changes in CoP trajectory as a result of such corrective feedback mechanisms are intended to alter the displacement of CoM, thus keeping it within the BoS.

Quantitative method for the analysis of univariate and bivariate CoP time series

The underlying idea is to model the statokinesigram as a fractional Brownian motion (fBm) and therefore decompose the oscillatory patterns of CoP time series into short- and long-time stochastic processes related to the open- and closed-loop, respectively. The statokinesigram is modeled as a random walk of CoP displacement in the AP ( $y$  axis) and ML ( $x$  axis) directions. The analysis involves the calculation of quadratic displacements ( $\Delta r^2$ ) between all pairs of  $n$  samples ( $r_i$  and  $r_{i+m}$ ) of CoP times series separated by a time interval ( $\Delta t$ ), such that  $m$  corresponds to the number of CoP samples in  $\Delta t$  (see equations 1 and 2) [4, 5]:

$$(1) \langle \Delta r^2 \rangle_{\Delta t} = \frac{\sum_{i=1}^{N-m} (\Delta r^2)}{N-m}, \text{ where}$$

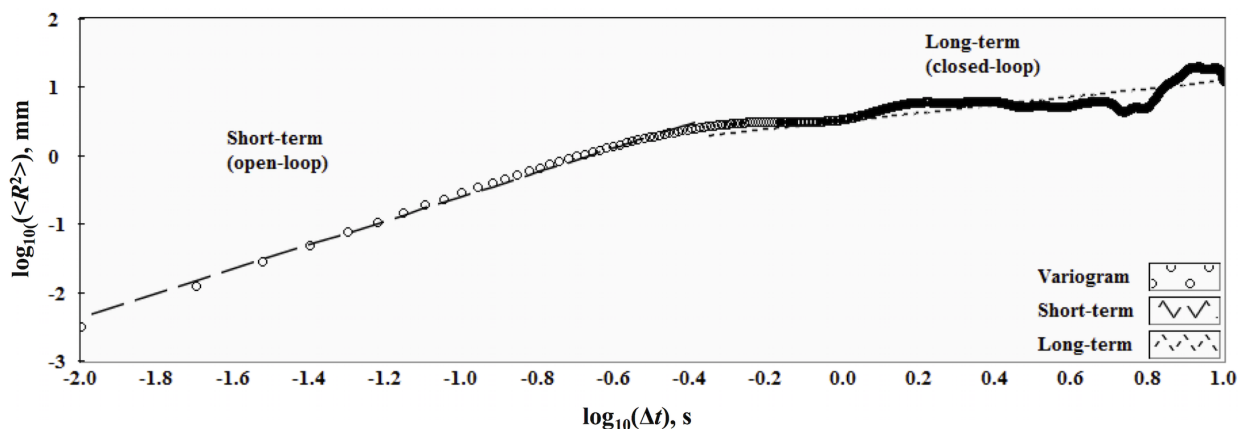
$$(2) \langle r^2 \rangle = \langle x^2 \rangle + \langle y^2 \rangle,$$

The repetition of the this iterative process for increasing values of  $m$ , usually in the range  $m = 0.1-10$  s, generates

a distribution of the mean quadratic displacements in either the ML and AP directions ( $\langle x^2 \rangle$  and  $\langle y^2 \rangle$ ), i.e. a statokinesigram ( $\langle r^2 \rangle$ ), versus the time interval  $\Delta t$  between samples (Fig. 1), namely a stabilogram-diffusion plot [4, 5] or variogram [8]. An empirical threshold (the critical point [ $\Delta t_c, \langle \Delta r^2 \rangle_c$ ], where  $j = x, y, r$ ) is estimated from the intersection of two straight lines representing the separation of the short- and long-time processes. Finally, the following variables are used to fit the lines to the variogram for the quantification of the postural control processes: 1) the diffusion coefficients  $D_{js}$  and  $D_{jl}$ , as computed from the slopes of the lines fitted to the short-term (subscript  $s$ ) and long-term (subscript  $l$ ) regions, respectively; and 2) the scaling exponents  $H_{js}$ , and  $H_{jl}$  as calculated from the slopes of the log-log plots of the short- and long-term regions, respectively [4, 5].

Evidence supporting the concept of position-based postural control

Scientists started searching for evidence of open and closed control loops shortly after its existence was proposed almost three decades ago [4, 5]. Various studies presented by the founding authors showed that the open-loop control mechanisms act during a time interval of less than 1 s in healthy subjects. This short-time window reinforced the idea that postural control processes are not solely based on feedback information [5]. Another study on healthy subjects showed that visual feedback reduces body sway, suggesting that feedback control acting for longer time periods could reduce the CoM displacement [9]. The simultaneous assessment of CoP displacement and surface electromyograms (sEMG) revealed positive latencies from 0.25 s to 0.3 s between the electrical activity of the lateral gastrocnemius muscle and sagittal CoP displacement, which further corroborated the hypothesis of anticipatory postural adjustments [10]. As another example, the higher positive latency between sEMG of the lateral gastrocnemius and AP CoP displacement observed after a muscle fatigue protocol suggests



Signal acquisition set-up: postural task – bipedal upright stance with open eyes and wide BoS; force platform – AccuSwayPlus (AMTI, USA); sampling frequency – 100 Hz; trial duration – 60 s; signal processing – bias and trend removal followed by a second order low-pass Butterworth filter at 2.5 Hz in direct and reverse order

Figure 1. Quantitative method for assessing the critical point in position-based control of posture

that the open-loop may be modified by physiological stress such as physical exercise [11].

The hypothesis of anticipatory mechanisms based on a sequence of motor adjustments was applied to the development of the sway-density curve (SDC), a plot of the quantity of CoP samples inside a fixed radius circle as a function of postural task time [8]. Comparisons between different quantitative methods for CoP signal analysis – traditional and mechanical ones – suggested that the variogram parameters better expressed the postural control process [12]. Additionally, variogram-derived parameters could be used to detect differences in the postural control of young and elderly subjects even if they have a low risk of falling [12]. In the variogram, the low frequencies (slower components) of body sway were related to inertial body characteristics while the higher frequencies (faster components) were related to intermittent muscle activity [13]. It was also observed in healthy subjects that postural control was affected if visual feedback was delayed [13]. In addition, stabilogram-diffusion parameters exhibited increased values in patients with Parkinson's disease, suggesting an altered contribution of open- and closed-loops in postural control [14].

#### Criticisms of the concept of position-based postural control

The concept of position-based postural control has been strongly criticized due to inaccuracies found in the quantitative methods proposed by original authors [3]. Another general objection against the fBm model of CoP displacement is that it disregards the biomechanics of the inverted pendulum and its intrinsic instability [8]. Moreover, the open-loop has a higher level of stochastic activity than the closed-loop, and does not appear to present a plausible biomechanical explanation of postural control [15]. While fBm is an adequate model for physical systems dominated by diffusion processes, it is questionable when applied to oscillatory biomechanical systems [8].

Variogram parameters exhibited low power to distinguish healthy individuals from patients with Parkinson's disease or presenting osteoporosis as compared with statistical estimators [8]. Moreover, variogram parameters are not easily interpreted and/or related to the physiological systems controlling upright stance [8]. What is more, alternative interpretations beyond open- and closed-loops have been applied to fBm modeling of the variogram. For instance, the closed-loop can be interpreted as either an exploratory process [16] or as a delay factor due to the time dispended by the central nervous system (CNS) to gather and combine all sensory information so as to generate corresponding motor output [17].

Methodologically, it was argued that both control loops result from statistical artifacts of variogram analysis, since this quantitative method was not adapted to

a bounded time series [15]. A bounded time series is mathematically defined as a function  $f(t)$  for which there exists a real number  $M$  such that  $|f(t)| \leq M$ , i.e.  $f(t)$  cannot have a large amplitude regardless of the length of the data set. In particular, it was argued that postural control could not be explained by variogram analysis [7]. There are two common methods used to characterize the serial correlation properties of CoP data: the variogram and detrended fluctuation analysis (DFA). By definition, variance of fBm displacement is calculated as a power function of time, i.e. the base is the time interval  $\Delta t$  during which the displacement is observed. Equations 3 and 4 can be used for calculating the variance of displacement, considering either the variogram or the DFA, respectively:

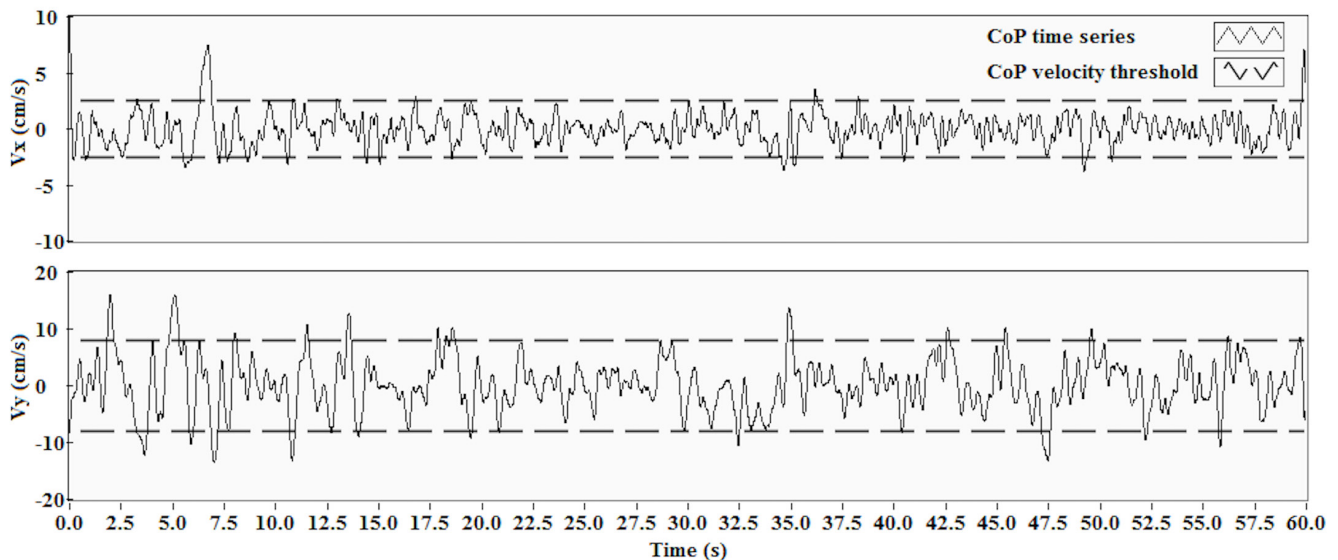
$$(3) \text{Var}(\Delta x) \propto \Delta t^{2H}$$

$$(4) \text{SD}(\Delta x) \propto \Delta t^H$$

In equations 3 and 4,  $\Delta x$  represents the displacement and exponent  $H$  represents the nonlinear function in the range of  $H = 0-1$ . These equations express the diffusion property specific to the fBm processes whose characteristics depend on  $H$ ; a higher  $H$  refers to a more diffusive fBm. However, the diffusion can be interpreted as the probabilistic dispersion of the process with respect to its initial position, after a specific time interval  $\Delta t$ , for multiple repetitions of this process. When fBm is given by  $H > 0.5$ , it corresponds to the Brownian motion proportional to the variation of dispended time [3, 6]. While the variogram calculates the average variance of CoP displacement with respect to  $\Delta t$ , DFA is based on the evaluation of the variability of CoP displacement within variable path lengths and  $\Delta t$ . DFA corresponds to the average of the standard deviation of the time series; it can be integrated and determined as a function of the path length interval. Due to the integration step included in the analysis, the DFA method directly assesses the serial correlation properties and not the differentiated series as in the variogram. Since equation 4 is predicted to have values of  $H$  ranging between 1 and 2, if the series under evaluation is a fBm,  $H = 0.5$  is a borderline value for the diffusion properties of DFA where the analyzed series is non-stationary. Therefore, it was shown that the variogram does not provide the best statistical interpretation for postural control [15, 18].

#### The concept of velocity-based postural control

In this concept, stable upright posture is maintained through intermittent motor control [7]. Postural adjustments occur when univariate CoP instantaneous velocity (AP or ML) crosses a threshold, indicating a change in the CoP displacement trajectory and, consequently, a change in the CoM trajectory to try and keep it inside the BoS.



Signal acquisition set-up: postural task – bipedal upright stance with open eyes and wide BoS; force platform – AccuSwayPlus (AMTI, USA); sampling frequency – 100 Hz; trial duration – 60 s; signal processing – bias and trend removal followed by a second order low-pass Butterworth filter at 2.5 Hz in direct and reverse order

Figure 2. Quantitative method for assessment of the threshold in velocity-based control of posture; upper panel represents the time series of center of pressure (CoP) velocity in the mediolateral direction ( $V_x$ ), lower panel shows the time series of CoP velocity in the anteroposterior direction ( $V_y$ )

#### Quantitative method for the analysis of univariate CoP time series

The underlying idea of this concept is based on the calculation of CoP instantaneous velocities separately from AP and ML stabilograms and to estimate the CoP velocity boundaries for each axis. Two empirical variables were proposed to determine the threshold for postural adjustments from both CoP velocity time series: 1) the standard deviation of CoP velocity ( $SDV_x$  and  $SDV_y$  for the ML and AP directions, respectively) and 2) the average absolute maximal velocity (AAMV) calculated from non-overlapped 2-s epochs of the univariate CoP velocity time series (Figure 2) [19].

#### Evidence supporting the concept of velocity-based postural control

Several studies published before the establishment of the velocity-based theory suggested that velocity information has an important role in the postural control of undisturbed upright stance. In healthy subjects, a coupling was observed between body sway velocity and the velocity of either the supporting surface (corresponding to somatosensory inputs) or a visual display [20, 21]. Other evidence comes from observations finding that absolute angular velocity was the best variable in controlling the vertical position of the body, modelled as an inverted pendulum, on a 'slack line' [22]. Therefore, it was suggested that the CNS adopts a postural control strategy that depends on velocity information provided through multisensory integration [23]. Changes in CoM velocity indicate the direction and magnitude of its dis-

placement in the next time steps. Therefore, velocity information seems to be highly useful for the CNS to anticipate CoM position and produce compensatory adjustments through CoP displacement. These facts are corroborated by the known precision of the sensory systems in the perception of velocity information, which respond to instantaneous velocity better than to absolute position [23, 24].

Few studies have applied the velocity-based concept in full, likely due to its relatively recent introduction. A longitudinal study [25] found the estimation of CoP mean velocity in the ML direction to be effective way in assessing the effects of ageing on postural stability. Another study [19] hypothesized that CoP velocity variables are relevant for assessing fall risk in elderly subjects. Based on this hypothesis, a comparative analysis of several quantitative methods for the estimation of various CoP variables (traditional parameters, wavelet transformation, analysis of time series regularity, and analysis of fractal properties) suggested that CoP velocity was a good descriptor to distinguish the nature of the postural task under investigation [17]. A recent study [26] proposed a method to assess the temporal variation in the structure of CoP position and velocity time series and showed that both short-range persistent and long-range anti-persistent behaviors are influenced (but not generated) by CoM movements. In addition, these authors suggested that the proposed method might improve the differentiation of postural adjustments in elderly persons and patients with neurodegenerative diseases.



### Criticisms of the concept of velocity-based control of posture

At present, few objections in the literature were found against this proposed concept, again likely due to its novelty, although many studies have emphasized the need for a more comprehensive research. An initial criticism was based on observation of persistent behavior for short-range CoP velocity time series and anti-persistent for long-range time series using DFA analysis [18]. Considering that the value of  $\Delta t$  (equations 3 and 4) for which the CoP signal behavior changes from persistent to anti-persistent is denominated as *crossover*, this finding is in agreement with the position-based theory [4, 5] but not with the velocity-based concept [15], as the latter does not describe the crossover phenomenon in time series.

Another criticism emerged from the discussion on intermittent versus continuous postural adjustments [22]. The intermittent strategy used for maintaining quasi-static upright posture is based on the assumption that small deviations are not detected by the controlling structures in the CNS but that corrective adjustments are generated when the position or velocity exceeds a given threshold, if any [27]. Nevertheless, this velocity-based concept is only a formalized approach based on statistical theories, and its plausibility has not been analyzed at other levels of analysis (e.g. neurological or biomechanical).

### Research perspectives on kinematic-based concepts in human movement science

This debate between the position- and velocity-based concept is centered on the identification of a variable that presents crossover (transition from persistent to anti-persistent correlations). Several issues were identified within this review that need consideration in future studies on human postural control.

Regarding the position-based concept [4, 5], there is no quantitative method for estimating the spatial limit in the transition between open and closed control loops. Notice also that the actual threshold is the time interval  $\Delta t$  between successive CoP samples that corresponds with an abrupt change in quadratic displacement behavior. Since postural performance, as described by postural stability variables, is proportional to the CoP area within the BoS, it is necessary to develop methods that *locate* the spatial limits inside the BoS and can indicate the transition between open- and closed-loops. Regarding the velocity-based theory [7, 19], the more major aspects are related to empirical thresholds. First of all, these thresholds have been estimated for each postural task, but why there is a change in threshold due to changes in sensory information input remains unknown. One may suggest estimating such thresholds from ‘more stable’ postural tasks (e.g. wide BoS with full visual input) and extrapolating them to more challenging postural tasks (e.g. with no visual input, limited BoS, or reduced soma-

tosensory input) as a reference value. Second of all, these thresholds are calculated for CoP univariate time series (stabilogram) and it is not known if this reasoning applies to CoP bivariate time series (statokinesigram). Finally, another important debate concerns the nature of the variable of interest in the velocity-based concept; maximal velocity or velocity SD are related with the crossover theory, while average velocity involves a completely different approach. From this point of view, the problem is not “Is velocity the controlled variable?” but “How is velocity controlled?”

A combination of kinematic variables to understand postural control mechanisms has been proposed as an alternative approach to the usage of a single variable. Indeed, position-velocity analysis is hardly a new method in human movement science. For instance, a phase plane graph (i.e. velocity vs. position) was useful in studying the balance of healthy young adults and patients with bilateral vestibular hypofunction [28]. This phase plane graph also presented good test-retest reliability in several postural tasks (eyes open/closed and rigid surface/foam) [29]. These studies reinforce the need for the development of quantitative methods that allow the simultaneous assessment of CoP position and velocity, as they appear to be more useful in clinical interpretation and have higher sensitivity and specificity to changes in postural control. In this context, simultaneous assessment implies developing a method that combines CoP position and velocity in the same plot structure and related quantitative/qualitative analysis as in the phase plane graph. Such a simultaneous assessment strongly differs from the current practice of computing several amplitude- and velocity-related parameters from the same CoP signal and interpreting them, since this simple yet useful practice cannot help answer new questions on postural control such as “Where in the BoS is it necessary to increase CoP velocity to prevent falling?” Even combined parameters such as a frequency measure (calculated as the ratio of CoP velocity/position) may not contribute to answering this question. This question is legitimized by speculation that velocity-based postural control occurs in the central region of the stabilogram, where CoP instantaneous velocity attains maximal absolute values [7].

Based on the present review, it is suggested that the joining of kinematic variables in a single method may be particularly useful. On the one hand, high CoP velocities should be avoided near the boundaries of the base of support since there may be no time for efficient postural adjustment at such a location [30]. On the other hand, high CoP velocities near the boundaries of the base of support may be necessary to quickly redirect the body’s CoM towards the egocentric reference of posture in more challenging conditions or after a fall is initiated. Therefore, as a ‘scientific exercise’, a graphical method for the simultaneous assessment of CoP position and velocity is depicted in Figure 3. This graphical method uses the

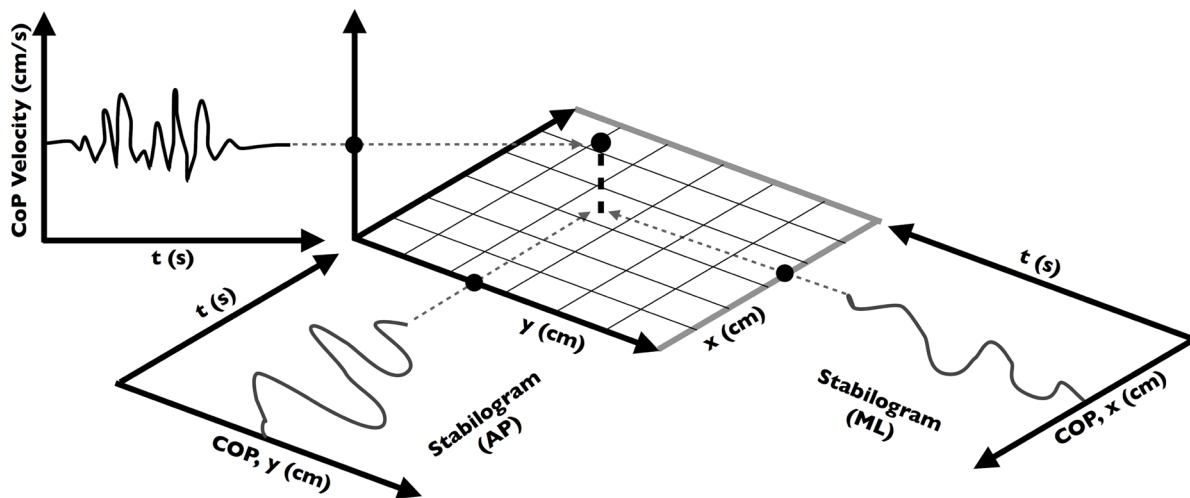


Figure 3. Schematic suggestion of a quantitative method for the simultaneous assessment of CoP position and velocity; stabilograms in the anteroposterior ( $y$  axis – AP) and mediolateral ( $x$  axis – ML) directions are used to ‘map’ the corresponding location of the sampled time series of CoP velocity into the statokinesigram

AP and ML coordinates of CoP to map the parameters derived from CoP instantaneous velocity in the instantaneous CoP position on the statokinesigram (e.g. mean or maximal velocity). The threshold for CoP velocity also may be used to map only those CoP coordinates that crossed the estimated threshold. Quantitative parameters could be derived for research on its diagnostic value in populations at a high risk of falling. In this way, the spatial distribution of CoP velocity might be studied as it relates to the CoP position inside the BoS.

Although these two concepts are apparently mutually exclusive, they apply a common framework and rationale explaining their assumptions and respective quantitative methods for studying postural control, which include the 1) determination of the biomechanical relationships between CoM and CoP, 2) estimation of the variables from CoP time series as acquired from force platforms, and 3) delimitation of an empirical threshold. The large amount of information derived from stabilometric tests that could be particularly useful in clinical practice is contrasted with the enormous difficulty involved in the interpretation such data in both concepts. Therefore, the results of experimental and clinical studies using the above-cited must be interpreted considering the current understanding of their characteristics and limitations.

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