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Notes on the margin of stability

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Notes on the margin of stability

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Abstract

The concept of the 'extrapolated center of mass (XcoM)', introduced by Hof et al. (2005, J. Biomechanics 38 (1), p. 1-8), extends the classical inverted pendulum model to dynamic situations. The vector quantity XcoM combines the center of mass position plus its velocity divided by the pendulum eigenfrequency. In this concept, the margin of stability (MoS), i.e., the minimum signed distance from the XcoM to the boundaries of the base of support was proposed as a measure of dynamic stability. Here we describe the conceptual evolution of the XcoM, discuss key considerations in the estimation of the XcoM and MoS, and provide a critical perspective on the interpretation of the MoS as a measure of instantaneous mechanical stability.

Keywords: Extrapolated center of mass, gait stability, dynamic balance, biomechanics, locomotion

Nomenclature

AP	anteroposterior
b	distance between CoP and XcoM
b_{avg}	average distance between CoP and XcoM over a step
$b_{initial}$	distance between CoP and XcoM at initial contact
b_{min}	minimal distance between CoP and XcoM in a step
BoS	base of support
CoM	center of mass
CoP	center of pressure
eBoS	effective base of support
g	acceleration of gravity = 9.81 m s^{-1}
l	effective pendulum length
MoS	margin of stability
ML	mediolateral
u_{min}	minimum boundary CoP
u_{max}	maximum boundary CoP
v_x	CoM velocity
$v_{x\|T}$	relative CoM velocity
v_T	treadmill velocity
x	horizontal projection of the CoM on the ground
XcoM	extrapolated center of mass
ω_0	eigenfrequency of pendulum = $\sqrt{\frac{g}{l}}$

1. Introduction

The control of stability can be described to a certain extent by a simple mechanical system, the so-called 'inverted pendulum' model. In line with this model, the vertical projection of the center of mass (CoM) needs to stay within the boundaries of the base of support (BoS) to maintain stability in static situations. Yet, this condition does not hold during dynamic situations. To define stability in dynamic situations such as walking, one must account for the velocity of the CoM. The '*extrapolated center of mass*' (XcoM) is equivalent to the position of the CoM plus its velocity divided by the pendulum eigenfrequency, a constant specific to stature. The signed distance '*b*' between the BoS and XcoM, was termed the '*margin of stability'* (MoS). Hof et al. (2005) proposed the minimum distance from the XcoM to the boundaries of the BoS, b_{min}, as a measure of stability during dynamic situations. Owing to its simplicity and wide applicability, the XcoM and MoS have enjoyed tremendous popularity since they were first introduced by At L. Hof in 2005. In this perspective article, we detail the evolution of the concept and the estimation and interpretation of the XcoM and MoS.

2. Conceptual evolution of the extrapolated center of mass

Stability control during quiet standing can be described by the motion of an inverted pendulum (Figure 1, Winter (1995)). The human body is modeled as a stick placed on the ground at the center of pressure (CoP) with a whole-body CoM high above the ground. The ground reaction force originating at the CoP, is acting on the CoM. The inverted pendulum falls to the left when the CoP is to the right of the CoM and vice versa. To prevent the inverted pendulum from falling over, the position of the CoP can be controlled by muscle action. Thus, in the *classic inverted pendulum model*, the CoM (x) needs to stay within the boundaries of the BoS ($u_{\mathrm{min}} < x < u_{\mathrm{max}}$) to maintain stability.

Pai and colleagues (Iqbal and Pai, 2000; Pai et al., 2000; Pai and Patton, 1997) showed that this condition (CoM within BoS) is not applicable to dynamic situations. The velocity of the CoM needs to be accounted for to predict if stability can be regained. That is, even when the CoM lies within the BoS but the CoM velocity is pointing away, stability may not be achieved. Likewise, if the CoM is outside of the BoS, stability can be regained if the CoM velocity is pointing towards the BoS. Based on extensive simulations (accounting for environmental, anatomical, and physiological constraints), Pai and Patton (1997) predicted the CoM velocity-position limits for terminating movement and stability recovery. This aligned with work by Townsend (1985), who was the first to present a model showing that stable gait can be achieved by foot placement, taking the CoM position and velocity at the time of foot placement into account in an inverted pendulum model with a moveable BoS.

Notably, it was Hof who showed that stability in dynamic situations can be predicted by simple mechanical reasoning (Figure 1; Hof (2007, 2008); Hof et al. (2005)). Derived from the linear inverted pendulum model, he introduced and coined the term *'extrapolated center of mass'* (XcoM). The proposed vector quantity XcoM is the velocity and eigenfrequency adjusted projection of the CoM. The XcoM is calculated as

$$XcoM = x + \frac{v_x}{\omega_0} \tag{1}$$

in which *x* is the vertical projection of the CoM on the ground and v_x is the velocity of the CoM. The eigenfrequency, a constant related to stature is denoted as

$$\omega_0 = \sqrt{\frac{g}{l}} \tag{2}$$

where *g* is the gravitational acceleration and *l* is the effective pendulum length. From this, stability can be quantified as the minimum signed distance from the XcoM to the boundaries of the BoS, b_{min}.

One of the limitations when estimating the MoS is the assumption of an infinitely fast CoP displacement, whereas in reality there is a finite reaction and displacement time of the CoP due to muscle activation dynamics necessary to displace the CoP. This problem has been discussed for standing balance but is still unaddressed for walking (Hof and Curtze, 2016). Experimental results on humans standing on two feet undergoing sudden postural perturbations showed that only a fraction, some 30%, of the area of the physical BoS can effectively be used (eBoS) to achieve stability (Hof and Curtze, 2016). In summary, two key concepts emerged from Hof's research to describe stability in different scenarios: the positions XcoM and the interval eBoS.

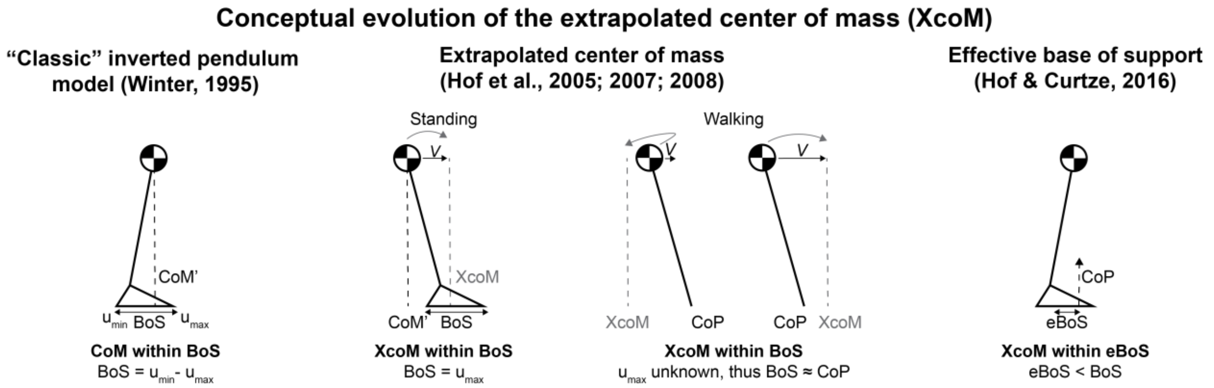

Figure 1. Conceptual evolution of the extrapolated center of mass.

3. The margin of stability during standing and walking

During quiet standing, the CoM and XcoM projected positions on the ground coincide closely due to the low CoM velocities. The XcoM will always remain within the boundaries of the BoS resulting in positive b_{min}. In more dynamic situations, like standing on tiptoes, the XcoM can be outside of the BoS, resulting in negative b_{min}. Such negative margins can only be recovered using counter-rotation movements of the trunk, arms or legs in the absence of external support (Hof et al., 2005). These movements go beyond what is described within the inverted pendulum model (Hof, 2007; Otten, 1999).

During walking, the XcoM precedes the sinusoidal trajectory of the CoM (Figure 2). To maintain a steady walking speed, humans place their feet at a certain distance posterior and lateral to the XcoM, thereby redirecting the movement of the XcoM and CoM. The distance at which the CoP under the foot is placed to the XcoM is a measure of the instantaneous mechanical stability of the body configuration during walking. In the mediolateral (ML) direction, a negative b_{min} (XcoM lateral to CoP) represents a situation in which the inverted pendulum falls beyond the BoS, requiring a lateral shift of the CoP, e.g., by a crossover step, to maintain forward walking. A positive b_{min} indicates that the XcoM does not exceed the lateral CoP position and the pendulum is falling towards the stepping foot.

While the BoS is clearly defined by the stepping feet in ML direction, this is not the case in the anterior direction. To move forward at a steady velocity, the combined CoP stays behind the XcoM at all times during the gait cycle (Figure 2; see also Hof (2008), equations 21 and 22). Therefore, the MoS is negative in cases where the XcoM exceeds the CoP in the forward or lateral directions (Hof, 2008).

Note that Hof et al. (2005) did not introduce the MoS as a measure of stability in the anteroposterior (AP) direction as the XcoM is not moving towards a boundary but rather always exceeds the boundary. However, there are a few scenarios in which a clear AP boundary can be defined. As a person terminates gait, the negative AP MoS will change to a MoS of zero, which represents the configuration in which the inverted pendulum comes to a perfect standstill above the CoP (Figure 3), terminating gait. Further experimental validation of the concept in the AP direction was provided by Arampatzis et al. (2008) and Curtze et al. (2010) using forward lean-and-release tasks. Here, stability recovery performance following the lean-and-release could be distinguished by positive and negative MoS values of the first recovery step.

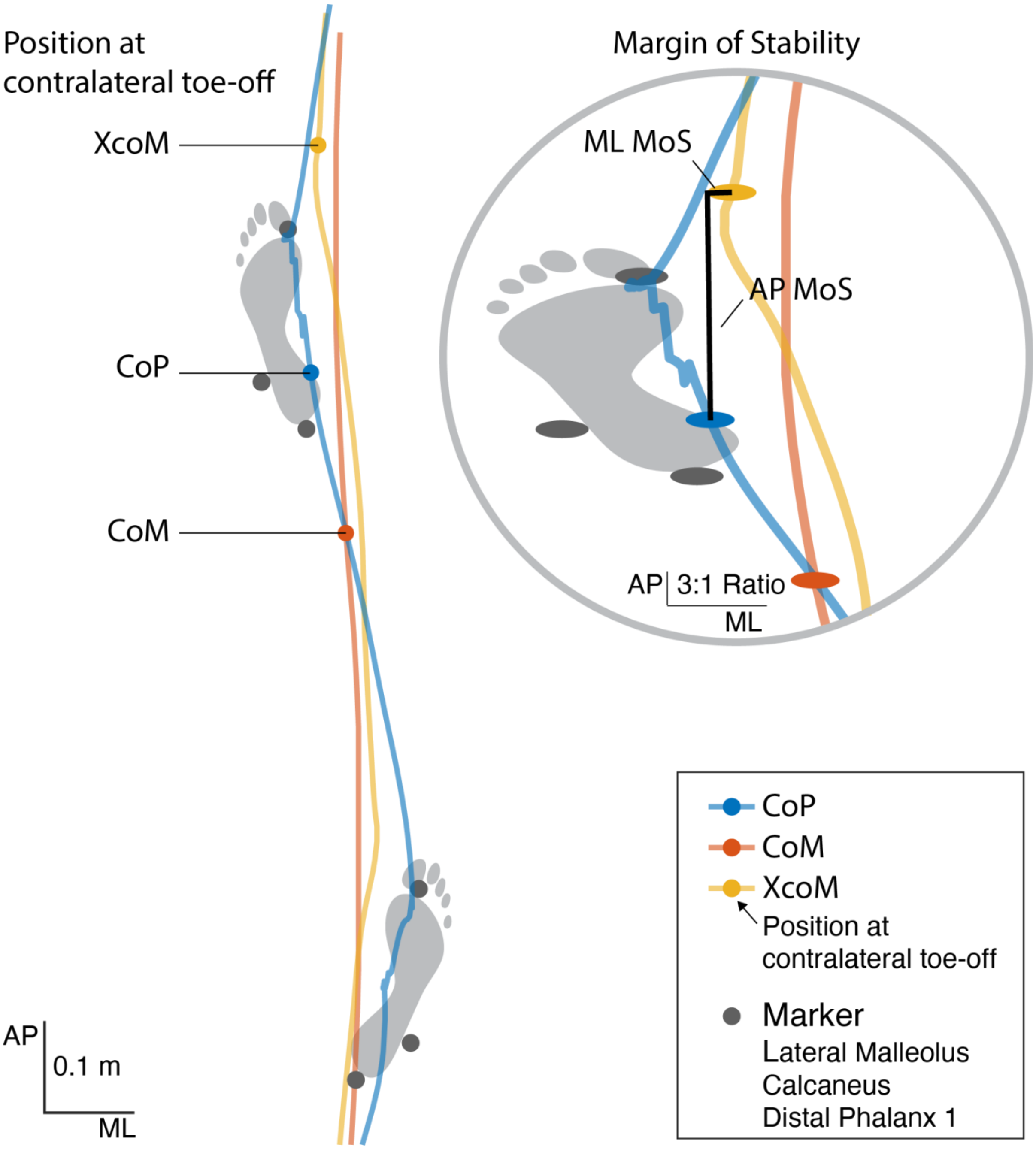

Figure 2. Instantaneous position of the XcoM, CoP and CoM during gait at contralateral toe-off and the resultant margin of stability, i.e., the indicated distance (black lines) between CoP and XcoM in AP and ML direction.

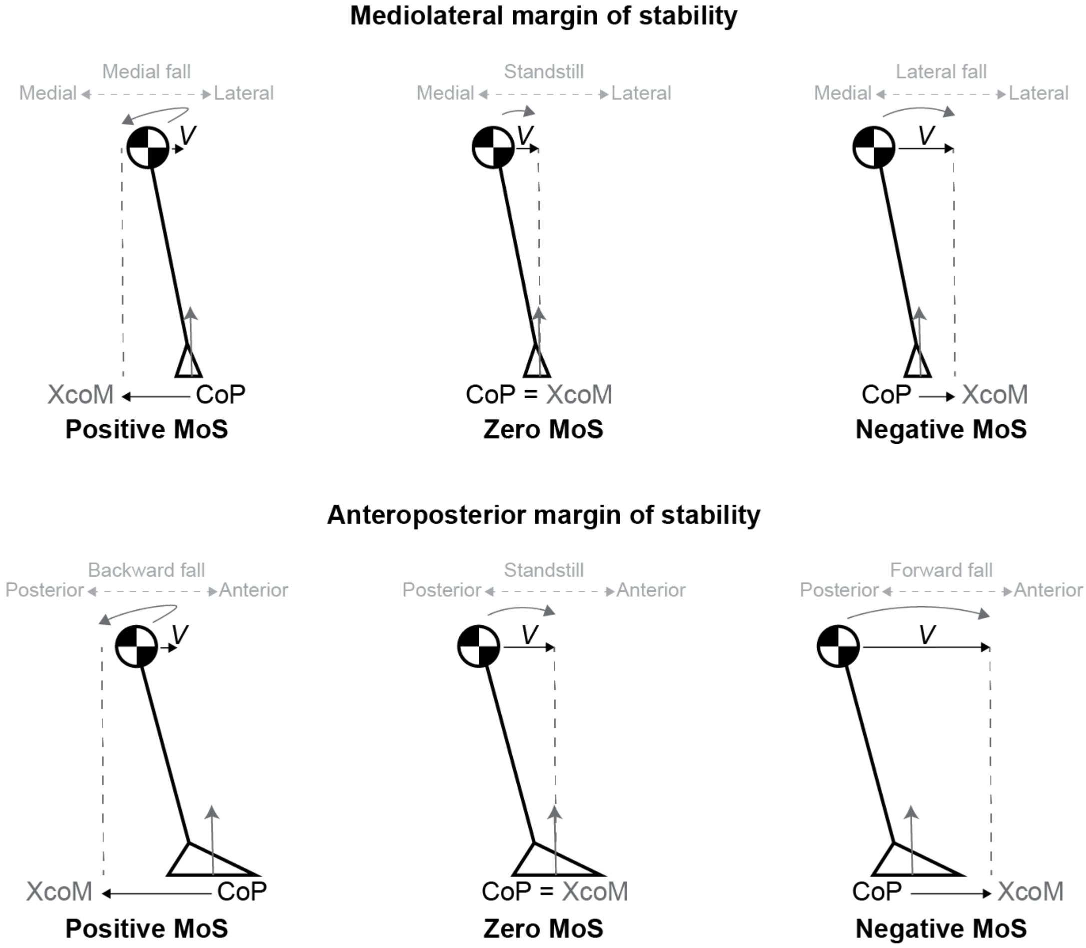

Figure 3. Configurations of the XcoM and CoP and their resulting mediolateral MoS (top) and anteroposterior MoS (bottom). Note that the magnitude of the vector v increases from left to right with, consequently, a changing XcoM position.

4. Estimating the margin of stability

In the following sections, we will discuss how to define the boundary of the BoS in standing and walking, estimate the CoM and XcoM position and velocity and choose the timing of the MoS in walking. Due to specific assumptions of the inverted pendulum model, e.g., that the pendulum length does not change, that the inverted pendulum is non-deformable or rigid, or that no external forces, other than gravity and ground reaction forces, should act upon the model (Geursen et al., 1976; Hof et al., 2005; Winter, 1995), certain tasks may lead to violations of the model, such as walking with a cane or handrail support. Users should keep this in mind and avoid applying the MoS to balance and gait tasks in which the participants' movement departs substantially from one that can reasonably be modeled by the inverted pendulum model. We provide recommendations for best practices for calculating the margin of stability (Box 1) and a reporting checklist (Appendix A).

Box 1. Recommendations on the calculation and interpretation of the margin of stability

Calculation of the extrapolated center of mass and the margin of stability

The extrapolated center of mass (m) is calculated as

$$XcoM = x + \frac{v_x}{\omega_0} \quad (3),$$

in which x is the vertical projection of the CoM (m) on the ground, v_x is CoM velocity (m s^{-1}), $\omega_0 = \sqrt{\frac{g}{l}}$ is the eigenfrequency of the pendulum, g is the gravitational constant (m s^{-2}), and l is effective pendulum length (m). For movements in the frontal plane, the effective pendulum length of the compound pendulum can be estimated as 1.34 times the trochanteric height and measured from the lateral malleolus to greater trochanter (Massen and Kodde, 1979). For the sagittal plane, the effective pendulum length can be estimated as 1.24 times trochanteric height (Geursen et al., 1976). Note that during treadmill walking v_x must account for belt speed (v_T) in the anteroposterior direction ($v_x = v_{x|T} + v_T$), no adjustments are needed in the mediolateral direction or during overground walking.

The margin of stability (m) is calculated as

$$MoS = BoS - XcoM \quad (4)$$

Reporting convention of the margin of stability

A negative MoS indicates the direction of instability, the inverted pendulum accelerates away from the BoS.

$ML\ MoS = ML\ BoS - ML\ XcoM$, i.e., negative if the ML XcoM is lateral to the ML BoS.

$AP\ MoS = AP\ BoS - AP\ XcoM$, i.e., negative if the AP XcoM is anterior to the AP BoS.

Boundary of the base of support

In situations where the effective BoS is unknown, such as while walking, the combined CoP should be used as a proxy of the BoS.

Estimation of the center of mass

An accurate estimation of CoM velocity and position is accomplished from force plate data using a filtering procedure (double integration of the ground reaction force divided by mass; Hof (2005), Buurke et al. (2023)) or by using a full-body kinematic model. Reduced kinematic models may be used only if both the position of the CoM and the velocity of the CoM is captured with sufficient accuracy during a given task. Careful, task-specific validation is warranted.

Timing of the margin of stability during the gait cycle

The true MoS, the most unstable point in a gait cycle, is advised to be defined as the minimal signed distance b_{min}, between the CoP and the XcoM in the ML direction.

The margin of stability is not an indicator of global gait stability

The MoS should not be used as an indicator for global gait stability in a general sense and should rather be interpreted as an instantaneous measure of mechanical stability of the body configuration. The MoS is directly related to minimal impulse needed to destabilize a person (Hof et al., 2005).

4.1 Defining the boundary of the base of support

The boundaries of the BoS describe the possible area in which the CoP (*u*) can travel. In the original definition (Hof et al., 2005), the boundary of the BoS for standing is u_{max}. Given the finite reaction of displacement time of the CoP, the effective BoS (eBoS) that can be used for stability control is substantially smaller, only ⅓ of the physiological BoS (Hof and Curtze, 2016). Therefore, to calculate the boundary of the BoS while standing, experimentally determining the eBoS, when possible or practical, would be the most valid approach. During walking, the XcoM is outside of the BoS of either stance foot (Hof, 2008) for most of the time and the eBoS has not been defined. The CoP, as the location of the ground reaction force acting on the XcoM, is therefore the preferred reference point for calculation the MoS (i.e., CoP - XcoM) during walking (as in Hof (2007, 2008); Hof et al. (2005); Hof et al. (2010)).

Alternative definitions of the BoS (anatomical boundary or area between the feet) during standing and walking lead to an over- or underestimation of the BoS boundary. A marker placed on the physical boundary of the foot, e.g., the medial malleolus, the lateral malleolus, the foot’s distal phalanx I or dorsal on the calcaneus, can be too far medial, lateral, anterior or posterior to the effective u_{max} and will lead to an over- or underestimation of the ML and AP MoS (Figure 2 and 4). Note that even during forward and backward leaning, the AP CoP does not reach the anatomical boundary of the foot where a marker might be placed (Figure 3 Hof et al. (2005) and Figures 1 and 2 Eysel-Gosepath et al. (2016)).

4.2 Estimation of the (extrapolated) center of mass

Valid calculation of the XcoM requires accurate estimation of both the CoM position and velocity. Hof et al. (2005) (see also Hof (2005)) introduced a simple method to estimate the CoM projection at ground level from force plate data, which can be used to calculate the MoS. Despite the relative simplicity of Hof’s proposed force plate method, kinematic, segment-based CoM estimations have been dominant for calculating the MoS in the literature since. For a detailed comparison of a force plate method with a kinematic, multi-segment body model see Buurke et al. (2023).

The full-body kinematic segmented-based CoM estimation has been followed by simplified, reduced kinematic models to estimate CoM position and velocity. A critical consideration for such reduced kinematic models is that while some point on the trunk reasonably corresponds to the whole-body CoM during walking, this does not hold true for CoM velocity (Zelik and Adamczyk, 2016). For more dynamic movements and tasks that involve acute stability recovery actions, a single point on the trunk may not suffice for either. Despite the recent popularity of reduced kinematic models, few validation studies of reduced kinematic models for specific tasks and setups have been conducted (e.g., Süptitz et al. (2013)) and the potential problems with reduced kinematic models for estimating the CoM position and velocity during gait and turning have been well documented (Havens et al., 2018; Huntley et al., 2017; Vanrenterghem et al., 2010). As a result, caution is warranted when using reduced kinematic models and thorough, task and setup-specific validation is recommended.

4.3 The choice of timing when assessing the margin of stability

During walking, the choice of timing when assessing the MoS is not arbitrary and should be carefully considered. In the literature, the MoS has been estimated at multiple instances in the gait cycle (Figure 4). However, in the original definition by Hof et al. (2005), the minimum spatial ML MoS (b_{min}) was calculated as the minimal signed ML distance between the XcoM and the CoP during the single stance phase of walking. Generally, b_{min} occurs close to the moment of contralateral toe-off (Hof et al., 2005; Hof et al., 2007). A relative comparison of the MoS at initial contact ($b_{initial}$) and the average (b_{avg}) over a step was used to describe the contribution of the lateral ankle strategy during prosthetic walking (Hof et al., 2007). Yet, during double support, a linear inverted pendulum model is less valid, since it does not account for push-off and collision impulses (Donelan et al., 2002). Contrary to the ML MoS, the AP MoS is always negative during steady-state walking (see Figure 4C), because at foot contact, the CoP is placed at a certain, 'constant' distance behind/posterior to the XcoM to maintain a steady gait speed (Hof, 2008).

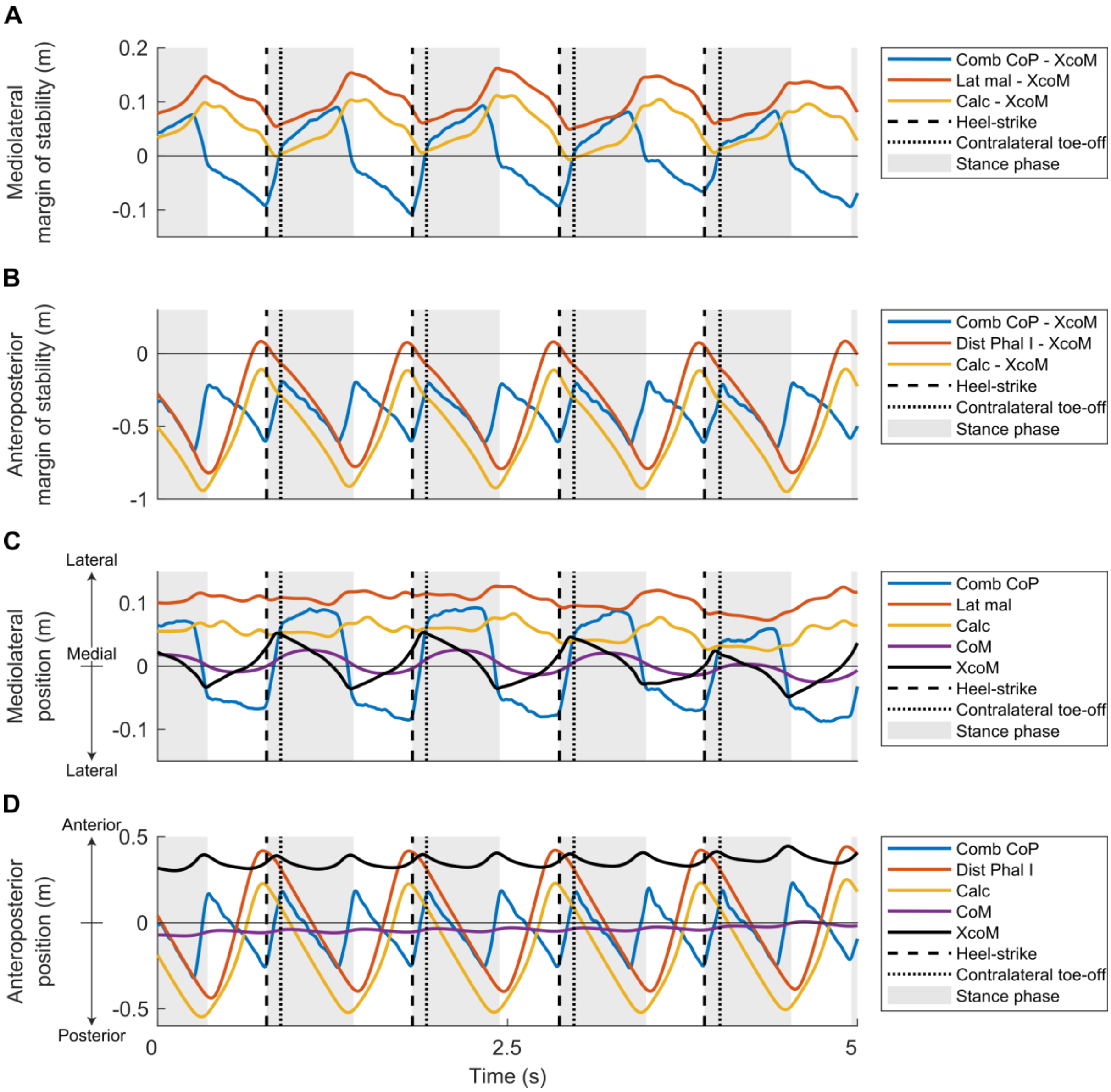

Figure 4. Illustration of the implications of base of support boundary and gait event choices in experimental data of a representative subject walking at 1.4 m s^{-1} (data only shown for one side; data from Buurke et al. (2023). The time instance of heel-strike is visualized as a vertical dashed line and contralateral toe-off as a vertical dotted line in all subplots. A) The mediolateral margin of stability calculated as the mediolateral distance between the extrapolated center of mass (XcoM) and the combined center of pressure (Comb CoP), the lateral malleolus marker (Lat mal), and the Calcaneus marker (Calc). The difference in mediolateral margin of stability between CoP and marker-based is up to 20 cm at heel-strike and 5 cm at contralateral toe-off. The marked difference in amplitude and phase-shift depending on base of support definition should be noted. Note that during the swing phase, no GRF is acting on the XcoM and no MoS can be assumed for the shown foot. B) The anteroposterior margin of stability calculated as the distance between the anteroposterior XcoM and the Comb CoP, the Distal Phalanx 1 marker (Dist Phal I), and Calc. The difference in anteroposterior margin of stability between CoP and marker-based is up to 60 cm at heel-strike and 15 cm at contralateral toe-off. The marked difference in amplitude and phase-shift depending on base of support definition should be noted. C) The mediolateral position of the Comb CoP, Lat mal, Calc, Center of Mass (CoM) and XcoM. D) The anteroposterior position of the Comb CoP, Dist Phal I, Calc, CoM, and XcoM.

4.4 Additional considerations for estimating the margin of stability during walking

Due to the XcoM accounting for the velocity of the CoM, the AP MoS during walking is tightly linked to gait speed, with increasing speeds leading to more negative AP MoS (Hof, 2008; McCrum et al., 2019; Süptitz et al., 2012). Reporting of the MoS in the AP direction has been inconsistent in the literature (e.g. Hak et al. (2013)); however given the instability in this direction (XcoM is anterior to the CoP), able-bodied people walking with a steady forward velocity should be reported as having negative AP MoS (Hof (2008), Equations 21 and 22).

The experimental context may bring some additional considerations for calculating the MoS during walking. Two specific examples are treadmill walking and curved walking or turning. To estimate the velocity of the CoM during treadmill walking, the relative motion (Galileo, 1632) of the treadmill belt needs to be accounted for by adding the belt velocities (Hof, 2008; Süptitz et al., 2012). This correction has been overlooked in some applications of the MoS during treadmill walking (Buurke et al., 2020; Darter et al., 2018; Eichenlaub et al., 2023; Kao et al., 2018; McAndrew Young and Dingwell, 2012; McAndrew Young et al., 2012). Alternatively, at each instant the distance traveled can be added to the CoP and CoM positions before CoM velocity and XcoM are calculated (Figure 1 in Hak et al., 2013). A lack of adjustment for treadmill speed can be suspected when the AP MoS values are unrealistically large and positive, alongside XcoM position values that are unrealistically small. Regarding curved walking and turning, the global and local reference frames fall out of alignment when gait diverges from straight ahead. To account for this constant change in reference frame during curved walking and turning, kinematic data need to be rotated to a trajectory-fixed or body-fixed reference frame before extracting XcoM position and MoS (e.g., He et al. (2018); Fino et al. (2020); for a detailed discussion, see Ho et al. (2023)). Walking and turning follow the simple rule that one needs to be unstable in the direction of heading.

5. Interpreting the margin of stability

In keeping with Hof et al. (2005), the MoS is an instantaneous measure of mechanical stability of the body configuration directly related to the minimal impulse needed to destabilize a person (Hof et al. (2005), equation 8). A stable or unstable MoS can only describe the instantaneous mechanical stability of the person and does not necessarily indicate their global gait stability or their general fall risk while walking, which is evidenced by multiple studies reporting larger MoS values in groups with increased risk of falls which has been suggested to be a compensation strategy for various acute or chronic deficits (Buurke et al., 2020; Hof et al., 2007; Hohne et al., 2011; Lin et al., 2022; Vistamehr et al., 2016). The unilateral increase in ML MoS that can be observed in groups with gait asymmetries, for instance in amputee gait (e.g., Gates et al. (2013); Hof et al. (2007)) and post-stroke gait (e.g., Buurke et al. (2020); Tisserand et al. (2018)), also illustrates that a higher MoS does not necessarily reflect global gait stability or general fall risk. Rather, an asymmetric ML MoS in these populations demonstrates how humans can exploit the passive dynamics of walking to efficiently increase instantaneous mechanical stability by altering step width and bilateral stance times (Buurke et al., 2019; Hof, 2021). Asymmetries in the underlying gait pattern are thereby exploited to unilaterally increase the ML MoS on the prosthetic, paretic or otherwise affected side, for efficiency and stability of the gait pattern. Though the observation of large MoS in fall-prone individuals may seem paradoxical (Kazanski et al., 2022), it is consequential, in that they appear to exploit the natural dynamics of the mechanical system (linear IP model) thereby reducing the need for active neural control (Hof, 2021). In summary, MoS is a purely mechanical measure of instantaneous gait stability and does not reflect global gait stability or its underlying neural control.

6. Conclusion

The XcoM concept is an extension of the classic inverted pendulum model to describe stability in dynamic situations. The *margin of stability* can be derived from the XcoM concept as a measure of instantaneous mechanical stability. Like any model, the XcoM is valid only in situations in which the underlying assumptions of the model are met, specifically those of a linearized pendulum. Different methods for estimating the XcoM and MoS are not interchangeable and will affect results and interpretation.

Appendix A: Margin of stability reporting checklist

Topic	**#**	**Description**	**Reported** Yes/No/NA
Calculating			
CoM	1	The CoM was estimated based on ground reaction forces, a full-body kinematic model, or a validated reduced kinematic model.	
XcoM	2	The XcoM was calculated as: $XcoM = x + \frac{v_x}{\omega_0}$	
Relative velocities	3	The relative motions are accounted for, e.g., surface speed in treadmill walking. Thus, $v_x = v_{x\|T} + v_T$ in which $v_{x\|T}$ is the velocity of the CoM with respect to treadmill and v_T is the velocity of the treadmill belt.	
MoS	4	The MoS was calculated as: $MoS = BoS - XcoM$	
Asymmetric MoS	5	The MoS was calculated for the left and right leg separately.*	
Reporting			
MoS	6	Mean and distribution are reported to aid interpretation in the walking context (i.e., perturbed vs. unperturbed, treadmill vs. overground), alongside potential asymmetries and spatiotemporal gait parameters.	
Direction of the MoS	7	The direction of the margin of stability was reported in all written text, figures and tables.	
Timing of the MoS	8	The local minima or instance at which the MoS was calculated was reported.	
Boundary of the BoS	9	The definition of the boundary of the BoS was reported.	
Walking speed	10	Walking speed was reported to aid interpretation of the AP MoS	
Reduced kinematic model	11	Specifications and references to the validation of reduced kinematic models were provided.**	
Interpreting			
Interpreting the MoS	12	The MoS was interpreted as an instantaneous, but not global measure of mechanical stability.	

**Only applicable in case of potential asymmetries, e.g., in unilateral perturbations, unilateral assistance or populations with gait asymmetries.*

***Only applicable if a reduced kinematic model was used.*

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Conflicts of Interest Statement

The authors have no conflicts of interest to declare.

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