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A New Perspective on the Walking Margin of Stability

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Abstract

A reliable stability metric is needed to identify fall susceptibility that better addresses fall prevention and improves gait rehabilitation. One available metric is the margin of stability (MOS), which is calculated using the body's center of mass (COM) position and velocity along with the location of the maximum center of pressure (COP_{max}). However, the maximum MOS (MOS_{max}) has several limitations that may limit stability assessment because of its assumptions of fixed COP_{max} and constant ground reaction force (GRF), which are not applicable to gait. To address these limitations, a modified MOS equation that includes COP position and velocity and is not dependent on a constant GRF is presented here. The MOS determined by this equation was significantly lower than MOS_{max} throughout most of single limb support for normal walking gait. This finding indicates the MOS_{max} metric may lack sensitivity to instability as it may still be positive when the actual MOS indicates existing or impending instability. This comparison also showed that the MOS might offer additional information about walking stability relevant to gait assessment for fall prevention and rehabilitation. However, like other stability metrics, this capability must be established with further investigations of perturbed and pathological gait.

Keywords

Stability; walking; balance; falls

Introduction

Reliable and clinically meaningful identification and treatment of fall susceptibility should help reduce the personal and economic costs associated with fall injuries and reduce the mortality rate for severe fall injuries. Presently, the utility of existing stability metrics as reliable predictors of falls is still being investigated^{1–7}. One of these metrics, the margin of stability (MOS)⁸, incorporates center of mass (COM) and center of pressure (COP) data that represent both kinematic and kinetic elements of movement, respectively. Another feature of the MOS is its potential to identify likely points of fall susceptibility within a stride, as it is

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measured continuously and not averaged over multiple strides. This feature also makes the MOS an appealing metric for assessing responses to discrete perturbations. However, in its present form, the MOS has some limitations with regard to walking stability.

The advantage of the MOS perspective versus the traditional base of support (BOS) analysis is that it considers the trajectory of the COM so that it defines stability as a condition for which the COM is within the BOS and will remain within the BOS based on its current position and velocity. The MOS is currently based on a model originally developed to analyze stability during quiet stance (Figure 1) with an equation of motion developed from the fundamental Euler equation for a single inverted pendulum:

$$(u - x) mg = I\alpha \approx -ml^2 \frac{\ddot{x}}{l} \quad (1)$$

Rearranging this equation to eliminate the mass (m) term and produce a solvable differential equation yields:

$$x = \ddot{x} \frac{l}{g} - u = \frac{\ddot{x}}{\omega_0^2} - u, \quad \omega_0 = \sqrt{\frac{g}{l}} \quad (2)$$

where u is the COP position, x is the COM position, g represents acceleration due to terrestrial gravity, and l is the distance from the ankle to the COM. If a constant COP position (u) is assumed, the following equation establishes the relationship between the 'extrapolated' COM and COP position:

$$x_0 + \frac{v_0}{\omega_0} \leq u \quad (3)$$

After substituting u with the maximal COP position, u_{max} , this relationship yields the existing maximal MOS (MOS_{max}) equation:

$$b = \left| u_{max} - \left(x_0 + \frac{v_0}{\omega_0} \right) \right| = MOS_{max} \quad (4)$$

Before proceeding further, several variables are changed to reduce ambiguity and improve consistency. The COM position (x) and velocity (v) are changed to x_{COM} and v_{COM} , respectively. Also, COP position is changed to x_{COP} . With these changes, equation (4) becomes:

$$MOS_{max} = \left| x_{COP_{max}} - \left(x_{COM_0} + \frac{v_{COM_0}}{\omega_0} \right) \right| \quad (5)$$

Instead of including only COM and COP positions (x_{COM} and x_{COP} , (x_{COP} is 'u' in the original MOS equation⁸)), the MOS adds an 'extrapolated' center of mass component (COM_{extrp} (originally X_{COM} ⁸)). COM_{extrp} includes both COM position and velocity (v_{COM}), represented by the parenthetical term on the right-hand side of equation (1). This term reflects the combined effect of the COM position and its trajectory toward the BOS boundary as established by the COP position (x_{COP}).

Even though the MOS has been used to assess walking stability^{9–11}, there are several limitations of the MOS as currently defined. The first limitation is that the MOS inverted pendulum model was originally developed for anterior-posterior standing sway with both feet approximated as a single support. This model makes the MOS applicable only when the body's COP can be approximated as a single point, as in single limb support (SLS). Additionally, the MOS equation was developed with the assumption of a constant ground reaction force (GRF) equivalent to the subject's weight. This approximation is appropriate for quiet stance, but not across a stride cycle, during which the GRF changes continuously as weight is transferred from one foot to the other and back. Because x_{COP} is constant in equation (1), the typical practice is to calculate a maximum MOS (MOS_{max}) based on a maximal COP position (x_{COPmax}), which is established by the boundaries of the foot contact area. As with the constant GRF assumption, x_{COPmax} as defined by foot contact area is relatively stable during quiet stance. However, during walking, x_{COPmax} changes with each foot's stance phase progression. For example, at initial and final contact, only part of the foot contacts the support surface and there is often considerable internal and external rotation throughout the stride, which will move x_{COPmax} medially or laterally and change the BOS. This last limitation can be addressed if x_{COP} is allowed to vary with time, as is x_{COM} , resulting in an MOS based on the actual, not maximal, COP location. Once the COP position is allowed to vary with time, it will also have a velocity and its own trajectory, which will also continuously affect the MOS.

The limitation of the assumed fixed COP location is cited in the original MOS development as 'Case b' of different stability scenarios⁸, which suggests that the foundational differential equation should be solved for 'non-constant $u(t)$ ', which then leads to the inclusion of a COP velocity term (v_{COP}). Presented here is a solution for that scenario that eliminates the need to assume a constant GRF and a fixed maximal COP position, producing a more generalized form of the MOS equation that is applicable for both standing and walking stability assessment. Comparisons of this generalized MOS and MOS_{max} are then presented for individuals with normal walking gait.

Methods

Generalized MOS Equation Development

To eliminate the need to track a variable GRF, a modified version of the original inverted pendulum model was used to examine frontal plane stability during walking (Figure 1). Instead of treating the ankle as a planar hinge joint, the leg, ankle, and foot are treated as a single structural member with the COM at one end and the GRF applied at the other. This change places the focus on the effective moment arm created by the relative COM and COP positions and the forces at each end of the arm. Summing moments and applying the same inertial approximation used for the original MOS equation, the following relationship is established:

$$x_{COP} \times GRF - (x_{COP} - x_{COM})mg = I\alpha \approx -ml^2 \frac{\ddot{x}_{COM}}{l} \quad (6)$$

By using a Galilean coordinate transformation that establishes x_{COP} as the frame of reference origin, the GRF produces no effective moment ($x_{COP}=0$) and no longer needs to be included in the equation of motion. The coordinate transformation also produces new COM position and velocity variables x'_{COM} and v'_{COM} , respectively,

$$x'_{COM}(t) = x_{COM}(t) - x_{COP}(t) \quad (7)$$

$$v'_{COM}(t) = v_{COM}(t) - v_{COP}(t) \quad (8)$$

and the equation of motion becomes:

$$x'_{COM}(t) = \frac{\ddot{x}'_{COM}(t)}{\omega_0^2} \quad (9)$$

with the following initial conditions:

$$x_{COM}(t=0) = x'_{COM_0}, \quad \dot{x}'_{COM}(t=0) = v'_{COM_0} \quad (10)$$

The equation of motion (9) is now similar to equation (2), except that the COP position is embedded in the x'_{COM} term. and therefore now has the solution:

$$x'_{COM}(t) = \frac{e^{\omega_0 t} (v'_{COM_0} + \omega_0 x'_{COM_0})}{2\omega_0} - \frac{(v'_{COM_0} - \omega_0 x'_{COM_0})}{2\omega_0 e^{\omega_0 t}} \quad (11)$$

Applying the same limiting condition used for the original MOS of $x'_{COM}(t) = 0$ (i.e., $x_{COP}(t) = x_{COM}(t)$ at the limit of stability) and eliminating the $2\omega_0$ term produces the equation:

$$e^{2\omega_0 t} = \frac{(v'_{COM_0} - \omega_0 x'_{COM_0})}{(v'_{COM_0} + \omega_0 x'_{COM_0})} \quad (12)$$

Taking the natural logarithm of both sides of equation (12) yields:

$$t = \tau = \frac{\ln \left\{ \frac{v'_{COM_0} - \omega_0 x'_{COM_0}}{v'_{COM_0} + \omega_0 x'_{COM_0}} \right\}}{2\omega_0} \quad (13)$$

The time-to-contact (τ) will be real only for a condition of instability, whereas a stable condition will produce an infinite τ because the vertical projection of the COM will never reach and/or pass x_{COP} , based on the current COM and COP positions and velocities. In other words, the combined COM and COP velocities are not sufficient to overcome the current distance between the COM and COP. For equation (13) to produce a real value (unstable condition), the bracketed quantity in equation (13) must result in a positive real number.

$$\left\{ \frac{v'_{COM_0} - \omega_0 x'_{COM_0}}{v'_{COM_0} + \omega_0 x'_{COM_0}} \right\} \quad (14)$$

Because v'_{COM_0} is positive and x'_{COM_0} is negative (see Figure (1)), the numerator within the brackets is positive. Therefore, the denominator of equation (14) must also be positive to produce a positive real number, or:

$$v'_{COM_0} + \omega_0 x'_{COM_0} > 0 \quad (15)$$

which establishes the condition for instability. Therefore, a stable condition will meet the opposite condition (<0). By dividing both sides by ω_0 and reversing the coordinate transformations, the stability condition is now:

$$\frac{v_{COM_0} - v_{COP_0}}{\omega_0} + (x_{COM_0} - x_{COP_0}) < 0 \quad (16)$$

which can be rearranged to form a generalized MOS equation:

$$MOS = \left| (x_{COP_0} + \frac{v_{COP_0}}{\omega_0}) - (x_{COM_0} + \frac{v_{COM_0}}{\omega_0}) \right| \quad (15)$$

Note that the COM terms that comprise the extrapolated COM are still present. Likewise, the COP terms can now be combined to form an ‘extrapolated COP’, quantifying the combined COP position and velocity. Also note that the assumption of a fixed maximal COP will eliminate the v_{COP} term, producing equation (5).

Whereas the original form of the MOS quantified the maximum MOS available (MOS_{max}) and was based solely on foot and body positions, equation (8) quantifies the actual MOS at any given time (MOS). In essence, this more generalized form of MOS establishes whether the effective moment arm—the distance between x_{COM} and x_{COP} —is sufficient to prevent instability based on current COM and COP velocities. Including actual COP positions and velocities in the MOS provides insight into some of the neuromechanical responses to varying dynamic conditions. This feature becomes especially useful for the study of discrete gait perturbation responses and unstable gait.

Experimental Validation

Validation of MOS as defined in equation (8) was performed using data collected from 14 healthy children (7 male/7 female, Age: 12.5 ± 3.0 years, Height: 152 ± 13.8 cm, Weight: 48 ± 16.2 kg) at the National Institutes of Health (NIH) Clinical Center and approved by the NIH Institutional Review Board. Parental written informed consent was obtained for each participant and written assent was obtained from each participant. Three-dimensional lower extremity kinematic and spatiotemporal data was collected at 120 Hz with a 10-camera motion capture system (Vicon, Oxford, UK) using a 34-marker model¹² and analyzed using Visual3D software (C-Motion, Germantown, MD, USA). Pelvis COM data was taken from the Visual3D model and foot COP locations were obtained using three walkway force plates

(AMTI, Watertown, MA, USA) with data sampled at 1080 Hz and downsampled to 120 Hz. $x_{COP_{max}}$ was approximated as the lateral foot marker on top of the foot near the fifth metatarsal. Equation of motion solution and data analyses were performed using MATLAB 7.12.0 (MathWorks, Natick, MA, USA). COM and COP velocities were calculated from displacements by differentiation using a central difference equation, a cubic spline interpolation, and a fourth order Butterworth filter. Significant differences were determined by plotting means with the 95% confidence intervals and noting significant differences when confidence intervals did not overlap.

Results

A comparison across 14 individuals of actual and maximum medio-lateral (M-L) MOS and MOS_{max} during single-limb support (approximately 20% to 80% of each leg's stance phase) reveals a divergence between the two metrics starting at 10–20% of SLS (Figure 2). More importantly, from about 50% of SLS to its completion, MOS is significantly less than MOS_{max} . This difference indicates a 'reserve' between the actual MOS that an individual establishes while walking and the maximum possible MOS that could be established.

Discussion

This expanded and more generalized MOS equation includes v_{COP} and maintains the original MOS features of simplicity, kinematic and kinetic representation, and instantaneous measurement. Essentially, the MOS reflects the neuromechanical adjustments made to maintain stability versus the kinematic quantification of body trajectory and foot placement provided by MOS_{max} . If possible, both MOS and MOS_{max} should be examined simultaneously, as MOS quantifies the MOS that is maintained during SLS, whereas MOS_{max} quantifies the maximum MOS that could possibly be established.

The comparison of MOS and MOS_{max} shows that past walking studies that assessed stability using $MOS_{max}^{9-11,13}$ may have been limited because the MOS_{max} is significantly higher than the actual MOS, which was not included in these MOS_{max} assessments. However, the MOS is still based on an inverted pendulum model, which constrains MOS stability assessment to SLS. the generalized equation still does not include the effects of hip moments, but does now allow for the continuous COP adjustments accomplished primarily through ankle eversion/inversion. Because kinematic data used here was originally collected for a different study, whole-body COM was not available. For unperturbed gait, the vertical projection of the medio-lateral pelvic COM and whole-body COM will be similar. Additionally, the same COM trajectory is used for both equations, so the comparative effects should be minimal.

For assessing fall susceptibility, the MOS is more likely to detect instability, as its values are generally closer to zero (Figure 2) and more sensitive to sudden changes in support or body dynamics. As opposed to MOS_{max} , the MOS reflects COP adjustments made to accommodate constantly updated sensory input related to maintaining stability. This feature will be especially useful for examining responses during discrete perturbations and to

compare stability in individuals with normal, perturbed, and pathological gait. However, the true usefulness of the MOS as a stability metric must still be established.

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Figure 1.

Comparison of original and modified inverted pendulum models for MOS equation development (shown in frontal plane for M-L stability). Original variable designations for COM location and velocity and COP location are shown in parentheses.

Figure 2.

Comparisons of MOS and MOS_{max} means (heavier lines) and confidence intervals (shaded areas) show MOS was generally smaller than MOS_{max} and significantly smaller for the second half of SLS.