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Evaluation of Time-to-Contact Measures for Assessing Postural Stability

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Postural stability has traditionally been examined through spatial measures of the center of mass (CoM) or center of pressure (CoP), where larger amounts of CoM or CoP movements are considered signs of postural instability. However, for stabilization, the postural control system may utilize additional information about the CoM or CoP such as velocity, acceleration, and the temporal margin to a stability boundary. Postural time-to-contact (TtC) is a variable that can take into account this additional information about the CoM or CoP. Postural TtC is the time it would take the CoM or CoP, given its instantaneous trajectory, to contact a stability boundary. This is essentially the time the system has to reverse any perturbation before stance is threatened. Although this measure shows promise in assessing postural stability, the TtC values derived between studies are highly ambiguous due to major differences in how they are calculated. In this study, various methodologies used to assess postural TtC were compared during quiet stance and induced-sway conditions. The effects of the different methodologies on TtC values will be assessed, and issues regarding the interpretation of TtC data will also be discussed.

***Key Words*:** postural stability, center of mass, center of pressure, time-to-contact

Postural stability is often assessed by measuring the amount of postural sway of the center of mass (CoM) or center of pressure (CoP). A system exhibiting a small amount of CoM or CoP excursion is considered more stable than a system exhibiting a larger amount of excursion (Woollacott, Shumway-Cook, & Nashner, 1986). Recent research has argued against these interpretations of postural instability. For example, ACL injured patients (Davids, Kingsbury, George, O'Connell, & Stock, 1999) and older individuals (van Emmerik & van Wegen, 2002) may exhibit less postural sway compared to healthy younger persons under certain conditions. Measures that examine only spatial aspects of postural movements may be inadequate in determining overall postural stability.

An alternative measure of stability that incorporates both spatial and temporal aspects of postural sway is known as time-to-contact (TtC) (Riccio, 1993; Slobounov, Slobounova, & Newell, 1997). This is an adaptation of the tau (τ) control variable originally outlined by Lee (1976). Lee found that optical flow is used to control actions based on the time it would take to contact a surface in the environment. Riccio (1993) calculated TtC as the time it would take the CoP, given its current trajectory and velocity, to contact the stability boundary (defined by the perimeter of the feet). The advantage of this methodology is that assessments of postural stability include both spatial (displacement) and temporal (velocity and acceleration) aspects of postural movements relative to the base of support. Riccio (1993) postulated that TtC is directly perceivable by the individual and provides information regarding the time needed to reverse a perturbation before loss of balance.

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Since the original inception by Riccio (1993), postural TtC measures have been calculated in different ways. Researchers have varied on (a) how the base of support is assessed, (b) whether the CoP or CoM is used as the relevant postural trajectory, (c) the filtering techniques used, and (d) the calculations used with regard to how the CoP or CoM trajectory is extrapolated to the boundary of the base of support (Slobounov et al., 1997; van Wegen, van Emmerik, & Riccio, 2002).

Although postural TtC measures appear to hold promise in their ability to assess postural stability, the use of dissimilar methodologies makes interpretations of TtC data and comparisons between studies difficult. The purpose of this study was to compare two different techniques (Riccio 1993 vs. Slobounov et al. 1997) used to calculate postural TtC during both quiet stance and self-induced rhythmic movements. The impact of the noted variations in research methodologies on TtC values will be assessed, followed by recommendations on how to consider these effects when interpreting TtC data.

Methods

One healthy male participant (25 yrs, 1.85 m, 76.4 kg) was recruited. Two force platforms (AMTI), one under each foot, were used to calculate net CoP position (Winter, 1995). Six motion capture cameras (MCU240, Qualisys) were used to calculate CoM position. Data were synchronized and sampled at 100 Hz. Kinematic data were collected using a 12-segment whole-body passive marker set. CoM location was calculated utilizing a model based on Plagenhoef (1983).

A trapezoidal stability boundary was determined by having the participant stand (feet shoulder width apart) on the force platforms. These boundaries were marked and maintained in all conditions (Figure 1). The participant was tested under five conditions: quiet stance, voluntary anterior-posterior (AP) sway at approximately 0.5 and 1 Hz, and voluntary medial-lateral (ML) sway at approximately 0.5 and 1 Hz. In the quiet stance condition he was instructed to stand as still as possible. For the voluntary oscil-

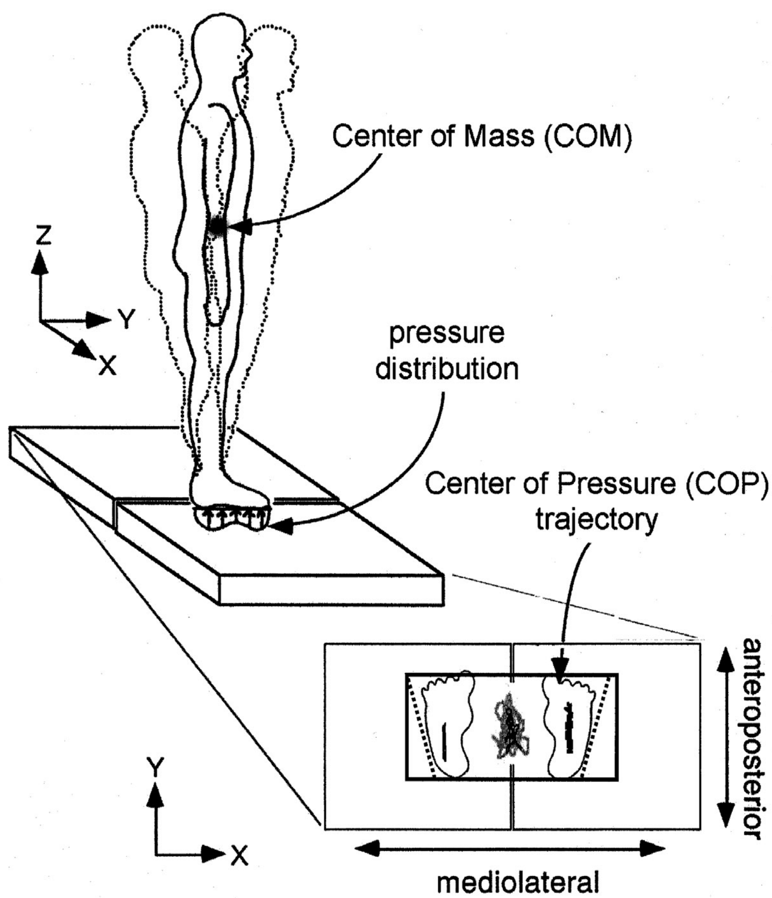

Figure 1 – Two force plates were used in this experiment. The CoP trace under each foot is shown as well as the calculated net CoP (gray) and CoM (black). TtC was calculated using both the CoP and CoM within a trapezoidal base of support. The medial and lateral boundaries of the trapezoid were calculated based on straight lines containing the positions of the 5th metatarsal heads and lateral malleoli of the left and right feet, respectively. The anterior boundary was determined by a straight line across the toes intersecting the side boundaries, while the posterior boundary was determined by a straight line across the heels intersecting with the side boundaries. Differences have emerged regarding where the medial and lateral boundaries are placed. While some studies have simply made the boundaries rectangular (solid lines around the feet), others have made the boundaries trapezoidal (dotted lines around the feet).

lations he entrained sway to a metronome. In all conditions the participant was instructed not to move his feet, and data were collected for 10 seconds.

The effect of cutoff frequency was examined by filtering all data with a fourth-order, zero-lag low-pass Butterworth filter using cutoff frequencies ranging from 3 to 30 Hz in 3-Hz intervals. After filtering, the displacement of the CoP and CoM was calculated and the TtC was determined using both the TtCs (Slobounov et al., 1997) and TtCr (Riccio, 1993) methodologies.[1]

In the TtCs method, the x and y positions of the virtual trajectory were parameterized by introducing a time variable τ.

$$x(\tau) = r_{ox}(t_i) + v_{ox}(t_i)\,\tau + \frac{a_{ox}(t_i)\,\tau^2}{2} \qquad (1)$$

$$y(\tau) = r_{oy}(t_i) + v_{oy}(t_i)\,\tau + \frac{a_{oy}(t_i)\,\tau^2}{2} \qquad (2)$$

where $r_{ox}(t_i)$ and $r_{oy}(t_i)$, $v_{ox}(t_i)$ and $v_{oy}(t_i)$, and $a_{ox}(t_i)$ and $a_{oy}(t_i)$ are the instantaneous x and y positions, instantaneous x and y velocities, and the instantaneous x and y accelerations of the CoP at a specific instant in time (t_i), respectively. The overall stability boundary was constructed as a trapezoid in which each side boundary was represented by a line defined as

$$y - y_b = m(x - x_b) \qquad (3)$$

where m is the slope of the line and x_b and y_b are the coordinates of an arbitrary point on the line. The time it took the virtual trajectory to intersect the boundary was found by substituting Equations 1 and 2 into Equation 3. Algebraic rearrangement resulted in

$$A\tau^2_b + B\tau_b + C = 0 \qquad (4)$$

where $A = \frac{a_{oy}(t_i) - ma_{ox}(t_i)}{2}$,

$B = v_{oy}(t_i) - mv_{ox}(t_i)$, $C = r_{oy}(t_i) - y_b - m(r_{ox}(t_i) - x_b)$, and τ_b = the virtual time to contact the side boundary at that instant. This quadratic equation was then solved for τ_b. Note that depending on the specific side boundary, τ_b may have one, two, or no real solutions. Essentially, the path of the virtual trajectory is parabolic and may intersect the side boundary one or two times or not at all. After examining each side boundary, we recorded the smallest positive τ_b as the overall TtC at that time instant.

Riccio (1993) calculated TtC by simply taking the instantaneous distance of the CoP to the stability boundary divided by the instantaneous velocity. Acceleration information was not taken into account, resulting in a virtual trajectory that was linear.

At each instant in time, the TtC was calculated resulting in a TtC time-series across the entire trial (Figures 2b and 2d) that was further processed to yield a final "global" TtC value. In the TtCs method the final TtC value was determined by averaging the entire time-series (Figure 2b). In the TtCr method TtC was determined by averaging 10 local minima (although any number of local minima could have been used) across the time-series (Figure 2d). The use of local minima was necessary because TtC values approach infinity as velocity approaches zero. Values approaching infinity are rare in the TtCs method because both velocity and acceleration would have to be close to zero for this to occur.

Results

Selected TtC trajectories computed using the TtCs (Slobounov et al., 1997) and TtCr (Riccio, 1993) methodologies are shown in Figure 2. In the TtCs method the trajectories are generally parabolic due to the differential directions between the velocity and acceleration vectors (Figure 2a). In the TtCr method the trajectories are linear (Figure 2c). The difference in trajectory shapes is due to the inclusion of an acceleration term in the TtCs calculations.

During quiet stance the acceleration term in the TtCs calculation produced shorter contact times compared to the TtCr method (see Figure 3a). In the sway conditions the opposite results were found, whereby the TtCs method generally produced longer contact times compared to the TtCr method (see Figure 3b).

Filtering can have large effects on the higher derivatives used in the TtC calculations. The results show that the quiet stance condition (using both methods) was more sensitive to the choice of filter cutoff frequency compared to active sway (Figure 3). This was likely due to the low-amplitude high frequency nature of CoP and CoM movements

[1] We refer to Riccio's (1993) method as the TtCr method, and to Slobounov et al.'s (1997) method as the TtCs method. In the literature, the TtCr method is often referred to as time to boundary, and the TtCs method as virtual time to contact.

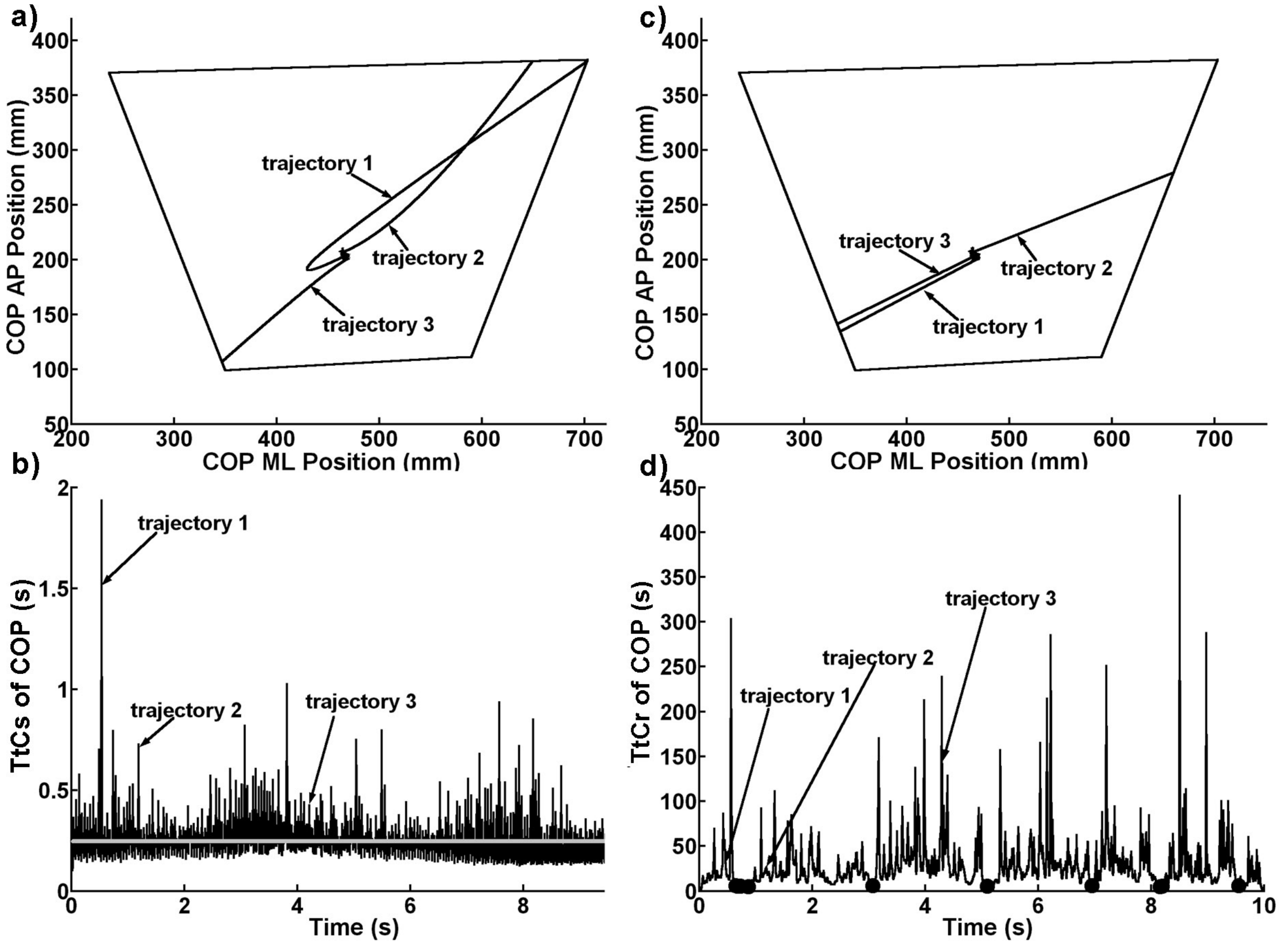

Figure 2 – Three selected TtC (using CoP) trajectories to the boundary of support during quiet stance (a) and the resulting TtC time series (b) using the TtCs method. The same three selected trajectories to the boundary of support during quiet stance (c) and the resulting TtC time series (d) using the TtCr method. Although the TtC was determined using the same three points, the different calculations yield dramatically different trajectories and ultimately very different TtC values.

during quiet stance. TtC differences as large as 10 s (CoM) and 5 s (CoP) emerged when using cutoff frequencies between 3 Hz and 12 Hz.

TtC calculations associated with a larger dominant oscillation such as in the voluntary sway condition seemed to be less affected by the choice of cutoff frequency. As the self-imposed dominant oscillation increased (between 0.5 and 1 Hz), the effects of filtering decreased in both the AP and ML sway conditions (Figures 3b and 3c). It appears that filtering reduces the higher frequencies in the TtC time series during sway conditions for both methods, but does not greatly change the minima (TtCr method) or average (TtCs method) TtC values (Figure 4).

Regardless of the methodology chosen to calculate TtC, the values can be determined from either the CoP or the CoM trajectories. TtC values were longer in all conditions for both calculation techniques when using the CoM (Figures 3a–3c). Longer TtC values emerge because the velocity, acceleration, and amount of excursion of the CoM are much smaller than the CoP.

Discussion

Although TtC measures yield information on postural stability that may not be captured using traditional spatial measures, the differences outlined above need to be carefully assessed before these measures are employed. Some recommendations are outlined below.

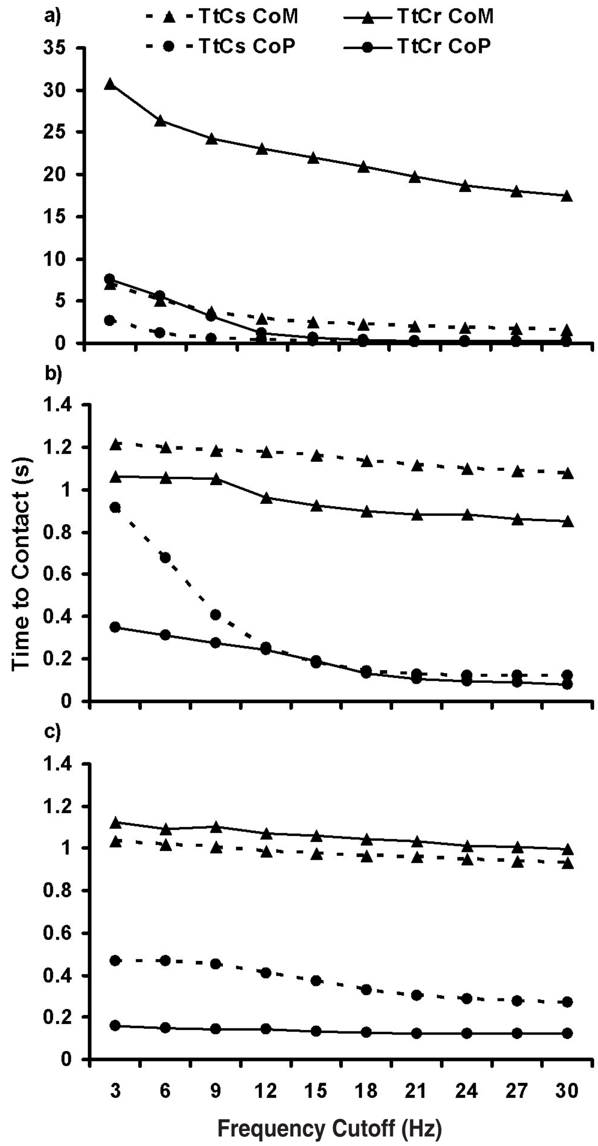

Figure 3 – TtC of the CoM (triangles) and the CoP (circles) as a function of filtering frequency. Values generated using both TtCr (solid line) and TtCs (dashed) methods are shown for three different conditions: (a) quiet stance, (b) 0.5 Hz AP sway, and (c) 1 Hz AP sway. Trends in the ML conditions were virtually identical and thus are not shown here.

In the TtCs method the final value is obtained from an average of the entire TtC time series and not just an average of the minima. It is therefore reasonable to assume the TtCs method is more representative of boundary relevant dynamics over the entire trial. On the other hand, long TtC values would be ignored using the TtCr methodology because only local minima are included in the final averaging. These minima may represent the points in time that are the biggest threat to balance.

It was shown that during active rhythmic sway, TtC values were longer using the TtCs calculation as opposed to using the TtCr calculation. These longer times in the TtCs calculation may exist because the acceleration and velocity vectors are typically pointing in different directions near the reversal point. In this case, if the acceleration is large enough, the boundary that the trajectory contacts may be very different from that found using the TtCr method. For example, if the instantaneous velocity vector were directed forward and the acceleration were directed backward, the virtual trajectory would contact the front boundary using the TtCr method but may contact the front or rear boundary using the TtCs method, depending on the acceleration magnitude.

In the current data the rhythmic and quiet stance conditions responded differently to manipulations of cutoff frequency. Movement frequency and filter cutoff frequency may have potentially large effects on measures of TtC. This could have important implications for studies that use the TtC measure as an index of postural stability. Comparison between different conditions such as quiet stance, sway, or reaching tasks may be difficult, as each of these movements occurs at different frequencies. Even if the task is the same, differences in TtC values may still arise if the participant groups have different postural dynamics. For example, patients with Parkinson's disease show tremor during quiet stance and dynamic movements (Duval, Sadikot, & Panisset 1994) while healthy individuals do not.

When comparing groups such as these, the choice of filter cutoff frequency may influence whether or not differences are found between the groups. This is because, as the present study has demonstrated, filtering at different cutoff frequencies can have nonlinear effects on TtC values (see Figure 3). Therefore, differences between groups at one cutoff frequency may be either nonexistent or enhanced at a different cutoff frequency.

Overall, it appears that during sway conditions the TtCs method is affected by filtering to a larger extent than the TtCr method. This is because the TtCs method uses acceleration information and is therefore more sensitive to filtering. If calculating TtC during dynamic sway movements, it may be beneficial to use the TtCr method, which may be more robust to imposed sway movements.

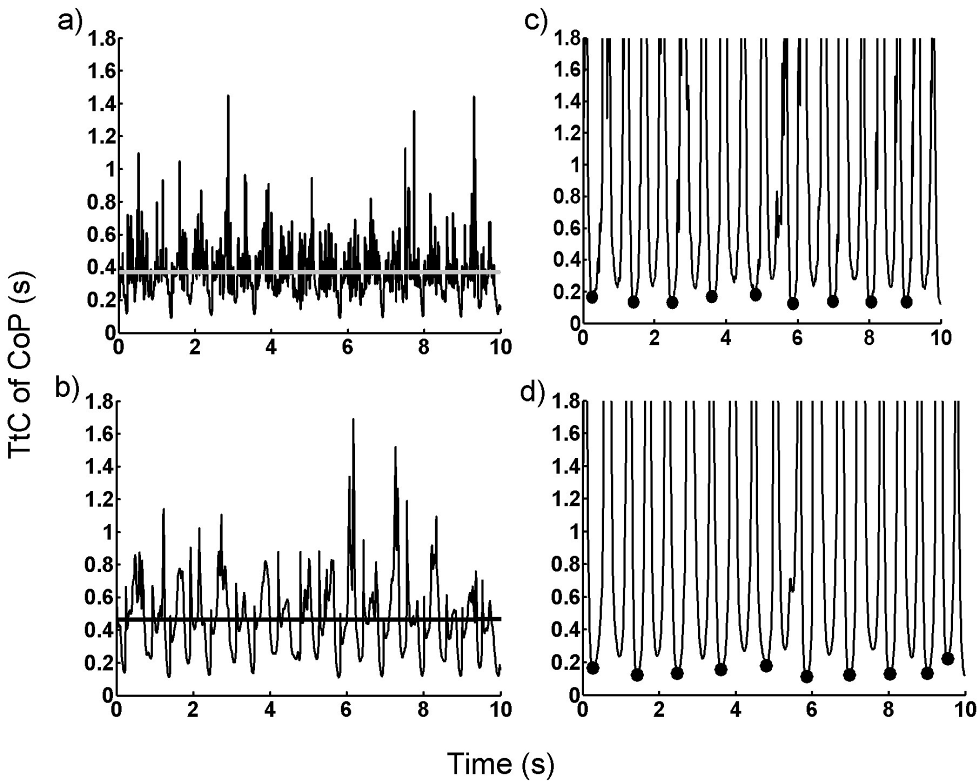

Figure 4 – TtC time series low-pass filtered at (a) 15 Hz and (b) 6 Hz using the TtCs method during a voluntary active sway condition at 1 Hz. Horizontal line represents the average TtC calculated in each condition. TtC time series filtered at (c) 15 Hz and (d) 6 Hz using the TtCr method during a voluntary active sway condition at 1 Hz. Average TtC is calculated as the average of the minima chosen in each time series. Minima are shown as solid black circles in each time series. Increasing the cutoff frequency reduces noise in the TtC time series of each method but does not ultimately change to a large extent the final TtC value.

TtC values calculated using the CoP or CoM measure different aspects of postural control, which may lead to different interpretations of postural stability (Winter, 1995). For example, van Wegen (2005) found that patients with Parkinson's disease had a longer TtC compared to healthy controls when TtC was calculated from the CoM. Using the same participants, the opposite results were found when TtC was calculated using the CoP. Riccio (1993) suggested that CoP is the more relevant variable because it is the controlling variable. Other researchers have argued that CoM is a better indicator of postural stability (Hof, Gazendam, & Sinke, 2005; Winter, 1995).

A disadvantage of using the CoP is that it makes interpretation of the TtC measure more difficult. There are very clear consequences to the CoM going outside the base of support, namely that the individual will fall or have to take a step. However, there are no direct consequences to the CoP hitting the stability boundary.

The choice to use CoP versus CoM should be made based on the nature of the investigation. Researchers who are interested in separating clinical populations may prefer to use the CoP in the TtC calculation due to its ease of implementation. Researchers concerned with using TtC as part of a postural control feedback scheme may prefer to use the CoM.

Assessment of stability boundaries can also affect TtC. In some studies, for computational simplicity, the stability boundaries were defined as a rectangle encompassing the area of stance around the foot (Riccio, 1993; van Wegen et al., 2002). Other studies used a convex polygon or trapezoid as the boundary around the foot (Hof et al., 2005; Slobounov, Moss, Slobounova, & Newell, 1998) (Figure 1). After the boundaries are assessed, the trajectories are extrapolated to the boundary. This extrapolation is necessary because the trajectories never actually reach the boundary. In earlier studies (van Wegen et al., 2002), postural TtC was calculated to both the AP and ML boundaries separately. Other studies (including the present study) calculated the TtC to whichever boundary is contacted first depending on its current trajectory (Figure 2). Extrapolating trajectories to individual AP or ML boundaries is necessary if one wishes to examine specific directional control strategies (e.g., van Wegen et al., 2002). Otherwise the TtC data are more intuitive if it is calculated to the true boundary position of contact.

When calculating TtC, the data may be more intuitive if the shape of the boundary is more representative of the base of support formed by the participant's feet. Therefore, the use of a multisegmented polygon (rather than a simple rectangle) to describe the shape of the boundary is recommended. The equations developed by Slobounov et al. (1997) can easily be manipulated to define the boundary using many segments. Also, when conducting research on patient populations, it may be worthwhile to describe the boundaries functionally as well as anatomically. Functional boundaries may be important because the ability of patients to operate at the limits of their stability boundaries may be drastically reduced compared to healthy individuals. The use of functional stability boundaries to calculate postural TtC has previously been employed to assess postural differences between healthy and aged individuals (Slobounov et al., 1997).

In conclusion, this paper has outlined several important issues regarding the use of TtC as a measure of postural stability. It was found that calculation techniques influence TtC values of quiet stance and voluntary sway in different ways. It was also shown that the choice of filter cutoff frequency can have a large impact on TtC values, and therefore must be chosen carefully. The choice of method should ultimately depend on the research question of interest. However, we feel that in most tasks the TtCs method will be more representative of overall postural control because it incorporates acceleration in its calculations.

The TtC measure was originally developed by studying birds in freefall where acceleration was virtually constant. Conversely, in human postural control there are certainly accelerations present. Therefore, higher order measures (such as the TtCs method) may be needed to completely capture the rich dynamics inherent in the control of posture.

Acknowledgments

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