ONLINE SUPPLEMENT

1. The Definition of the Base of Support

There is no fixed base of support (BOS) during human gait cycle. This may indeed be one of the most fascinating aspects of human locomotion which is characterized by cyclic alteration of its BOS to prevent an actual fall while achieve its mobility and at a low energy cost. The size (as determined by the step length or the foot length) and the direction of the BOS are constantly and often smartly changing. It equals to the outline area of one foot during the single-stance phase or of both feet and that in-between during double-stance phase. Its alteration between these two phases comes discontinuously and abruptly, all the while the rest of the body segment motion remains in a seamless and continuous motion that all contribute to smooth forward progression of the center of mass (COM). Where to place the next foot (in vector term) is certainly not trivial, and it has anything and everything to do with the central nervous system's detection and its determination of the stability limits of the state at the time and its projection of the future.

For all practical purposes, we have to reframe this complex human locomotion in a mathematically continuous manner for each stance phase. In all previous studies from this research group, we have been using the rear edge (or the heel) of the leading foot immediately after its touchdown as the reference point to calculate the relative position of the COM to the BOS regardless it is in double- or single-stance phases during its stance cycle until the touchdown of the contralateral foot. By then, the computation will have a reset to use the contralateral rear edge as the reference point. We used this approach to ensure the continuity for the comparison of stability among events. We understand this treatment is artificial and may even be arbitrary. On the other hand, it is also the most intuitive and straightforward one for us. Our previous experimental work has shown that the COM stability relative to the leading heel at touchdown can be a predictor of an impending falls among older adults (Bhatt et al., 2011). To make the present study comparable to all our previous ones, we used the leading heel as the reference point to calculate the relative position of the COM to the BOS.

2. Derivations of Equations for Calculating Sensitivities

2.1 Joint position

Based on the parameters shown in Fig. 1, the positions of all joint centers and toes/heels can be computed as follows,

$$
\begin{aligned}
x_{\mathrm{r,hee}} &= 0 \\
x_{\mathrm{r,ank}} &= l_1 \cos(\theta_1 + \alpha) \\
x_{\mathrm{r,kne}} &= l_1 \cos(\theta_1 + \alpha) - l_2 \sin(\theta_1 + \theta_2) \\
x_{\mathrm{r,hip}} &= l_1 \cos(\theta_1 + \alpha) - l_2 \sin(\theta_1 + \theta_2) - l_3 \sin(\theta_1 + \theta_2 + \theta_3) \\
x_{\mathrm{l,hip}} &= l_1 \cos(\theta_1 + \alpha) - l_2 \sin(\theta_1 + \theta_2) - l_3 \sin(\theta_1 + \theta_2 + \theta_3) - l_4 \sin\theta_4 \\
x_{\mathrm{l,kne}} &= l_1 \cos(\theta_1 + \alpha) - l_2 \sin(\theta_1 + \theta_2) - l_3 \sin(\theta_1 + \theta_2 + \theta_3) - l_4 \sin\theta_4 \\
&\quad - l_3 \sin(\theta_6 - \theta_1 - \theta_2 - \theta_3 - \theta_5) \\
x_{\mathrm{l,ank}} &= l_1 \cos(\theta_1 + \alpha) - l_2 \sin(\theta_1 + \theta_2) - l_3 \sin(\theta_1 + \theta_2 + \theta_3) - l_4 \sin\theta_4 \\
&\quad - l_3 \sin(\theta_6 - \theta_1 - \theta_2 - \theta_3 - \theta_5) - l_2 \sin(\theta_6 + \theta_7 - \theta_1 - \theta_2 - \theta_3 - \theta_5) \\
x_{\mathrm{l,hee}} &= l_1 \cos(\theta_1 + \alpha) - l_2 \sin(\theta_1 + \theta_2) - l_3 \sin(\theta_1 + \theta_2 + \theta_3) - l_4 \sin\theta_4 \\
&\quad - l_3 \sin(\theta_6 - \theta_1 - \theta_2 - \theta_3 - \theta_5) - l_2 \sin(\theta_6 + \theta_7 - \theta_1 - \theta_2 - \theta_3 - \theta_5) \\
&\quad - l_1 \cos(\alpha - \theta_6 - \theta_7 - \theta_8 + \theta_1 + \theta_2 + \theta_3 + \theta_5)
\end{aligned}
\tag{S1}
$$

where, $\theta_{1,2,3,\cdots,8}$ respectively indicated the joint angle of the leading foot, leading ankle, leading knee, pelvic rotation, leading hip, trailing hip, trailing knee, and trailing ankle. l_1 represented the distance between ankle and heel. l_2 and l_3 were the segment length of leg and thigh, respectively. l_4 depicted the width of the pelvis. $h_{2,3,4}$ respectively indicated the distance from the distal end to the COM of the leg, thigh, and HAT. $m_{2,3,4}$ respectively was the segmental mass of the leg, thigh, and HAT (Fig. 1).

2.2 COM position (x_{COM})

The foot accounts for only 1.4% mass of the whole body and much less than the mass of other segments. So both feet were excluded from the COM position calculation in order to simplify the computation procedure. The COM position at the anteroposterior direction related to the leading heel can be calculated as,

$$
x_{\mathrm{COM}} = \frac{m_2 (x_{\mathrm{r,leg}} + x_{\mathrm{l,leg}}) + m_3 (x_{\mathrm{r,thi}} + x_{\mathrm{l,thi}}) + m_4 x_{\mathrm{hat}}}{2m_2 + 2m_3 + m_4} \tag{S2}
$$

Each item in above equation is calculated by:

$$x_{\mathrm{r,leg}} = l_1 \cos\left(\theta_1 + \alpha\right) - h_2 \sin\left(\theta_1 + \theta_2\right)$$

$$x_{\mathrm{r,thi}} = l_1 \cos\left(\theta_1 + \alpha\right) - l_2 \sin\left(\theta_1 + \theta_2\right) - h_3 \sin\left(\theta_1 + \theta_2 + \theta_3\right)$$

$$x_{\mathrm{hat}} = l_1 \cos\left(\theta_1 + \alpha\right) - l_2 \sin\left(\theta_1 + \theta_2\right) - l_3 \sin\left(\theta_1 + \theta_2 + \theta_3\right) - \frac{1}{2} l_4 \sin\theta_4 - h_4 \sin\left(\theta_1 + \theta_2 + \theta_3 + \theta_5\right)$$

$$x_{\mathrm{l,thi}} = l_1 \cos\left(\theta_1 + \alpha\right) - l_2 \sin\left(\theta_1 + \theta_2\right) - l_3 \sin\left(\theta_1 + \theta_2 + \theta_3\right) - l_4 \sin\theta_4 - \left(l_3 - h_3\right) \sin\left(\theta_6 - \theta_1 - \theta_2 - \theta_3 - \theta_5\right)$$

$$x_{\mathrm{l,leg}} = l_1 \cos\left(\theta_1 + \alpha\right) - l_2 \sin\left(\theta_1 + \theta_2\right) - l_3 \sin\left(\theta_1 + \theta_2 + \theta_3\right) - l_4 \sin\theta_4 - \left(l_3 - h_3\right) \sin\left(\theta_6 - \theta_1 - \theta_2 - \theta_3 - \theta_5\right) - \left(l_2 - h_2\right) \sin\left(\theta_6 + \theta_7 - \theta_1 - \theta_2 - \theta_3 - \theta_5\right)$$

As a function of seven independent variables, $\theta_{1,2,3,\cdots,7}$, x_{COM} can thus be expressed,

$$x_{\mathrm{COM}} = x_{\mathrm{COM}}\left(\theta_{1,2,3,\cdots,7}\right) = l_1 \cos\left(\theta_1 + \alpha\right) + \frac{ m_2 \begin{bmatrix} -\left(h_2 + l_2\right) \sin\left(\theta_1 + \theta_2\right) - l_3 \sin\left(\theta_1 + \theta_2 + \theta_3\right) \\ -l_4 \sin\theta_4 - l_3 \sin\left(\theta_6 - \theta_1 - \theta_2 - \theta_3 - \theta_5\right) \\ -\left(l_2 - h_2\right) \sin\left(\theta_6 + \theta_7 - \theta_1 - \theta_2 - \theta_3 - \theta_5\right) \end{bmatrix} + m_3 \begin{bmatrix} -2 l_2 \sin\left(\theta_1 + \theta_2\right) - \left(h_3 + l_3\right) \sin\left(\theta_1 + \theta_2 + \theta_3\right) \\ -l_4 \sin\theta_4 - \left(l_3 - h_3\right) \sin\left(\theta_6 - \theta_1 - \theta_2 - \theta_3 - \theta_5\right) \end{bmatrix} + m_4 \begin{bmatrix} -l_2 \sin\left(\theta_1 + \theta_2\right) - l_3 \sin\left(\theta_1 + \theta_2 + \theta_3\right) - \frac{1}{2} l_4 \sin\theta_4 \\ -h_4 \sin\left(\theta_1 + \theta_2 + \theta_3 + \theta_5\right) \end{bmatrix} }{2 m_2 + 2 m_3 + m_4} \tag{S3}$$

By taking x_{COM}'s partial derivatives with respect to each joint angle, we obtained the sensitivity of x_{COM} to each joint angle:

$$c_1=\frac{\partial x_{\mathrm{COM}}}{\partial\theta_1}=-l_1\cos\left(\theta_1+\alpha\right)+\frac{\begin{array}{l}m_2\left[\begin{array}{l}-\left(h_2+l_2\right)\cos\left(\theta_1+\theta_2\right)-l_3\cos\left(\theta_1+\theta_2+\theta_3\right)\\+l_3\cos\left(\theta_6-\theta_1-\theta_2-\theta_3-\theta_5\right)\\+\left(l_2-h_2\right)\cos\left(\theta_6+\theta_7-\theta_1-\theta_2-\theta_3-\theta_5\right)\end{array}\right]\\+m_3\left[\begin{array}{l}-2l_2\cos\left(\theta_1+\theta_2\right)-\left(h_3+l_3\right)\cos\left(\theta_1+\theta_2+\theta_3\right)\\+\left(l_3-h_3\right)\cos\left(\theta_6-\theta_1-\theta_2-\theta_3-\theta_5\right)\end{array}\right]\\+m_4\left[\begin{array}{l}-l_2\cos\left(\theta_1+\theta_2\right)-l_3\cos\left(\theta_1+\theta_2+\theta_3\right)\\-h_4\cos\left(\theta_1+\theta_2+\theta_3+\theta_5\right)\end{array}\right]\end{array}}{2m_2+2m_3+m_4}\tag{1}$$

$$c_2=\frac{\partial x_{\mathrm{COM}}}{\partial\theta_2}=\frac{\begin{array}{l}m_2\left[\begin{array}{l}-\left(h_2+l_2\right)\cos\left(\theta_1+\theta_2\right)-l_3\cos\left(\theta_1+\theta_2+\theta_3\right)\\+l_3\cos\left(\theta_6-\theta_1-\theta_2-\theta_3-\theta_5\right)\\+\left(l_2-h_2\right)\cos\left(\theta_6+\theta_7-\theta_1-\theta_2-\theta_3-\theta_5\right)\end{array}\right]\\+m_3\left[\begin{array}{l}-2l_2\cos\left(\theta_1+\theta_2\right)-\left(h_3+l_3\right)\cos\left(\theta_1+\theta_2+\theta_3\right)\\+\left(l_3-h_3\right)\cos\left(\theta_6-\theta_1-\theta_2-\theta_3-\theta_5\right)\end{array}\right]\\+m_4\left[\begin{array}{l}-l_2\cos\left(\theta_1+\theta_2\right)-l_3\cos\left(\theta_1+\theta_2+\theta_3\right)\\-h_4\cos\left(\theta_1+\theta_2+\theta_3+\theta_5\right)\end{array}\right]\end{array}}{2m_2+2m_3+m_4}\tag{2}$$

$$c_3=\frac{\partial x_{\mathrm{COM}}}{\partial\theta_3}=\frac{\begin{array}{l}m_2\left[\begin{array}{l}l_3\cos\left(\theta_1+\theta_2+\theta_3\right)\\+l_3\cos\left(\theta_6-\theta_1-\theta_2-\theta_3-\theta_5\right)\\+\left(l_2-h_2\right)\cos\left(\theta_6+\theta_7-\theta_1-\theta_2-\theta_3-\theta_5\right)\end{array}\right]\\+m_3\left[\begin{array}{l}-\left(h_3+l_3\right)\cos\left(\theta_1+\theta_2+\theta_3\right)\\+\left(l_3-h_3\right)\cos\left(\theta_6-\theta_1-\theta_2-\theta_3-\theta_5\right)\end{array}\right]\\+m_4\left[\begin{array}{l}-l_3\cos\left(\theta_1+\theta_2+\theta_3\right)\\-h_4\cos\left(\theta_1+\theta_2+\theta_3+\theta_5\right)\end{array}\right]\end{array}}{2m_2+2m_3+m_4}\tag{3}$$

$$c_4=\frac{\partial x_{\mathrm{COM}}}{\partial\theta_4}=-\frac{l_4\cos\theta_4}{2}\tag{4}$$

$$c_5=\frac{\partial x_{\mathrm{COM}}}{\partial\theta_5}=\frac{\begin{array}{l}m_2\left[\begin{array}{l}l_3\cos\left(\theta_6-\theta_1-\theta_2-\theta_3-\theta_5\right)\\+\left(l_2-h_2\right)\cos\left(\theta_6+\theta_7-\theta_1-\theta_2-\theta_3-\theta_5\right)\end{array}\right]\\+m_3\left[\left(l_3-h_3\right)\cos\left(\theta_6-\theta_1-\theta_2-\theta_3-\theta_5\right)\right]\\+m_4\left[-h_4\cos\left(\theta_1+\theta_2+\theta_3+\theta_5\right)\right]\end{array}}{2m_2+2m_3+m_4}\tag{5}$$

$$m_2\begin{bmatrix} -l_3\cos\left(\theta_6-\theta_1-\theta_2-\theta_3-\theta_5\right) \\ -\left(l_2-h_2\right)\cos\left(\theta_6+\theta_7-\theta_1-\theta_2-\theta_3-\theta_5\right) \end{bmatrix}$$

$$c_6=\frac{\partial x_{\mathrm{COM}}}{\partial\theta_6}=\frac{+m_3\left[-\left(l_3-h_3\right)\cos\left(\theta_6-\theta_1-\theta_2-\theta_3-\theta_5\right)\right]}{2m_2+2m_3+m_4}$$

$$c_7=\frac{\partial x_{\mathrm{COM}}}{\partial\theta_7}=\frac{m_2\left[-\left(l_2-h_2\right)\cos\left(\theta_6+\theta_7-\theta_1-\theta_2-\theta_3-\theta_5\right)\right]}{2m_2+2m_3+m_4}$$

2.3 Step length (s)

The step length, defined as the distance between both heels at TD in the anteroposterior direction, can be calculated as,

$$\begin{aligned} s&=s\left(\theta_{1,2,3,\cdots,8}\right)\\ &=x_{\mathrm{r,hee}}-x_{\mathrm{l,hee}}\\ &=-l_1\cos\left(\theta_1+\alpha\right)+l_2\sin\left(\theta_1+\theta_2\right)+l_3\sin\left(\theta_1+\theta_2+\theta_3\right)+l_4\sin\theta_4\\ &\quad+l_3\sin\left(\theta_6-\theta_1-\theta_2-\theta_3-\theta_5\right)+l_2\sin\left(\theta_6+\theta_7-\theta_1-\theta_2-\theta_3-\theta_5\right)\\ &\quad+l_1\cos\left(\alpha-\theta_6-\theta_7-\theta_8+\theta_1+\theta_2+\theta_3+\theta_5\right) \end{aligned} \tag{S4}$$

The sensitivity of s to each joint angle:

$$\begin{aligned} e_1=\frac{\partial s}{\partial\theta_1}&=l_1\sin\left(\theta_1+\alpha\right)+l_2\cos\left(\theta_1+\theta_2\right)+l_3\cos\left(\theta_1+\theta_2+\theta_3\right)-l_3\cos\left(\theta_6-\theta_1-\theta_2-\theta_3-\theta_5\right)\\ &\quad-l_2\cos\left(\theta_6+\theta_7-\theta_1-\theta_2-\theta_3-\theta_5\right)-l_1\sin\left(\alpha-\theta_6-\theta_7-\theta_8+\theta_1+\theta_2+\theta_3+\theta_5\right) \end{aligned}$$

$$\begin{aligned} e_2=\frac{\partial s}{\partial\theta_2}&=l_2\cos\left(\theta_1+\theta_2\right)+l_3\cos\left(\theta_1+\theta_2+\theta_3\right)-l_3\cos\left(\theta_6-\theta_1-\theta_2-\theta_3-\theta_5\right)\\ &\quad-l_2\cos\left(\theta_6+\theta_7-\theta_1-\theta_2-\theta_3-\theta_5\right)-l_1\sin\left(\alpha-\theta_6-\theta_7-\theta_8+\theta_1+\theta_2+\theta_3+\theta_5\right) \end{aligned}$$

$$\begin{aligned} e_3=\frac{\partial s}{\partial\theta_3}&=l_3\cos\left(\theta_1+\theta_2+\theta_3\right)-l_3\cos\left(\theta_6-\theta_1-\theta_2-\theta_3-\theta_5\right)\\ &\quad-l_2\cos\left(\theta_6+\theta_7-\theta_1-\theta_2-\theta_3-\theta_5\right)-l_1\sin\left(\alpha-\theta_6-\theta_7-\theta_8+\theta_1+\theta_2+\theta_3+\theta_5\right) \end{aligned}$$

$$e_4=\frac{\partial s}{\partial\theta_4}=l_4\cos\theta_4$$

$$\begin{aligned} e_5=\frac{\partial s}{\partial\theta_5}&=-l_3\cos\left(\theta_6-\theta_1-\theta_2-\theta_3-\theta_5\right)\\ &\quad-l_2\cos\left(\theta_6+\theta_7-\theta_1-\theta_2-\theta_3-\theta_5\right)-l_1\sin\left(\alpha-\theta_6-\theta_7-\theta_8+\theta_1+\theta_2+\theta_3+\theta_5\right) \end{aligned}$$

$$e_6 = \frac{\partial s}{\partial \theta_6} = l_3 \cos\left(\theta_6 - \theta_1 - \theta_2 - \theta_3 - \theta_5\right) + l_2 \cos\left(\theta_6 + \theta_7 - \theta_1 - \theta_2 - \theta_3 - \theta_5\right) + l_1 \sin\left(\alpha - \theta_6 - \theta_7 - \theta_8 + \theta_1 + \theta_2 + \theta_3 + \theta_5\right)$$

$$e_7 = \frac{\partial s}{\partial \theta_7} = l_2 \cos\left(\theta_6 + \theta_7 - \theta_1 - \theta_2 - \theta_3 - \theta_5\right) + l_1 \sin\left(\alpha - \theta_6 - \theta_7 - \theta_8 + \theta_1 + \theta_2 + \theta_3 + \theta_5\right)$$

$$e_8 = \frac{\partial s}{\partial \theta_8} = l_1 \sin\left(\alpha - \theta_6 - \theta_7 - \theta_8 + \theta_1 + \theta_2 + \theta_3 + \theta_5\right)$$

The sensitivity quantifies the extent to which the COM position or step length changes in response to the increment in the joint angle by one unit (i.e. one degree). Generally, positive/negative sensitivity values mean the increment of the joint angle would increase/decrease the COM position or step length. A joint with larger sensitivity influences more the COM position or step length in comparison with one with smaller sensitivity.