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Segmental contributions to the center of mass movement in normal gait

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ABSTRACT

Saunders et al.(1953) provided a qualitative description of the contributions to the center-of-mass (CoM) movement. The objective of this work is to analytically quantify and study the kinematic contributions to the CoM movement in gait. A ten-degree-of-freedom anthropomorphic link segment model is used. The choice of segment angles as the generalized coordinates and a subsequent reformulation enabled the decoupling of the expression for CoM position as a summation of the kinematic contributions of individual segments. Using data from literature, the segmental contributions to the CoM displacement are then studied. Results show that the sagittal plane rotation of the shank and thigh of the stance leg are the major contributors to the CoM movement in the vertical and anterior-posterior directions. Additionally, forefoot rolling is seen to be a major contributor to the CoM vertical movement towards the end of the single support phase. In the medio-lateral direction, the frontal plane rotations of the pelvis and the stance leg are seen to be the major contributors. Results validate observations made by other researchers regarding the contributions of the degrees of freedom of the lower limbs to the CoM movement. The methodology can be extended to study asymmetric gait, such as the gait of a prosthesis user, where the properties and kinematics of the prosthetic limb are likely to differ from those of the unaffected side.

1. Introduction

The objective of human walking is the movement of the body's center-of-mass (CoM) from one location to another. The intricate neural and muscular coordination in the human body makes it challenging to understand the function of the numerous individual components in achieving a smooth trajectory of the CoM. In the case of asymmetric gait as in the case of a prosthesis user, the person cannot directly control the prosthetic limb but controls it through the residual limb segment. Therefore, therapy and training are used to ensure the person adapts the residual segments to the functional characteristics of the prosthesis. The ability to synthesize and analytically quantify the contribution of the individual components to the

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overall activity of human walking can provide valuable insights into the gait characteristics and aid in determining gait training strategies and in prosthesis design.[1]

Saunders et al. [1] used a compass gait model as a basis to explain the contributions of the six determinants of gait to vertical CoM movement in normal walking. Others [2–6] used direct measurements or simpler models to test the hypothesis of the six determinants of gait theory. Very few researchers [7,8] used analytical methods to quantify the contributions to CoM movement in gait. Hayot et al. [7] used a link-segment model with 16 segments to determine the CoM position. They chose six kinematic quantities to represent the six determinants of gait and used a 4-segment model connecting the center of pressure (CoP) to CoM to study the contributions of each of the chosen quantities. Their study of CoM trajectory was in comparison to compass gait to evaluate the six determinants of gait theory. The influence of segments other than the ones connecting the CoM to the CoP were not captured in their analysis. Lin et al. [8] studied the contributions of the DoFs to the CoM movement in all three directions. Their analysis required the direct measurement of the pelvis DoFs to determine the kinematics, and used partial derivatives of the position of CoM with respect to each DoF to study the contributions. They used a 10-segment 23 DoF model. However, their analysis did not capture the influence of segments other than the ones connecting the CoM to the CoP (as in Hayot et al. [7]).

In this work, a ten-DoF anthropomorphic link-segment model that includes DoFs corresponding to the determinants of gait is used to study the segmental contributions to the CoM trajectory in the single support (SS) phase. The classical equation for the position of center of mass is reformulated to obtain analytical expressions for the contributions of individual segment's angular DoFs to the CoM. The choice of segment angles as the generalized coordinates as opposed to the joint angles enabled the expression of the CoM position as a direct summation of contributions of individual segmental kinematics. Each term in the expression for the CoM position is a function of kinematics of one segment alone. Analytical expressions for the contributions of each segment's kinematics to the CoM movement are derived. The methodology described allows for the study of influence of all the segments to the CoM movement. Ankle-foot roll-over shape (AFROS) [9] is used to model the foot-ground interaction. Using kinematic data from literature [10], the contributions of individual segments and DoFs to the CoM displacement are studied.

2. Methods

2.1. Mathematical model

The anthropomorphic model consists of ten DoFs (Fig. 1). Assuming that the right leg is the stance leg and the left leg is the swing leg, the segments are: the foot, shank and thigh of the swing (left) leg, the foot-shank (modeled as a single segment) and thigh of the stance (right) leg and the pelvis connecting the right and left hips. The head, arms and trunk are modeled as a single segment connected rigidly to the mid-point of the pelvis. The segments of each leg are assumed to remain in the same plane and are connected by revolute joints at the ankle, knee and hip. Transverse plane rotation of the leg is assumed to be zero. The shank and ankle-foot complex of the stance leg is modeled using the AFROS. The AFROS takes into account the foot deformation and the ankle flexion during this period. Therefore, the ankle DoF is not included separately. Thus, the stance leg has three DoFs - sagittal plane rotations of the shank (θ_{skr}) and thigh (θ_{thr}), and the frontal plane rotation of the leg as a whole (θ_{legr}). The swing leg has four DoFs - sagittal plane rotations of the foot (θ_{ftl}), shank (θ_{skl}) and thigh (θ_{thl}), and the frontal plane rotation of the leg as a whole (θ_{legl}). The HAT has three DoFs - rotation of the pelvis in the frontal (θ_{pelx}), transverse (θ_{pely}) and sagittal (θ_{pelz}) planes. The angles in the frontal, transverse and sagittal planes are measured as the orientation of the body-fixed x, y or z-axis with respect to the ground-fixed X, Y and Z axes, respectively. X is along the anterior-posterior (A-P) direction, Y is along the vertical direction and Z is along the medial-lateral (M-L) direction.

2.2. Segmental contributions formulation

A methodology similar to the one described in [11] is used to obtain the segmental contributions. The position of the whole body center of mass (CoM) is given by

$$M\vec{P}_{com} = m_{skr}\vec{P}_{skr} + m_{thr}\vec{P}_{thr} + m_{hat}\vec{P}_{hat} + m_{skl}\vec{P}_{skl} + m_{thl}\vec{P}_{thl} + m_{ftl}\vec{P}_{ftl}, \tag{1}$$

where, m_i and P_i are the mass and CoM positions, respectively of segment i and M is the total mass. The subscripts *skr, thr, hat, thl, skl* and *ftl* indicate the right shank, right thigh, HAT, left thigh, left shank and left foot, respectively. Choosing segment orientations with respect to the ground fixed coordinate system as the generalized coordinates, the CoM positions of each of the segments are given by

$$\begin{aligned}
\vec{P}_{skr} &= \vec{P}_{ankr} + \mathbf{T}_{skr}\vec{r}_1,\\
\vec{P}_{thr} &= \vec{P}_{ankr} + \mathbf{T}_{skr}(\vec{r}_1 + \vec{r}_2) + \mathbf{T}_{thr}\vec{r}_3\\
\vec{P}_{hat} &= \vec{P}_{ankr} + \mathbf{T}_{skr}(\vec{r}_1 + \vec{r}_2) + \mathbf{T}_{thr}(\vec{r}_3 + \vec{r}_4) + \mathbf{T}_{pel}\vec{r}_5
\end{aligned}$$

[1] CoM Center of Mass, CoP Center of Pressure, DoFs Degrees of Freedom, SS Single Support, AFROS Ankle-Foot-Roll-Over-Shape, A-P Anterior Posterior, M-L Medial Lateral, HAT Head arms and trunk.

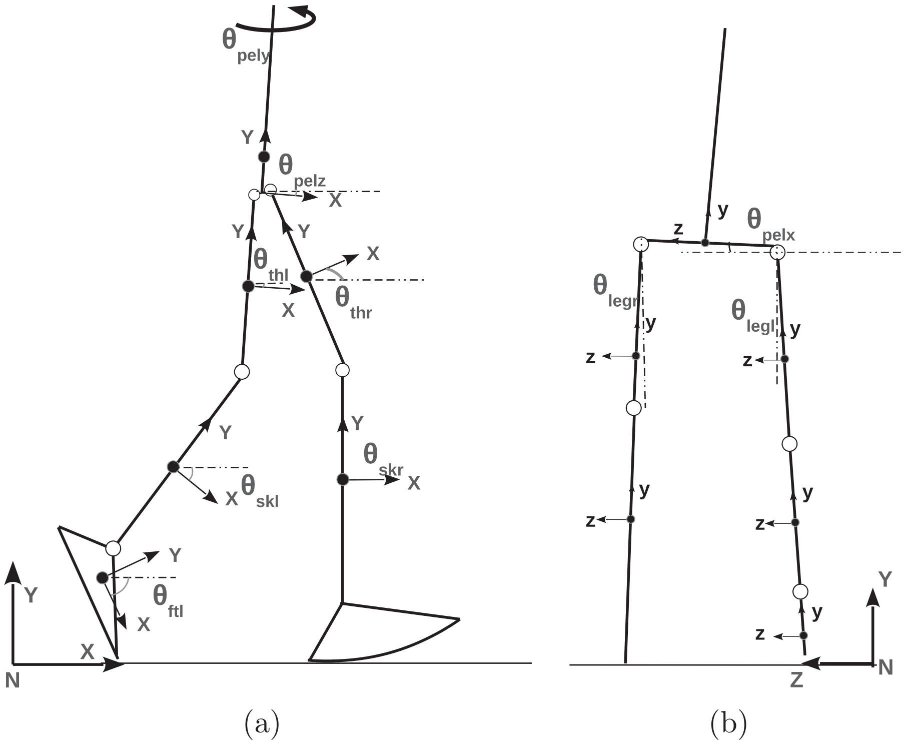


Fig. 1. Stick figure showing angles in the (a) sagittal plane and the (b) frontal plane.

$$
\begin{aligned}
\vec{P}_{thl} &= \vec{P}_{ankr} + \mathbf{T}_{skr}(\vec{r}_1+\vec{r}_2) + \mathbf{T}_{thr}(\vec{r}_3+\vec{r}_4) + \mathbf{T}_{pel}(\vec{r}_5+\vec{r}_6) + \mathbf{T}_{thl}\vec{r}_7\\
\vec{P}_{skl} &= \vec{P}_{ankr} + \mathbf{T}_{skr}(\vec{r}_1+\vec{r}_2) + \mathbf{T}_{thr}(\vec{r}_3+\vec{r}_4) + \mathbf{T}_{pel}(\vec{r}_5+\vec{r}_6) + \mathbf{T}_{thl}(\vec{r}_7+\vec{r}_8) + \mathbf{T}_{skl}\vec{r}_9\\
\vec{P}_{ftl} &= \vec{P}_{ankr} + \mathbf{T}_{skr}(\vec{r}_1+\vec{r}_2) + \mathbf{T}_{thr}(\vec{r}_3+\vec{r}_4) + \mathbf{T}_{pel}(\vec{r}_5+\vec{r}_6) + \mathbf{T}_{thl}(\vec{r}_7+\vec{r}_8)\\
&\quad + \mathbf{T}_{skl}(\vec{r}_9+\vec{r}_{10}) + \mathbf{T}_{ftl}\vec{r}_{11}.
\end{aligned} \tag{2}
$$

The definitions of the vectors $\vec{r}_1$ till $\vec{r}_{11}$ are given in the Appendix A. $\mathbf{T}_i$ is the transformation matrix relating the body-fixed coordinate system of the segment i to the ground fixed coordinate system. Each of these $\mathbf{T}_i$s are functions of angular orientations of the segment i. Using Eq. (2) in Eq. (1) and writing in matrix notation

$$
M\vec{P}_{com} = M\vec{P}_{ankr} + \begin{bmatrix}\mathbf{T}_{skr}\\ \mathbf{T}_{thr}\\ \mathbf{T}_{pel}\\ \mathbf{T}_{thl}\\ \mathbf{T}_{skl}\\ \mathbf{T}_{ftl}\end{bmatrix}' \begin{bmatrix}
\vec{r}_1 & \vec{r}_1+\vec{r}_2 & \vec{r}_1+\vec{r}_2 & \vec{r}_1+\vec{r}_2 & \vec{r}_1+\vec{r}_2 & \vec{r}_1+\vec{r}_2\\
\vec{0} & \vec{r}_3 & \vec{r}_3+\vec{r}_4 & \vec{r}_3+\vec{r}_4 & \vec{r}_3+\vec{r}_4 & \vec{r}_3+\vec{r}_4\\
\vec{0} & \vec{0} & \vec{r}_5 & \vec{r}_5+\vec{r}_6 & \vec{r}_5+\vec{r}_6 & \vec{r}_5+\vec{r}_6\\
\vec{0} & \vec{0} & \vec{0} & \vec{r}_7 & \vec{r}_7+\vec{r}_8 & \vec{r}_7+\vec{r}_8\\
\vec{0} & \vec{0} & \vec{0} & \vec{0} & \vec{r}_9 & \vec{r}_9+\vec{r}_{10}\\
\vec{0} & \vec{0} & \vec{0} & \vec{0} & \vec{0} & \vec{r}_{11}
\end{bmatrix} \begin{bmatrix} m_{skr}\\ m_{thr}\\ m_{hat}\\ m_{thl}\\ m_{skl}\\ m_{ftl}\end{bmatrix} \tag{3}
$$

or

$$
\vec{P}_{com} = \vec{P}_{ankr} + \begin{bmatrix}\mathbf{T}_{skr} & \mathbf{T}_{thr} & \mathbf{T}_{pel} & \mathbf{T}_{thl} & \mathbf{T}_{skl} & \mathbf{T}_{ftl}\end{bmatrix} \begin{bmatrix}\vec{k}_{skr}\\ \vec{k}_{thr}\\ \vec{k}_{pel}\\ \vec{k}_{thl}\\ \vec{k}_{skl}\\ \vec{k}_{ftl}\end{bmatrix}. \tag{4}
$$

where the $\vec{k}$s are constants and functions of segmental CoM distances and mass fractions. (The equations for k_is are shown in Appendix A). The position of the whole body CoM can now be written as

$$
\vec{P}_{com} = \vec{P}_{ankr} + \mathbf{T}_{skr}\vec{k}_{skr} + \mathbf{T}_{thr}\vec{k}_{thr} + \mathbf{T}_{pel}\vec{k}_{pel} + \mathbf{T}_{thl}\vec{k}_{thl} + \mathbf{T}_{skl}\vec{k}_{skl} + \mathbf{T}_{ftl}\vec{k}_{ftl} = \Sigma\vec{U}_i. \tag{5}
$$

In Eq. (1), each term $m_i\vec{P}_i$ are functions of angular positions of one or more segments. Whereas, in the form given by Eq. (5), each of the segmental contributions, $\mathbf{T}_i\vec{k}_i$, are functions of angular position of the segment i alone. For instance, the term $m_{thl}\vec{P}_{thl}$ in Eq. (1) is a function of θ_{skr}, θ_{thr}, θ_{legr}, θ_{pelx}, θ_{pely}, θ_{pelz}, θ_{thl} and θ_{legl}, while the term $\mathbf{T}_{thl}\vec{k}_{thl}$ in Eq. (5) is a function of only θ_{thl} and θ_{legl} - the sagittal plane and frontal plane rotations of the left thigh. The choice of segment angles as the generalized coordinates and the above reformulation decouples the expression for the CoM position into the contributions of individual segmental kinematics.

Although the formulation for the segmental contributions begins with the classical equation for the CoM of an n-link kinematic chain, the final form given by Eq. (5) is different in that each term $\mathbf{T}_i\vec{k}_i$ of Eq. (5) is a function of DoFs of one segment alone as opposed to $m_i\vec{P}_i$s in the classical equation where each term is a function of kinematics of one or more than one segmental angles. An example of a planar two-link kinematic chain is used (Appendix B) to explain the difference between the classical form of the equation for the center of mass and the reformulation described in this work.

The position of the ankle of the rolling foot $\vec{P}_{ankr}$ is given by

$$\vec{P}_{ankr} = R_{roll}\begin{bmatrix}\delta\theta_{skr}\\ 0\\ 0\end{bmatrix} + R_{roll}\hat{u} + \mathbf{T}_{skr}\vec{s}, \tag{6}$$

where, R_{roll} is the radius of the AFROS and $\delta\theta_{skr}$ is the change in the shank angle from heel contact, $\vec{s}$ is the vector from the center of the roll-over shape to the ankle, and $\hat{u} = (0, C_{legr}, S_{legr})'$. The notation used is $C_i = cos\cos(\theta_i)$ and $S_i = sin\sin(\theta_i)$. Both R_{roll} and $\vec{s}$ are obtained using Hansen's method [9] to determine the AFROS. Each $\mathbf{T}_i\vec{k}_i$ term in Eq. (5) is a function of the kinematics of the corresponding segment i. The segmental contributions to the position of the CoM are given by

$$\vec{U}_{roll} = \vec{P}_{ankr}, \tag{7}$$

$$\vec{U}_{skr} = k_{skrx}\begin{bmatrix}C_{skr}\\ C_{legr}S_{skr}\\ S_{legr}S_{skr}\end{bmatrix} + k_{skry}\begin{bmatrix}-S_{skr}\\ C_{legr}C_{skr}\\ S_{legr}C_{skr}\end{bmatrix}, \tag{8}$$

$$\vec{U}_{thr} = k_{thry}\begin{bmatrix}-S_{thr}\\ C_{legr}C_{thr}\\ S_{legr}C_{thr}\end{bmatrix}, \tag{9}$$

$$\vec{U}_{hat} = k_{pely}\begin{bmatrix}-C_{pely}S_{pelz}\\ C_{pelx}C_{pelz} - S_{pelx}S_{pely}S_{pelz}\\ S_{pelx}C_{pelz} + C_{pelx}S_{pely}S_{pelz}\end{bmatrix} + k_{pelz}\begin{bmatrix}S_{pely}\\ -S_{pelx}C_{pely}\\ C_{pelx}C_{pely}\end{bmatrix}, \tag{10}$$

$$\vec{U}_{thl} = k_{thly}\begin{bmatrix}-S_{thl}\\ C_{legl}C_{thl}\\ S_{legl}C_{thl}\end{bmatrix}, \tag{11}$$

$$\vec{U}_{skl} = k_{skly}\begin{bmatrix}-S_{skl}\\ C_{legl}C_{skl}\\ S_{legl}C_{skl}\end{bmatrix} \text{and} \tag{12}$$

$$\vec{U}_{ftl} = k_{ftlx}\begin{bmatrix}C_{ftl}\\ C_{legl}S_{ftl}\\ C_{legl}S_{ftl}\end{bmatrix} + k_{ftly}\begin{bmatrix}-S_{ftl}\\ C_{legl}C_{ftl}\\ S_{legl}C_{ftl}\end{bmatrix}. \tag{13}$$

Coefficients k_{ix}, k_{iy} and k_{iz} indicate the respective X, Y and Z components of the corresponding $\vec{k}_i$. The ks have units of length. It can be seen that each of the expressions shown above is a function of DoFs of one segment only. For instance, $\vec{U}_{skl}$ in Eq. (12) is a function of sagittal plane rotation of the left shank θ_{skl} and the frontal plane rotation of the left shank θ_{legl}. (Note that in this model, the frontal plane rotation, θ_{legl}, is assumed to be the same for the three segments - foot, shank and thigh of each leg and hence θ_{legl} appears in Eqs. (11)–(13). Similarly, θ_{pelx}, θ_{pely} and θ_{pelz} - the DoFs of the pelvis appear only in $\vec{U}_{hat}$. Since $\vec{U}_i$ is the isolated contribution of the angular orientations of the segment i to the position of the CoM, the change in $\vec{U}_i$ represents the contribution of the angular displacements of the segment to the displacement of the CoM during gait. Data for segment masses, segment length estimates and kinematic data for normal gait are used in Eqs. (7)–(13) to determine the segmental contributions to the CoM movement.

3. Results and discussion

Using segment mass and length estimates from [12], the values of $\vec{k}$s in m are

$$\begin{aligned}
&\vec{k}_{skr} = (0.0006, 0.43, 0)', && \vec{k}_{thr} = (0, 0.37, 0)',\\
&\vec{k}_{pel} = (0, 0.196, -0.083)', && \vec{k}_{thl} = (0, -0.0486, 0)',\\
&\vec{k}_{skl} = (0, -0.0144, 0)' \text{ and } && \vec{k}_{ftl} = (0.0006, -0.0004, 0)'.
\end{aligned} \tag{14}$$

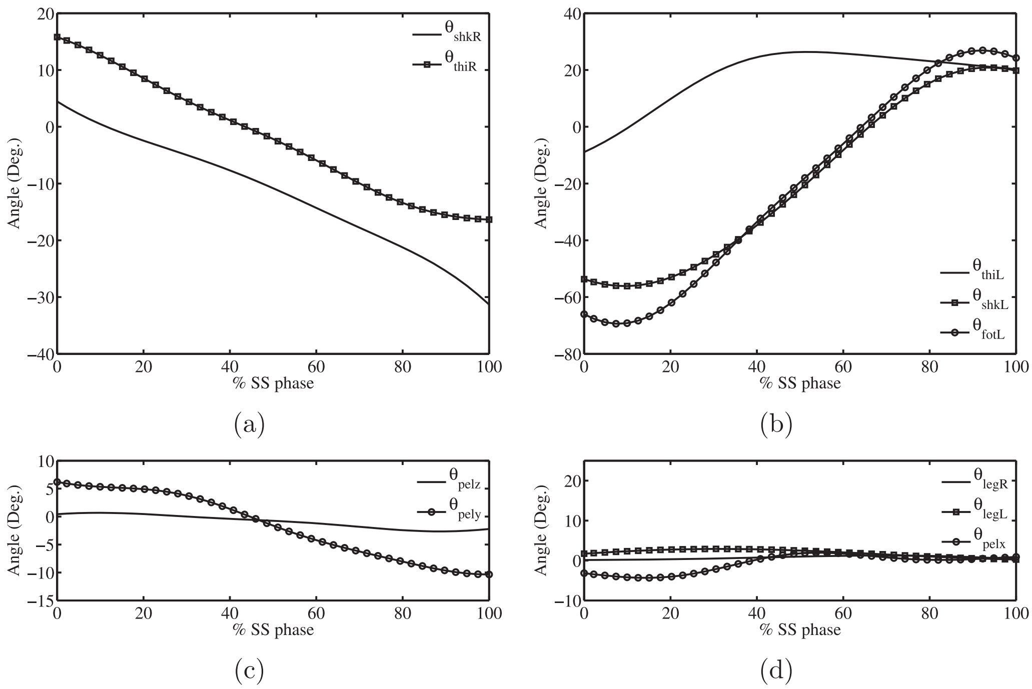


Fig. 2. Segmental kinematics adapted from [10]. (a) Sagittal plane rotation of the shank (θ_{skr}) and thigh (θ_{thr}) of the stance (right) leg, (b) sagittal plane rotation of the thigh (θ_{thl}), shank (θ_{skl}) and foot (θ_{ftl}) of the swing (left) leg, (c) rotation of the pelvis in the transverse plane (θ_{pely}) and sagittal plane (θ_{pelz}) and (d) frontal plane rotation of the right leg (θ_{legr}), left leg (θ_{legl}) and the pelvis (θ_{pelx}).

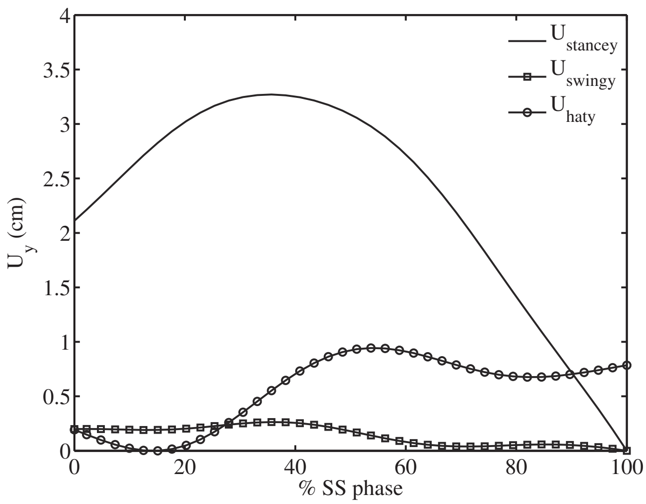
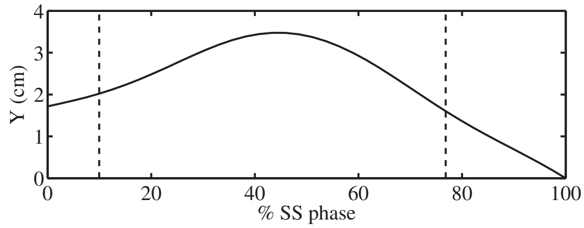


Fig. 3. Contributions of segments of the stance leg, segments of the swing leg and HAT to the vertical CoM position. All contributions are scaled such that the lowest value is zero.

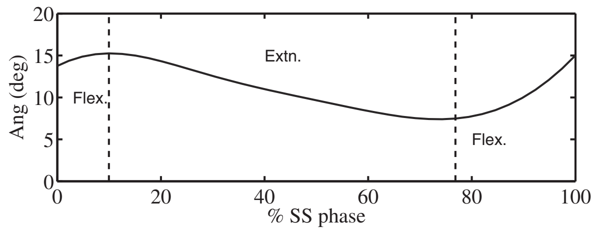
The sagittal plane kinematic data from [10] are used and the unknown kinematics are derived [11]. The CoP data and the shank angle data from heel contact to opposite heel contact are used to compute $R_{roll} = 0.42m$ and the vector $\vec{s} = [0.01; -0.32; 0]m$ of the AFROS. The kinematic data (Fig. 2) follow known trends for normal human walking [13]. Using these kinematics in Eqs. (7)–(13), the segmental contributions are obtained.

3.1. Contributions to the vertical CoM movement

The contributions of the segments of the swing leg ($U_{swingy} = U_{ftly} + U_{skly} + U_{thly}$) and that of the stance leg ($U_{stancey} = U_{rolly} + U_{skry} + U_{thry}$) and the HAT ($U_{haty}$) to the CoM movement in the vertical direction are shown in Fig (3). The segments of the swing leg contribute the least, the HAT DoFs (rotations of the pelvis in the three planes) contributes towards a



(a) Vertical CoM position.



(b) Stance knee angle. 'Flex.' indicates period of flexion and 'Extn.' indicates period of extension.

Fig. 4. Phase difference between the peak vertical CoM position the stance knee flexion.

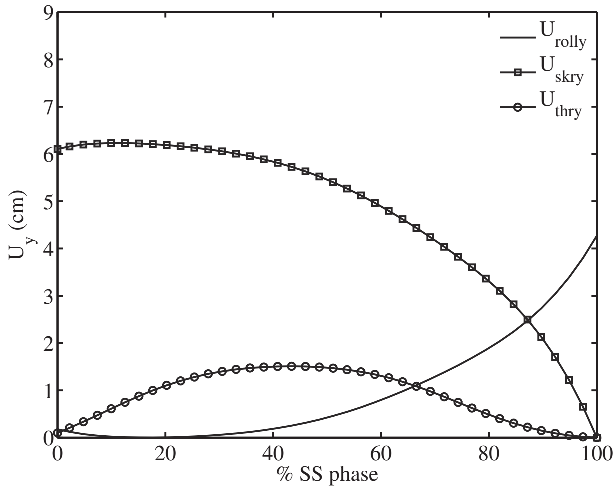


Fig. 5. Contributions of each of the segments of the stance leg, i.e., - the rolling foot, shank and thigh to the vertical CoM position. All contributions are scaled such that the lowest value is zero.

maximum positive displacement of about 1 cm around mid-stance and the segments of the stance leg contribute the highest to the CoM vertical displacement.

Gard and Childress [3] found that the knee flexion in stance phase (the third determinant of gait proposed by Saunders et al. [1]) occurs before the peak in the vertical CoM position and hence does not contribute to the decrease in the peak vertical CoM displacement. The knee angle data and CoM vertical position (Fig. 4) reported in this work also shows the phase shift of the stance phase knee flexion and peak vertical CoM position. The results for the contributions of the segments of the stance leg (Fig. 5) also show that, among the segments of the stance leg, the thigh segment solely contributes to the rise of the vertical CoM position from 0% –43% of the SS phase. During the rest of the SS phase, the shank and thigh segments contribute to a fall of the CoM vertical position while the forefoot rolling has an opposing effect and causes a rise in the CoM position. Others have seen this in terms of heel rise [6,14] and foot rolling [4] in their studies.

In order to study the contributions of each DoF of the HAT, one DoF at a time is set equal to zero in the equation for the HAT contribution (Eq. (10)) (Method similar to the one used by Della Croce et al. [6]). Setting θ_{pely} (pelvis rotation in the transverse plane) and θ_{pelz} (pelvis rotation in the sagittal plane) to zero has negligible effect on the vertical position of the

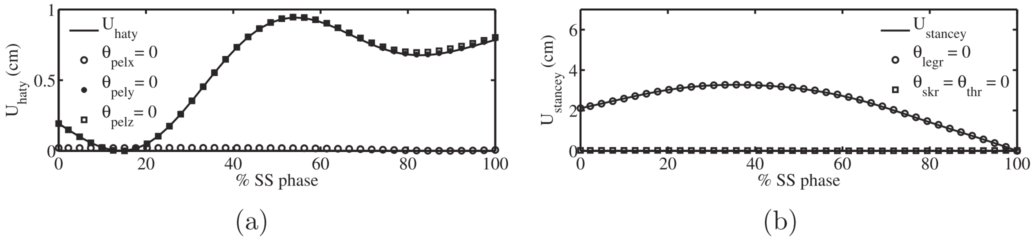


Fig. 6. Segmental contribution of the (a) HAT segment to the vertical CoM movement when each of the three DoFs are set equal to zero and that of the (b) segments of the stance leg to the vertical CoM movement when each of the DoFs are set equal to zero. All contributions are scaled such that the lowest value is equal to zero.

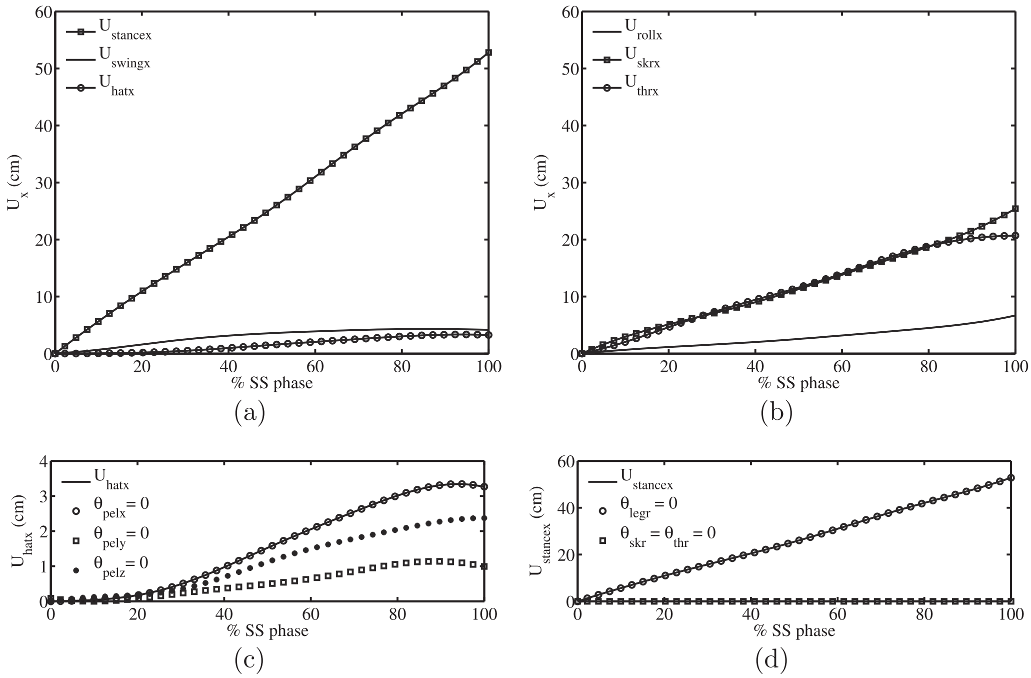


Fig. 7. Segmental contributions to the CoM movement in the A-P direction in the SS phase. (a) Contributions of segments of the stance leg, segments of the swing leg and HAT. (b) Contributions of each of the segments of the stance leg - (the rolling foot, shank and thigh) to the CoM movement. (c) Contribution of the HAT segment when each of the three DoFs are set equal to zero. (d) Contribution of segments of the stance leg when each of the DoFs are set equal to zero. All contributions are scaled such that the lowest value is equal to zero.

CoM (Fig. 6(a)). Experimental studies by Kerrigan et al. [5] also showed that first determinant of gait - the transverse plane rotation of the pelvis (θ_{pely}) has negligible influence on the vertical CoM position. On the other hand, setting θ_{pelx} (rotation of the pelvis in the frontal plane) to zero nullifies the contribution of the HAT to the CoM vertical position. This implies that the contribution of the HAT segment to the overall CoM vertical movement is due to the frontal plane rotation. This result also shows (as was seen in the experimental studies by Gard and Childress [2]) that the frontal plane rotation of the pelvis contributes to a rise (albeit by a small amount) and not fall of the peak CoM vertical position.

In the case of contributions of the DoFs of the stance leg (Fig. 6(b)), setting θ_{legr} equal to zero showed negligible change in $U_{stancey}$ implying that the frontal plane rotation of the leg has no influence on the vertical CoM trajectory. On the other hand, setting θ_{skr} and θ_{thr} to zero nullifies the contribution of the segments of the stance leg implying that the sagittal plane rotations of the stance shank and thigh and the rolling foot are the major determinants of the vertical CoM displacement.

3.2. Contributions to the CoM movement in the A-P direction

The kinematics of the stance leg contribute the most to the CoM position and displacement in the A-P direction (Fig. 7(a)). Among the segments of the stance leg, the shank and thigh segments show the highest contribution (Fig. 7(b)) in the A-P direction. For the data used, the shank and thigh kinematics cause a continuous forward progression of up to 20 cm and 25 cm, respectively, in the SS phase (Fig. 7(b)). The rolling foot causes a maximum positive A-P displacement of up to 6 cm in the SS phase. As expected, the DoFs in the frontal plane, θ_{pelx} and θ_{legr}(frontal plane rotation of the pelvis and

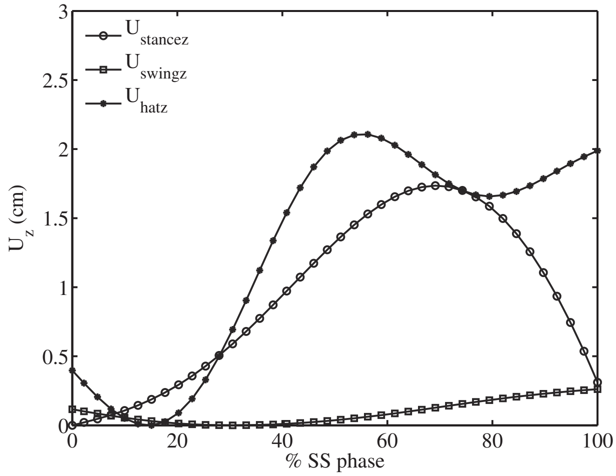


Fig. 8. Contributions of segments of the stance leg, segments of the swing leg and HAT to the CoM movement in the M-L direction. All contributions are scaled such that the lowest value is zero.

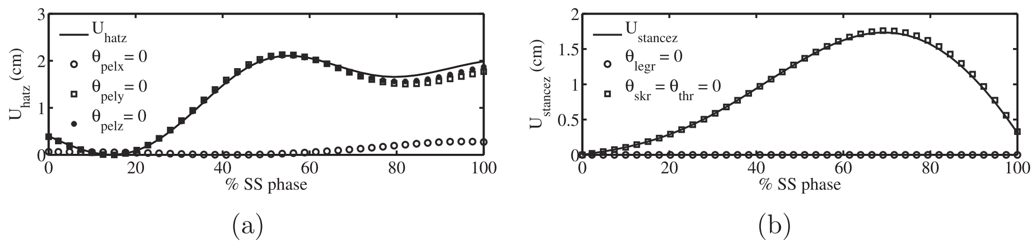


Fig. 9. (a) Contribution of the HAT segment to the CoM movement in the M-L direction when each of the three DoFs are set equal to zero. (b) Contribution of segments of the stance leg to the CoM movement in the M-L direction when each of the DoFs are set equal to zero. All contributions are scaled such that the lowest value is equal to zero.

stance leg respectively) do not contribute to the CoM displacement in the A-P direction (Fig. 7(c) and 7(d)). The contribution of the HAT and stance leg to the CoM position in the A-P direction, U_{hatx} and $U_{stancex}$, shows negligible change when θ_{pelx} and θ_{legr}, respectively are set equal to zero.

3.3. Contributions to the CoM movement in the M-L direction

The HAT and the stance leg contribute the most towards the trajectory of the CoM in the M-L direction (Fig. 8). The HAT causes a maximum displacement of around 2 cm and the stance leg causes a positive M-L displacement of around 1.7 cm up until 70% of SS phase. Towards the end of the SS phase, the stance leg moves rapidly in the opposite direction (negative displacement) until heel contact. Among the DoFs of the stance leg and the HAT, the DoFs in the frontal plane θ_{pelx} and θ_{legr} are the dominant contributor to the CoM position in the M-L direction. Setting θ_{pelx} and θ_{legr} to zero nullifies the contribution of the HAT and the stance leg to CoM position in the M-L direction (Fig. 9(a) and 9(b)). On the other hand, setting the rest of the DoFs (θ_{pely}, θ_{pelz}, θ_{skr} and θ_{thr}) to zero has a negligible effect on the corresponding segmental contributions implying that these DoFs have minimal effect on the CoM movement in the M-L direction.

Overall, for the kinematic data used, it is seen that the sagittal plane rotations of the stance shank, stance thigh and the forefoot rolling contributes to the CoM movement in the vertical and in A-P directions and the frontal plane rotations of the pelvis and the stance leg contributes to the CoM movement in the M-L direction. The methodology described in this work can be extended to study of contributions of all the DoFs of a more complex models to the CoM movement. The choice of segment angles as the generalized coordinates enabled the formulation (Eq. (1)) where the CoM position is expressed as the summation of contributions of individual segmental DoFs. Using segmental orientations as opposed to joint angles allows the decoupling of the CoM position into contributions of individual segmental kinematics.

Earlier studies [7,8] quantified the contributions of joint angles to the CoM movement. To study individual joint DoF contributions, Hayot et al. [7] introduced one DoF at a time into a model for compass gait. Lin et al. [8] on the other hand, used partial derivatives to study the contributions individually. The contributions were studied with reference to the six determinants of gait theory. Their expressions for the CoM position are functions of DoFs of only the kinematic chain that connects the CoM and CoP, i.e., the stance leg. This work presents a more general form for studying the contributions to the

CoM position, which is expressed as a summation of terms, $\vec{U}_i$s. Each $\vec{U}_i$ is a function of a particular segment's DoFs and the contributions of all the segments of the model can be studied individually or in combination.

A limitation of this work is the use of one data set to study the segmental contributions. Although the data used follow known trends for normal human walking [13] and the results, in general, agree with the findings in other experimental studies [2–5,7,8,14], more sets of kinematic data are needed to ascertained the findings in this work. Another limitation of this work is that the inter-segmental dependence cannot be studied using this method as the segment angles and not the joint angles are chosen as the generalized coordinates. Following a similar methodology and using joint angles as the generalized coordinates could provide insight into inter-segmental dependence.

An important finding of the segmental analysis of the CoM movement is the contribution of forefoot rolling to the CoM vertical displacement towards the end of the SS phase. Clinical studies have shown that insufficient forefoot rolling causes asymmetries in the gait of persons with partial-foot amputations [15,16], users of trans-tibial prostheses [17], persons with diabetic neuropathy [18,19] and in children with cerebral palsy [20]. Hutchins et al. [21], in their review of literature, found that rocker profiles can be altered to influence muscle activity patterns in the lower limbs. Chen et al. [22] found that addition of elastic material in the forefoot region not only reduced the activation of gastrocnemius muscles but also provided propulsive forces in running. Kerrigan et al. [14] and Gard and Childress [4] also studied the effect of heel rise and foot rolling respectively on the CoM movement. While they used simplified models to quantify the contribution of the rolling foot, in this work, the analytical expression that quantifies the effect of forefoot rolling (Eq. (7)) is derived systematically using an anthropomorphic model. This analytical expression could potentially be used by clinicians to determine the roll-over radius (R_{roll} in Eq. (7)) and the foot alignment (which determines the position of the center of the AFROS i.e, $\vec{s}$ in Eq. (7)) required for a prosthetic foot to ensure improved gait characteristics of a prosthesis user.

The methodology described in this work can be used with a complex multi-DoF model to systematically isolate and quantify the contributions of any DoF in the model. The form of equation could be used to quantify gait deviations and the compensatory adaptations in the kinematics in the case of asymmetric gait where the segmental properties of one limb differ significantly from the other.

4. Conclusions

The formulation of the segmental contributions to the CoM position enables the study of effects of individual segmental DoFs on the CoM trajectory without a priori assumption of their significance. Although further validation with more sets of kinematic data is required, the general conclusions of this work agree with the conclusions of other studies in literature. This work can be applied to study asymmetric gait where a person develops strategies to compensate for impairments. The methodology can be used to isolate the DoFs responsible for the changed CoM trajectory, and can likely form a basis for clinical therapy. Future work includes extending the methodology to double support and applications to asymmetric gait.

Appendix A

The vectors $\vec{r}_1$ till $\vec{r}_{11}$ are defined as

$\vec{r}_1$	right ankle to the CoM of the right shank,
$\vec{r}_2$	CoM of the right shank to the right knee,
$\vec{r}_3$	right knee to the CoM of the right thigh,
$\vec{r}_4$	CoM of the right thigh to the right hip,
$\vec{r}_5$	right hip to the CoM of the HAT segment,
$\vec{r}_6$	CoM of the HAT to the left hip,
$\vec{r}_7$	left hip to the CoM of the left thigh,
$\vec{r}_8$	CoM of the left thigh to the left knee,
$\vec{r}_9$	left knee to the CoM of the left shank,
$\vec{r}_{10}$	CoM of the left shank to the left ankle, and
$\vec{r}_{11}$	left ankle to the CoM of the left foot.

All the vectors are expressed in their respective local coordinate systems.
The vectors $\vec{k}_1$ till $\vec{k}_6$ are given by

$$\begin{aligned}
\vec{k}_1 &= M_{skr}\vec{r}_1 + (M_{thr} + M_{hat} + M_{thl} + M_{skl} + M_{ftl})(\vec{r}_1 + \vec{r}_2),\\
\vec{k}_2 &= M_{thr}\vec{r}_3 + (M_{hat} + M_{thl} + M_{skl} + M_{ftl})(\vec{r}_3 + \vec{r}_4),\\
\vec{k}_3 &= M_{hat}\vec{r}_5 + (M_{thl} + M_{skl} + M_{ftl})(\vec{r}_5 + \vec{r}_6),\\
\vec{k}_4 &= M_{thl}\vec{r}_7 + (M_{skl} + M_{ftl})(\vec{r}_7 + \vec{r}_8),\\
\vec{k}_5 &= M_{skl}\vec{r}_9 + (M_{ftl})(\vec{r}_9 + \vec{r}_{10}),\\
\vec{k}_6 &= M_{ftl}\vec{r}_{11},
\end{aligned} \tag{A.1}$$

where M_i is the mass fraction of the segment i.

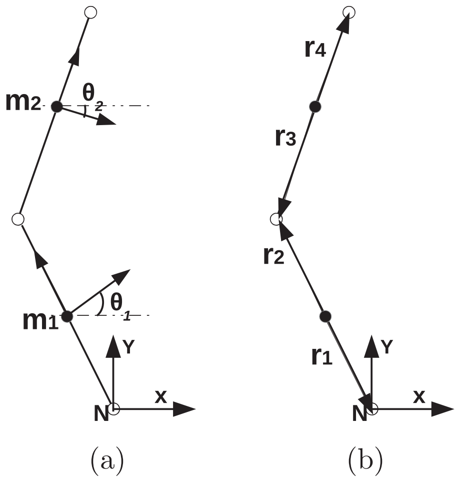


Fig. B1. A two-link kinematic chain. (a) shows the body fixed coordinate systems and (segment angles) angles made by the links with respect to the ground and (b) shows the position vectors in local coordinate systems.

Appendix B

The difference between the classical equation for center of mass of a planar two-link kinematic chain (Fig. B.10) and the equation for center of mass obtained using the formulation for segmental contributions shown in this work is described below.

The classical equation is

$$M\vec{P}_{com} = m_1\vec{P}_1 + m_2\vec{P}_2, \tag{B.1}$$

where, m_1 and m_2 are the masses of link 1 and 2, respectively, $M = m_1 + m_2$, $\vec{P}_1$ and $\vec{P}_2$ are the position vectors of centers of mass of link 1 and 2, respectively and $\vec{P}_{com}$ is the position of center of mass of the planar two-link kinematic chain. The equation can be rewritten as

$$\vec{P}_{com} = M_1\vec{P}_1 + M_2\vec{P}_2. \tag{B.2}$$

where, $M_1 = m_1/M$ and $M_2 = m_2/M$. Each of the terms in the above equation can be expanded as

$$\begin{aligned} M_1\vec{P}_1 &= M_1 r_1 \begin{bmatrix} -sin\theta_1 \\ cos\theta_1 \end{bmatrix} \text{and} \\ M_2\vec{P}_2 &= M_2(r_1 + r_2)\begin{bmatrix} -sin\theta_1 \\ cos\theta_1 \end{bmatrix} + M_2 r_3 \begin{bmatrix} -sin\theta_2 \\ cos\theta_2 \end{bmatrix} \end{aligned} \tag{B.3}$$

where, r_1, r_2 and r_3 are magnitudes of vectors $\vec{r}_1$, $\vec{r}_2$ and $\vec{r}_3$ respectively shown in Fig. B.10. Note that these vectors are expressed in the body's local coordinate systems and r_1, r_2 and r_3 are constant lengths. Using the formulation for segmental contributions described in this work, the final form of equation for the position of the center of mass is

$$\vec{P}_{com} = \mathbf{T}_1\vec{k}_1 + \mathbf{T}_2\vec{k}_2 \tag{B.4}$$

where,

$$\begin{aligned} \vec{k}_1 &= M_1(-\vec{r}_1) + M_2(-\vec{r}_1 + \vec{r}_2) \text{ and} \\ \vec{k}_2 &= M_2(-\vec{r}_3). \end{aligned} \tag{B.5}$$

Each of the terms of Eq. (B.4) are given by

$$\begin{aligned} \mathbf{T}_1\vec{k}_1 &= M_1 r_1 \begin{bmatrix} -sin\theta_1 \\ cos\theta_1 \end{bmatrix} + M_2(r_1 + r_2)\begin{bmatrix} -sin\theta_1 \\ cos\theta_1 \end{bmatrix} \text{and} \\ \mathbf{T}_2\vec{k}_2 &= M_2 r_3 \begin{bmatrix} -sin\theta_2 \\ cos\theta_2 \end{bmatrix}. \end{aligned} \tag{B.6}$$

Eqs. (B.3) and (B.6) clearly show the difference between the classical equation and the formulation shown in this work. Each of the terms of the classical equation are functions of one or more segment angles: $M_1\vec{P}_1$ is a function of θ_1 and $M_2\vec{P}_2$ is a function of θ_1 and θ_2. In the case of the formulation shown in this work, each term is a function of one angle only. $\mathbf{T}_1\vec{k}_1$ is a function of θ_1 (DoF of link-1) and $\mathbf{T}_2\vec{k}_2$ is a function of θ_2 (DoF of link-2).

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