Individual contributions of the lower limb muscles to the position of the centre of pressure during gait

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1. Introduction

To better understand the mechanisms underlying the dynamics of gait, it is important to investigate how individual muscles contribute to the ground reaction force and to the acceleration of the centre of mass (i.e. progression, balance, and support). This was analysed in numerous studies using forward dynamics and perturbation analysis (e.g. Arnold et al. 2007; Allen and Neptune 2012; Correa and Pandy 2013). Only one study (Moissenet et al. 2017) investigated how individual muscles contribute to ground reaction force and moment using inverse dynamics (Moissenet et al. 2014) and pseudo-inverse (Lin et al. 2011) methods. Still, only the contributions to the vertical component of the ground reaction force were compared to the ones reported in the literature (Pandy and Andriacchi 2010; Lin et al. 2011) and demonstrated good agreements.

Once the musculo-tendon forces were computed, a pseudo-inverse method (Moissenet et al. in press; Lin et al. 2011) was used to compute the contributions of each musculo-tendon force to ground reaction force and moment at the CoP, \( \mathbf{F}_0 \) and \( \mathbf{M}_0 \). The contributions of each segment weight \( \mathbf{m}^{\text{seg}}_0 \) was estimated in the same way. In a previous study (Moissenet et al. in press), these contributions to the ground reaction force were compared to the ones reported in the literature (Pandy and Andriacchi 2010; Lin et al. 2011) and demonstrated good agreements.

In the present study, we further analysed the contributions of each musculo-tendon force (and segment weight) to the position of the CoP. The position of this “induced” CoP was the matrix of generalised muscular lever arms and \( \mathbf{f} \) was the vector of musculo-tendon forces.

\[
\min \ J = \frac{1}{2} \begin{bmatrix} \mathbf{f} \\ \lambda_i \end{bmatrix} \mathbf{W} \begin{bmatrix} \mathbf{f} \\ \lambda_i \end{bmatrix} \text{ subject to :}
\]

\[
\mathbf{Z}_k^T \begin{bmatrix} \mathbf{L} & -\mathbf{K}_i^T \end{bmatrix} \begin{bmatrix} \mathbf{f} \\ \lambda_i \end{bmatrix} = \mathbf{Z}_k^T (\mathbf{G} \ddot{\mathbf{Q}} - \mathbf{P} - \mathbf{R})
\]

where \( J \) was the objective function, \( \mathbf{W} \) a diagonal matrix composed of the optimisation weights associated to the unknowns \( \begin{bmatrix} \mathbf{f} & \lambda_i \end{bmatrix} \) and \( \mathbf{Z}_k^T \) the orthogonal basis of the null space of the Jacobian sub-matrix \( \mathbf{K}_i^T \). As an inverse dynamics procedure, no foot-floor contact model is required.

2. Methods

A previously described (Moissenet et al. 2014, 2016) 3D lower limb musculoskeletal model consisting of five segments (i.e. pelvis, thigh, patella, shank and foot) and 5 joint degrees of freedom was used to perform this study and leaded to the dynamics equation: \( \mathbf{G} \ddot{\mathbf{Q}} + \mathbf{K} \lambda = \mathbf{R} + \mathbf{P} + \mathbf{L} \), where \( \mathbf{G} \) was the matrix of generalised accelerations, \( \mathbf{K} \) was the Jacobian matrix of both kinematic and rigid body constraints, \( \lambda \) was the vector of Lagrange multipliers, \( \mathbf{R} \) was the vector of generalised ground reaction (i.e. including the vectors of force \( \mathbf{F}_0 \) and moment \( \mathbf{M}_0 \) at the CoP), \( \mathbf{P} \) was the vector of generalised weights, \( \mathbf{L} \) was the vector of generalised muscular lever arms and \( \mathbf{f} \) was the vector of musculo-tendon forces.
were expressed. In the present moment (the position of the CoP and the ground reaction force and where (Sardain and Bessonnet 2004):

\[
\begin{bmatrix}
\chi_0 \\
x_0 \\
y_0 \\
z_0
\end{bmatrix} = \begin{bmatrix}
F_0'^{\mu} \times M_0'^{\mu} - (F_0'^{\mu} \cdot M_0^{\mu})F_0^{\mu} \times Y_0 \\
(F_0'^{\mu} \cdot Y_0)(F_0'^{\mu})^2 + F_0^{\mu} \times Z_0
\end{bmatrix}
\]

where \((x_0', y_0')\) was the position of the measured CoP and \((X_0, Y_0, Z_0)\) were the axes of the inertial coordinate system (ICS, with \(Y_0\) vertical) in which the generalised coordinates \(Q\), the position of the CoP and the ground reaction force and moment \((F_0, M_0)\) were expressed. In the present study, the individual muscle contributions were pooled in hip flexors, extensors, adductors, and abductors, knee flexors and extensors, and ankle plantarflexors and dorsiflexors.

This methods was applied to one gait cycle taken from our previous study (Moissenet et al. in press), i.e. on a male subject of 30 year old, 65 kg, 165 cm walking at preferred speed over level ground. The origin of the ICS was defined at the corner of the force plate.

3. Results and discussion

The contributions of a selection of musculo-tendon force and segment weight to the position of the CoP are depicted in Figure 1. The contributions of the weights of all segments and of the hip adductors tended to be inward with respect to the CoP trajectory, shifted and compressed posteriorly, and diverging medially at the end of the stance. The hip flexors and extensors demonstrated the more spread contributions, going both inward and outward during the stance. The contributions of the hip adductors, knee flexors and extensors were more generally aligned with the CoP trajectory, compressed posteriorly but shifted laterally, except for the hip abductors which had a short forward contribution almost superimposed with the CoP at the very end of the stance. The contributions of the ankle plantarflexors and dorsiflexors were the more aligned with CoP trajectory and were shifted anteriorly.

This description seems in line with the previous studies (e.g. Pandy and Andriacchi 2010) describing the individual muscle contributions to support (e.g. hip flexors and extensors), balance (e.g. hip adductors) and progression (e.g. ankle plantarflexors). It was interesting to observe that the contributions were distributed on both medial and lateral sides of the CoP trajectory. Moreover, most of the contributions were shifted and compressed posteriorly with respect to the CoP trajectory. It is the muscles spanning the ankle joint that mainly contribute to the anterior displacement of the CoP at the end of the stance.

This study has some limitations (i.e. musculoskeletal model of the right lower limb only, one subject, one motor task) and a more detailed analysis of the individual muscles and of the timing of their contributions is needed.

4. Conclusions

The individual muscle contributions to the position of the centre of pressure provide useful insights into the dynamics of human walking. The contributions were largely spread, mostly shifted and compressed posteriorly with respect to the CoP trajectory except for the plantarflexors.

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