Individual muscle contributions to the position of the centre of pressure

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Introduction

To better understand the mechanisms underlying 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 and support).

This was analysed in numerous studies using forward dynamics and perturbation analysis (e.g. Pandy and Andriacchi, 2010). Only one study (Moissenet et al., in press) investigated how individual muscles contribute to both ground reaction force and moment. Still, only the contributions to the vertical component of the ground reaction moment were analysed. The objective of the present study, knowing all the components of the ground reaction force and moment, is to investigate the individual muscle contributions to the position of the CoP.

Material and methods

One gait cycle taken from a previous study (Moissenet et al., in press) was used in this study (*i.e.* a male subject of 30 year old, 65 kg, 165 cm walking at preferred speed over level ground).

A previously described (Moissenet et al., 2014; Moissenet et al., in press) 3D lower limb musculoskeletal model consisting of 5 segments (i.e. pelvis, thigh, patella, shank and foot) and 5 joint degrees of freedom was used to perform this study (Fig. 1a). The dynamics equation has been written to introduce the musculo-tendon forces and Lagrange multipliers corresponding to the kinematic and rigid body constraints:

$$\mathbf{G}\ddot{\mathbf{Q}} + \mathbf{K}^{T}\boldsymbol{\lambda} = \mathbf{R} + \mathbf{P} + \mathbf{L}\mathbf{f}$$

where $\mathbf{G}$ was the matrix of generalised masses, $\ddot{\mathbf{Q}}$ was the vector of generalised accelerations, $\mathbf{K}^{T}$ was the Jacobian matrix of both kinematic and rigid body constraints, $\boldsymbol{\lambda}$ was the vector of Lagrange multipliers, $\mathbf{R}$ was the vector of generalised ground reaction (i.e. including the force $\mathbf{F}_0$ and moment at the CoP $\mathbf{M}_0$ vectors), $\mathbf{P}$ was the vector of generalised weights, $\mathbf{L}$ was the matrix of generalised muscular lever arms and $\mathbf{f}$ was the vector of musculo-tendon forces. The musculo-tendon forces and a selection of joint contact, ligament and bone forces were introduced in a one-step optimisation procedure in order to solve the muscular redundancy problem:

$$\min_{\begin{bmatrix}\mathbf{f}\\ \boldsymbol{\lambda}_1\end{bmatrix}} J = \frac{1}{2}\begin{bmatrix}\mathbf{f}\\ \boldsymbol{\lambda}_1\end{bmatrix}^{T}\mathbf{W}\begin{bmatrix}\mathbf{f}\\ \boldsymbol{\lambda}_1\end{bmatrix} \text{ subject to : } \begin{cases}\mathbf{Z}_{\mathbf{K}_2}{}^{T}\begin{bmatrix}\mathbf{L} & -\mathbf{K}_1{}^{T}\end{bmatrix}\begin{bmatrix}\mathbf{f}\\ \boldsymbol{\lambda}_1\end{bmatrix} = \mathbf{Z}_{\mathbf{K}_2}{}^{T}\left(\mathbf{G}\ddot{\mathbf{Q}} - \mathbf{P} - \mathbf{R}\right)\\ \begin{bmatrix}\mathbf{f}\\ \boldsymbol{\lambda}_1\end{bmatrix} \geq \mathbf{0}\end{cases}$$

where J was the objective function, $\mathbf{W}$ a diagonal matrix composed of the optimisation weights associated to the unknowns $[\mathbf{f}\,\boldsymbol{\lambda}_1]^{T}$ and $\mathbf{Z}_{\mathbf{K}_2{}^{T}}$ the orthogonal basis of the null space of the Jacobian sub-matrix $\mathbf{K}_2{}^{T}$. Once the musculo-tendon forces were computed, a pseudo-inverse method (Lin et al., 2011; Moissenet et al., in press) was used to compute the contributions of each musculo-tendon force to the ground reaction force and moment at the CoP $\mathbf{F}_0^{f^j}, \mathbf{M}_0^{f^j}$. The contribution of each segment weight $\mathbf{F}_0^{m_i\mathbf{g}}, \mathbf{M}_0^{m_i\mathbf{g}}$ was estimated a similar way. Then, the contributions of each musculo-tendon force (and segment weight) to the position of the CoP. The position of this "induced CoP" $(x_0^{f^j}, y_0^{f^j})$ was obtained by the equations of the non-central axis (Sardain and Bessonnet, 2004):

$$\begin{pmatrix}x_0^{f^j}\\ 0\\ z_0^{f^j}\end{pmatrix} = \frac{\mathbf{F}_0^{f^j} \times \mathbf{M}_0^{f^j}}{\left(\mathbf{F}_0^{f^j}\right)^2} - \frac{\left(\mathbf{F}_0^{f^j} \bullet \mathbf{M}_0^{f^j}\right)\mathbf{F}_0^{f^j} \times \mathbf{Y}_0}{\left(\mathbf{F}_0^{f^j} \bullet \mathbf{Y}_0\right)\left(\mathbf{F}_0^{f^j}\right)^2} + \begin{pmatrix}x_0\\ 0\\ z_0\end{pmatrix}$$

where (x_0, y_0) was the position of the measured CoP and ($\mathbf{X}_0$, $\mathbf{Y}_0$, $\mathbf{Z}_0$) were the axes of the inertial coordinate system (ICS, with $\mathbf{Y}_0$ vertical and the origin at the corner of the force plate) in which the generalised coordinates $\mathbf{Q}$, the position of the CoP and the ground reaction force and moment ($\mathbf{F}_0$, $\mathbf{M}_0$ as well as $\mathbf{F}_0^{f^j}, \mathbf{M}_0^{f^j}$) were expressed.

Results and discussion

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 (Fig. 1). The hip flexors and extensors demonstrated the more spread contributions, going both inward and outward. 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 plantar and dorsiflexors were the more aligned with CoP trajectory and were shifted anteriorly.

This description seems in line with the previous studies describing the 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 lower limb only, one subject, one motor task) and a more detailed analysis of the timing of these contributions is needed. Nevertheless, the individual muscle contributions to the position of the centre of pressure seem to provide useful insights into the dynamic of human walking.

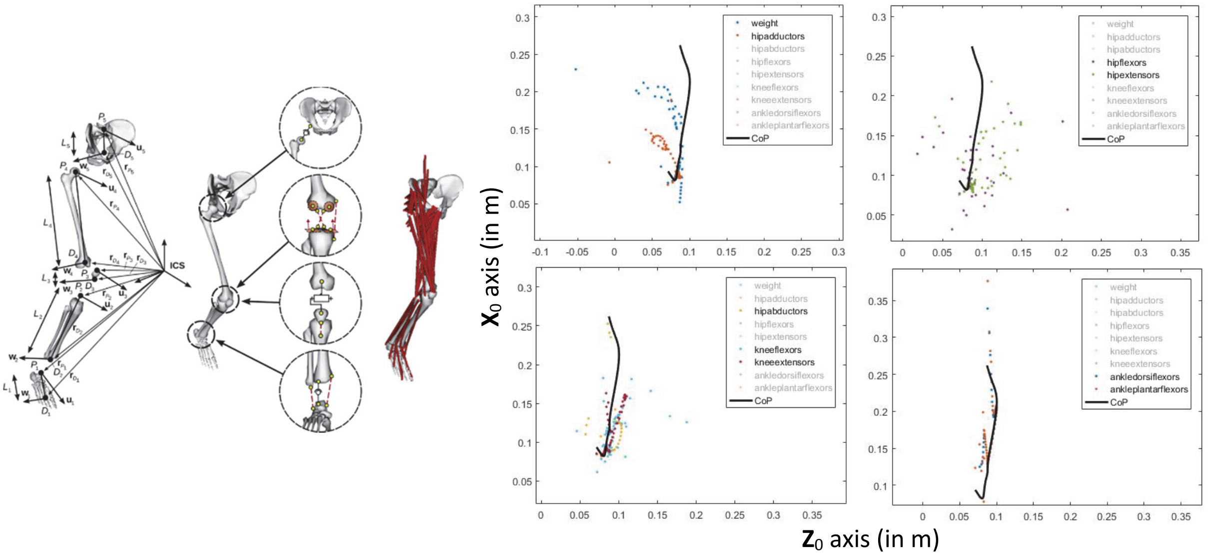

Fig. 1: 3D lower limb musculoskeletal model and individual muscle contributions to the position of the CoP

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