Extended Abstract

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Validation of a multi-objective optimisation for the estimation of the musculo-tendon, ligament, and joint contact forces during gait

Raphael Dumas[1], Laurence Cheze[1] and Florent Moissenet[2]

[1] *Univ Lyon, Université Claude Bernard Lyon 1, IFSTTAR, LBMC UMR_T9406, F69622, Lyon, France*
raphael.dumas@ifsttar.fr, laurence.cheze@univ-lyon1.fr
[2] *Centre National de Rééducation Fonctionnelle et de Réadaptation – Rehazenter,*
Laboratoire d'Analyse du Mouvement et de la Posture (LAMP), Luxembourg, Luxembourg
florent.moissenent@rehazenter.lu

Introduction

Musculoskeletal models are widely used in biomechanics to better understand muscle and joint function. The computational framework, typically based on inverse dynamics, involves an optimisation enabling the force-sharing problem to be solved for a given motor task. With the aim to simultaneously estimate the musculo-tendon, ligament, and joint contact forces, a multi-objective optimisation can be devised.

This study uses a musculoskeletal model of the lower limb with anatomical kinematic constraints. The equations of motion comprise the musculo-tendon forces and a selection of the Lagrange multipliers associated with the ligament and joint contact forces. All of these forces are estimated simultaneously by a multi-objective optimisation. The resulting musculo-tendon forces and joint contact forces are validated against experimental data, *i.e.* electromyographic signals (EMG) and instrumented prosthesis measurements, for five gait cycles of four subjects.

Material and methods

The equations of motion of the lower limb (*i.e.* foot, shank, patella, thigh and pelvis segments) can be written with natural coordinates to introduce the musculo-tendon forces and the Lagrange multipliers associated with the rigid body and kinematic constraints (*i.e.* ankle, knee, and hip joints) [1, 2]: $\mathbf{G}\ddot{\mathbf{Q}} + \mathbf{K}^T\boldsymbol{\lambda} = \mathbf{R} + \mathbf{P} + \mathbf{L}\mathbf{f}$, where $\mathbf{G}$ is the matrix of generalised masses, $\ddot{\mathbf{Q}}$ is the vector of generalised accelerations for all segments, $\mathbf{K}$ is the Jacobian matrix of the constraints, $\boldsymbol{\lambda}$ is the vector of Lagrange multipliers, $\mathbf{R}$ is the vector of generalised ground reaction, $\mathbf{P}$ is the vector of generalised weights, $\mathbf{L}$ is the matrix of generalised muscular lever arms, and $\mathbf{f}$ is the vector of musculo-tendon forces. The generalised accelerations, consistent with the constraints, are obtained by a multibody kinematics optimisation tracking experimental skin marker trajectories.

To solve the force-sharing problem, three objectives are simultaneously minimised:

$$\min_{\begin{pmatrix}\mathbf{f}\\ \boldsymbol{\lambda}_1\end{pmatrix}} \max \begin{pmatrix} J_1 = \dfrac{1}{n_1}\mathbf{f}^T\mathbf{f} \\ J_2 = \dfrac{1}{n_3}\left(\boldsymbol{\lambda}_1^l\right)^T \boldsymbol{\lambda}_1^l \\ J_3 = \dfrac{1}{n_2}\left(\boldsymbol{\lambda}_1^c\right)^T \boldsymbol{\lambda}_1^c \end{pmatrix} \text{ subject to } \begin{cases} \mathbf{Z}_{\mathbf{K}_2^T}\left[\mathbf{L} \quad -\mathbf{K}_1^T\right]\begin{pmatrix}\mathbf{f}\\ \boldsymbol{\lambda}_1\end{pmatrix} = \mathbf{Z}_{\mathbf{K}_2^T}\left(\mathbf{G}\ddot{\mathbf{Q}} - \mathbf{P} - \mathbf{R}\right) \\ \begin{pmatrix}\mathbf{f}\\ \boldsymbol{\lambda}_1\end{pmatrix}_{\min} \le \begin{pmatrix}\mathbf{f}\\ \boldsymbol{\lambda}_1\end{pmatrix} \le \begin{pmatrix}\mathbf{f}\\ \boldsymbol{\lambda}_1\end{pmatrix}_{\max} \end{cases} \qquad (1)$$

with $\boldsymbol{\lambda}_1$ a subset of the Lagrange multipliers (*i.e.* $\boldsymbol{\lambda}_1^l$ and $\boldsymbol{\lambda}_1^c$ are the ligament and joint contact forces), n_1, n_2 and n_3 the number of forces involved in J_1, J_2 and J_3, and $\mathbf{Z}_{\mathbf{K}_2^T}$ the orthogonal basis of the null space of the transpose of the Jacobian sub-matrix $\mathbf{K}_2$. This multi-objective optimisation is solved, at each sampled instant of time, with the function *fminmax* in Matlab (R2017b). The initial guess is simply a null vector. Regarding the upper and lower bounds, the musculo-tendon and ligaments forces can only be positive but some anterior and lateral joint contact forces can change sign. Maximal forces are identified from muscles physiological cross section area but remain unknown for ligament and joint contact forces and are set at infinite. For comparison of the estimated forces, the minimisation of a weighted sum of J_1, J_2 and J_3 is also processed (mono-objective optimisation) [1]. Weights have been defined empirically for this study through an iterative process aiming to reduce the root mean square error obtained for the total tibiofemoral joint contact force (*i.e.* the sum of the medial and lateral tibiofemoral contact forces).

Five gait cycles at comfortable speed are recorded with skin marker trajectories, ground reaction forces and moments, EMG, and medial and lateral tibiofemoral contact forces on four subjects implanted with an instrumented knee prosthesis (Grand Challenge competition to predict in vivo knee loads #1, #2, #3, #5) [3]. A semi-quantitative validation is performed by comparing estimated musculo-tendon forces patterns and measured EMG envelopes using the concordance coefficient (CC) [1]. Furthermore, the tibiofemoral contact forces are quantitatively validated by computing the root mean square error (RMSE) and the coefficient of determination (R^2) between estimated and measured forces.

Results and Discussion

On average, for mono-objective optimisations and multi-objective optimisations, CC are 63±5 % and 65±4 % (mean ± 1 SD) through the entire gait cycle, respectively, while goodness-of-fit parameters are RMSE: 0.32±0.06 BW (body weight) and 0.36±0.08 BW, R^2: 0.70±0.16 and 0.73±0.11 for the medial contact force, RMSE: 0.40±0.07 BW and 0.40±0.11 BW, R^2: 0.23±0.14 and 0.39±0.17 for the lateral contact force, and RMSE: 0.59±0.11 BW and 0.64±0.13 BW, R^2: 0.61±0.13 and 0.65±0.10 for the total contact force. Contact forces obtained for subject #2 are reported in Fig. 1. The results obtained in this study are comparable with the estimations of other non-personalised models [4].

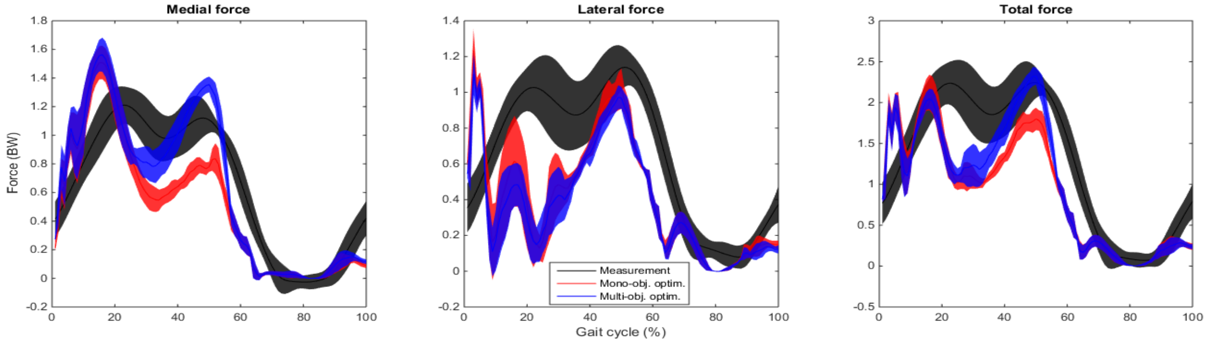

Fig. 1: Estimated and measured contact forces across gait cycles for subject #2

In conclusion, multi-objective optimisation can provide valid musculo-tendon and joint contact forces, in a similar way as a mono-objective optimisation with well-chosen weights. This procedure shows a high potential for introducing the musculo-tendon, joint contact, and ligament forces in different objectives and for minimising them simultaneously without an arbitrary weighting.

References

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