Simultaneous prediction of musculo-tendon, joint contact, ligament, and bone forces in the lower limb during gait

Raphael DUMAS [1], Florent MOISSENET[2], and Laurence CHEZE[1]

[1]*Université de Lyon, Lyon, France; LBMC, IFSTTAR, UMR T9406, Bron, France; Université Claude Bernard Lyon 1, Villeurbanne, France*

[2]*Rehazenter, Laboratoire d'Analyse du Mouvement et de la Posture, L-2674 Luxembourg, Luxembourg*

Correspondence: raphael.dumas@univ-lyon1.fr; 033 (0)472448575; 43 boulevard du 11 novembre 1918, 69622 Villeurbanne, France

Introduction

Musculo-tendon forces and joint reaction forces are typically predicted by computing first the musculo-tendon forces by a static optimisation procedure and by then deducing the joint reaction forces from the force equilibrium [1]. Moreover, the joint contact and ligament forces [2] as well as the bone forces [3] are rarely studied, because it requires complex models and multiscale simulations.
This study presents a rigid multi-body musculo-skeletal model allowing to compute the musculo-tendon, joint contact, ligament and bone forces all together by static optimisation, using a weighted criterion. The predicted forces are compared to the subject's measurements (EMG, knee prosthesis contact forces [4]) and to literature data [2, 5, 6].

Materials and Methods

A versatile 3D lower limb musculo-skeletal model [7, 8], consisting of pelvis, thigh, shank and foot segments and 43 muscular lines of action (taken from [9]), is used to perform this study (Fig.1.). Hip is modeled using a spherical joint, knee and ankle are modeled using parallel mechanisms (with sphere-on-plane contacts and isometric ligaments [10, 11]). This model uses generalised coordinates in a full dynamic equation of the lower limb: $\mathbf{G}\ddot{\mathbf{Q}} + \mathbf{K}^T\boldsymbol{\lambda} = \mathbf{E} + \mathbf{L}\mathbf{f}$ (Eq.1.),
where $\mathbf{G}$ is the generalised mass matrix, $\ddot{\mathbf{Q}}$ the generalised accelerations, $\mathbf{K}$ the Jacobian matrix of both kinematic and rigid body constraints, $\boldsymbol{\lambda}$ the Lagrange multipliers, $\mathbf{E}$ the external forces, $\mathbf{L}$ the generalised muscle moment arms and $\mathbf{f}$ the musculo-tendon forces.

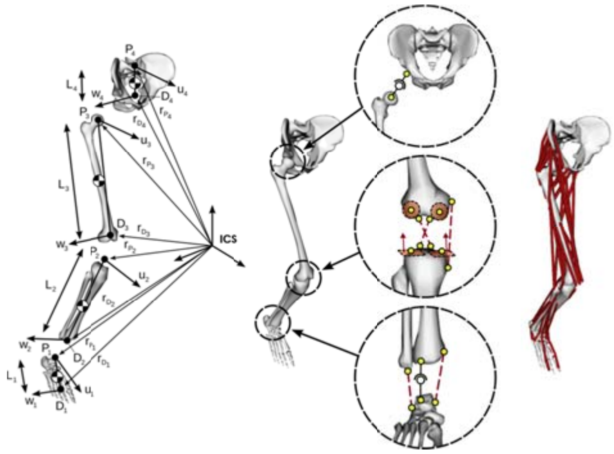

Figure 1. 3D lower limb musculo-skeletal model

The following linear system can be obtained from (Eq.1.): $\begin{bmatrix} \mathbf{L} & -\mathbf{K}_1{}^T & -\mathbf{K}_2{}^T \end{bmatrix} \begin{bmatrix} \mathbf{f} \\ \boldsymbol{\lambda}_1 \\ \boldsymbol{\lambda}_2 \end{bmatrix} = \mathbf{G}\ddot{\mathbf{Q}} - \mathbf{E}$ (Eq.2.),

where $\boldsymbol{\lambda}_1$ are the Lagrange multipliers corresponding straightforwardly to the joint contact, ligament, and bone forces [8], $\boldsymbol{\lambda}_2$ all the other ones, $\mathbf{K}_1$ and $\mathbf{K}_2$ the related Jacobian matrices.

Using a projection matrix $\mathbf{Z}_{\mathbf{K}_2}$ (composed of the eigenvectors of $\mathbf{K}_2^T\mathbf{K}_2$ corresponding to the null eigenvalues), the (Eq.2.) becomes: $\mathbf{Z}_{\mathbf{K}_2}^{\;T}\begin{bmatrix}\mathbf{L} & -\mathbf{K}_1^{\;T}\end{bmatrix}\begin{bmatrix}\mathbf{f}\\ \boldsymbol{\lambda}_1\end{bmatrix} = \mathbf{Z}_{\mathbf{K}_2}^{\;T}\left(\mathbf{G}\ddot{\mathbf{Q}} - \mathbf{E}\right)$ (Eq.3).

All the remaining unknowns $\begin{bmatrix}\mathbf{f} & \boldsymbol{\lambda}_1\end{bmatrix}^T$ in (Eq.3.) are then introduced in a typical static optimisation procedure [1] using a weighted criterion (i.e., weighted sum of forces squared). In this study, all these forces are predicted using the data from the “Second Grand Challenge Competition to Predict in Vivo Knee Loads” [4].

Results and Discussion

The patterns of the predicted musculo-tendon forces are generally in accordance with the envelopes of the main peaks of the subject’s EMG signals (Fig.2.).

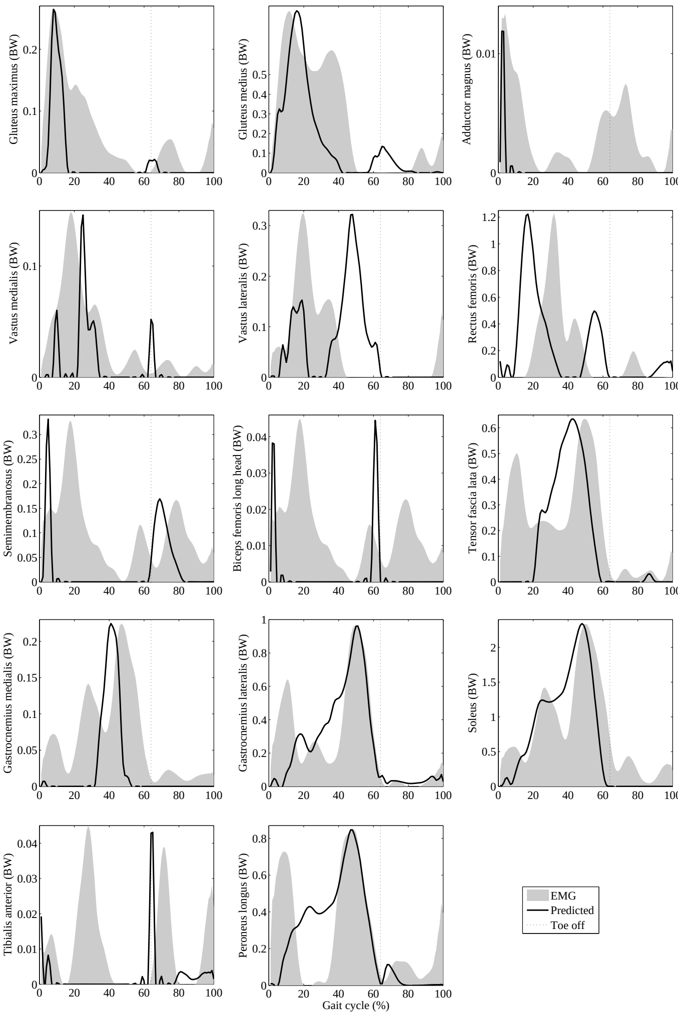

Figure 2. Predicted musculo-tendon forces and EMG signals during a gait cycle (%)

The amplitudes and patterns of the predicted knee contact forces (Fig.3.) are comparable to the subject’s in vivo measurements (root mean square error: 0.45 BW and correlation coefficient R: 0.89). The predicted hip and ankle contact forces, the ACL ligament, and femur force are also in good agreement with the literature [2, 5, 6].

Conclusion

The musculo-skeletal model used in this study allows to predict simultaneously musculo-tendon, joint contact, ligament and bone forces in line with the subject's measurements and the literature. The possibility to introduce other forces than the musculo-tendon forces in the static optimisation opens new horizons in order to better model the human physiology (e.g., joint pain). However, in this perspective, the minimisation of a weighted criterion may be seen as a limit of the current approach.

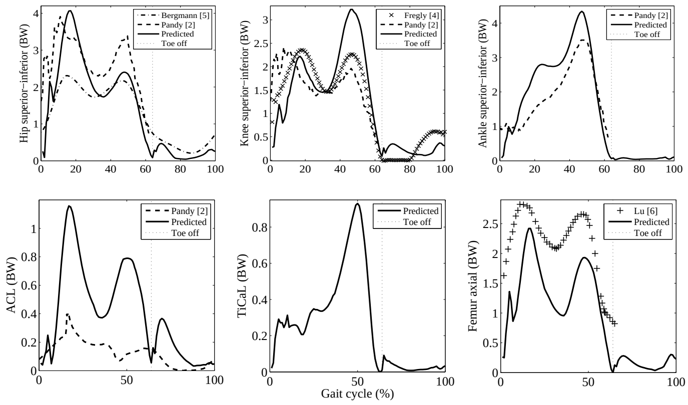

Figure 3. Predicted joint contact, ligament, and bone forces during a gait cycle (%)

References

1. Erdemir A, McLean S, Herzog W, van den Bogert AJ. Model-based estimation of muscle forces exerted during movements. *Clin Biomech*. 2007;**22(2)**:131-54. doi:10.1016/j.clinbiomech.2006.09.005

2. Pandy MG, Andriacchi TP. Muscle and joint function in human locomotion. *Annu Rev Biomed Eng*. 2010;**12**:401-33. doi: 10.1146/annurev-bioeng-070909-105259

3. Wehner T, Claes L, Simon U. Internal loads in the human tibia during gait. *Clin Biomech*. 2009;**24(3)**:299-302. doi:10.1016/j.jbiomech.2010.05.028

4. Fregly BJ, Besier TF, Lloyd DG, Delp SL, Banks SA, Pandy MG, D'Lima DD. Grand challenge competition to predict in vivo knee loads. *J Orthop Res*. 2012;**30(4)**:503-13. doi: 10.1002/jor.22023

5. Bergmann G, Deuretzbacher G, Heller M, Graichen F, Rohlmann A, Strauss J, Duda GN. Hip contact forces and gait patterns from routine activities. *J Biomech*. 2001;**34(7)**:859-71.

6. Lu TW, Taylor SJ, O'Connor JJ, Walker PS. Influence of muscle activity on the forces in the femur: an in vivo study. *J Biomech*. 1997;**30(11-12)**:1101-6.

7. Dumas R, Moissenet F, Gasparutto X, Cheze L. Influence of joint models on lower-limb musculo-tendon forces and three-dimensional joint reaction forces during gait. *Proc IME H J Eng Med*. 2012;**226(2)**:146 - 60. doi: 10.1177/0954411911431396

8. Moissenet F, Cheze L, Dumas R. Anatomical kinematic constraints: consequences on musculo-tendon forces and joint reactions. *Multibody Syst Dyn*. 2012:In press. doi: 10.1007/s11044-011-9286-3

9. Delp SL, Loan JP. A graphics-based software system to develop and analyze models of musculoskeletal structures. *Comput Biol Med*. 1995;**25(1)**:21-34. doi: 10.1016/0010-4825(95)98882-E

10. Di Gregorio R, Parenti-Castelli V, O'Connor JJ, Leardini A. Mathematical models of passive motion at the human ankle joint by equivalent spatial parallel mechanisms. *Med Biol Eng Comput*. 2007;**45(3)**:305-13. doi: 10.1007/s11517-007-0160-7

11. Feikes JD, O'Connor JJ, Zavatsky AB. A constraint-based approach to modelling the mobility of the human knee joint. *J Biomech*. 2003;**36(1)**:125-9.