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SIMULTANEOUS PREDICTION OF MUSCULO-TENDON, JOINT CONTACT, LIGAMENT AND BONE FORCES IN THE LOWER LIMB DURING GAIT USING A ONE-STEP STATIC OPTIMISATION PROCEDURE

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ABSTRACT

Instrumented prostheses, by measuring joint contact forces during a movement, give nowadays a unique opportunity to validate the ability of musculo-skeletal models in predicting internal forces.

In this study, a rigid multi-body musculo-skeletal model, allowing computing the musculo-tendon, joint contact, ligament and bone forces all together by static optimisation, using a weighted criterion, is presented.

The results show that the musculo-tendon forces are generally in accordance with the envelopes of the main peaks of the subject's EMG signals and that the amplitudes and patterns of the predicted joint contact, ligament and bone forces are in a good agreement with the measurements and with the literature. By allowing the introduction of other forces than the musculo-tendon forces in the static optimisation, this study opens new horizons in order to better model the human physiology (e.g., joint pain).

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 computing 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 (i.e., EMG, knee prosthesis contact forces [4]) and to literature data [2,5,6].

MATERIAL AND METHODS

A versatile 3D lower limb musculo-skeletal model [7,8], consisting of pelvis, thigh, patella, shank and foot segments and 43 muscular lines of action (taken from [9]), is used to perform this study (Fig 1.).

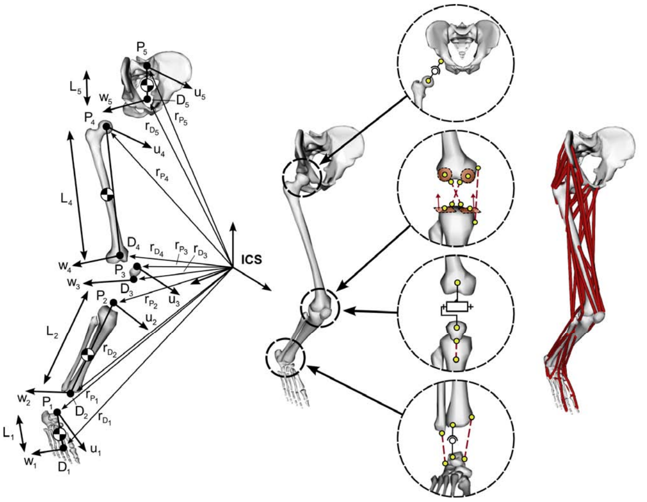

FIG 1. 3D LOWER LIMB MUSCULO-SKELETAL MODEL

Hip joint is modeled using a spherical joint and tibio-femoral, patello-femoral and ankle joints are modeled using parallel mechanisms (with sphere-on-plane contacts and isometric ligaments for the tibio-femoral joint [10] and the ankle joint [11] and with a hinge joint and isometric ligament for the patello-femoral joint [12]).

This model uses generalized coordinates in a full dynamic equation of the lower limb:

$$\mathbf{G}\ddot{\mathbf{Q}} + \mathbf{K}^T\boldsymbol{\lambda} = \mathbf{E} + \mathbf{L}\mathbf{f} \tag{1}$$

where $\mathbf{G}$ is the generalized mass matrix, $\ddot{\mathbf{Q}}$ the generalized 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 generalized muscle moment arms and $\mathbf{f}$ the musculo-tendon forces.

The following linear system can be obtained from (1):

$$\left[\mathbf{L} \quad -\mathbf{K}_1^T \quad -\mathbf{K}_2^T\right]\left[\mathbf{f} \quad \boldsymbol{\lambda}_1 \quad \boldsymbol{\lambda}_2\right]^T = \mathbf{G}\ddot{\mathbf{Q}} - \mathbf{E} \qquad (2)$$

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 equation (2) becomes:

$$\mathbf{Z}_{\mathbf{K}_2}^T\left[\mathbf{L} \quad -\mathbf{K}_1^T\right]\left[\mathbf{f} \quad \boldsymbol{\lambda}_1\right]^T = \mathbf{Z}_{\mathbf{K}_2}^T\left(\mathbf{G}\ddot{\mathbf{Q}} - \mathbf{E}\right) \qquad (3)$$

All the remaining unknowns $\left[\mathbf{f} \quad \boldsymbol{\lambda}_1\right]^T$ in equation (3) are then introduced in a typical static optimization procedure [1] using a weighted criterion (i.e., weighted sum of forces squared). In this study, all these forces are predicted using one gait cycle from the “Fourth Grand Challenge Competition to Predict in Vivo Knee Loads” [4].

RESULTS

The patterns of the predicted musculo-tendon forces are generally in accordance with the envelopes of the peaks of the subject’s EMG signals (Fig 2.). The predicted hip, tibio-femoral, patello-femoral and ankle joint contact forces, the ACL ligament, and femur force (Fig 3.) are also in good agreement with the literature [2,3,5].

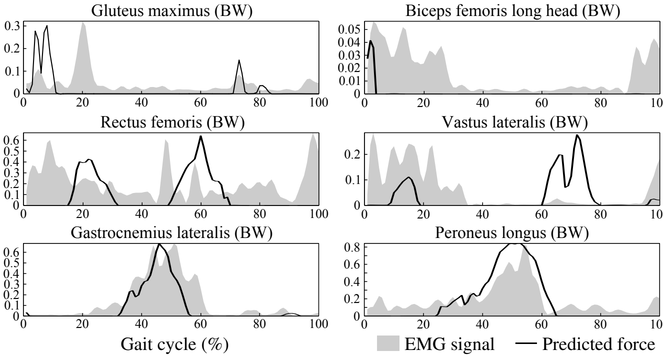

FIG 2. 3D LOWER PREDICTED MUSCULO-TENDON FORCES AND EMG SIGNALS DURING A GAIT CYCLE (%)

DISCUSSION

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.

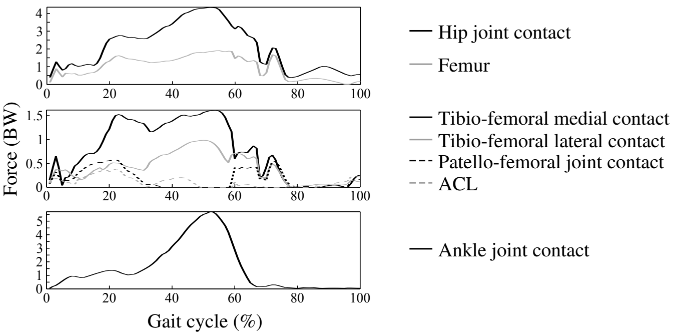

FIG 3. PREDICTED JOINT CONTACT, LIGAMENT, AND BONE FORCES DURING A GAIT CYCLE (%)

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