SENSITIVITY OF COMPUTATIONS OF MUSCULAR FORCES TO MODIFICATIONS OF GEOMETRIC MODEL DURING GAIT

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SUMMARY
Knowledge of muscular forces can contribute to assist in diagnoses and in treatments of persons suffering from locomotion disorders. We tackled the issue of muscular forces determination with the objective of its implementation in pathological disturbed movements’ studies, in particular in those about the walk of children suffering from cerebral palsy. We handled mainly with the question of the sensitivity of these calculations to geometrical changes in the musculoskeletal model. The dynamic model which we implemented was validated by comparing its results with the EMG signals on the one hand, and with literature data related to healthy subjects muscular forces, on the other hand. The sensibility of this model was then estimated with respect to (i) a modification of the femoral antetorsion and (ii) the modeling or not of the insertion of the muscle rectus femoris in post-operative conditions.

INTRODUCTION
Knowing the muscle forces and the intra-articular forces could improve the understanding of sensorimotor organization of the movement and could assist in diagnoses and treatment of persons suffering from musculoskeletal disorders. One way to compute these forces is to determine by optimization the unknowns (muscle forces) of the considered dynamic system. The solutions are oriented thanks to a criterion and constraints that are supposed to correspond to the physiology of the locomotor system. Much work focuses on identification of the latter. However, personalization of the musculoskeletal geometric model needs to be improved [1]. Furthermore, surgical treatments of locomotor disorders act mainly on the geometric parameters. Modifications of lever arms after surgery have already been evaluated [1,2] but no results have been published to determine the impact of those modifications on the dynamic calculations. In fact, surgery modifies some muscular lever arms and probably the muscular forces of the concerned muscles; nevertheless the effect on the global dynamic of the musculoskeletal system remains unknown mainly because of the agonist/antagonist organization of this over-actuated system. It is interesting to test the potential impact of an inappropriate geometrical modeling and to evaluate if the calculations of the muscular forces are sensitive enough to develop dynamic simulations of the effect of the surgery. Therefore we tested the effect of the modifications of the femoral antetorsion and of the insertion of the muscle rectus femoris on the calculation of the muscular forces during gait.

METHODS
The used geometrical model includes the bones of both lower limbs and 62 muscles. The osseous geometry is personalized on the basis of clinical measurements. The muscular paths are modeled with a convex wrapping algorithm [3]. A homogenous formulation of the dynamic model is conducted for the $k=1:N$ bones and the $n$ muscles inserted on $k$:

$A_{k}(R_{k}) = \Phi_{k+1/k}(R_{k}) + \Phi_{k-1/k}(R_{k}) + \Phi_{g/k}(R_{k}) + \sum_{j=1}^{n} \Phi_{j/k}(R_{k})$

This formulation permits the compact integration of the muscular forces $F_{j}$, the joint forces $f$ and the passive joint torques $c$ inside the $\Phi$ matrices which correspond to the actions of the $k-1$ and $k+1$ bones, of the gravity and of the muscular forces. The matrix $A_{k}$ gathers the dynamic resultant and the dynamic moment for each $k$ bone. Constrained static optimization is computed (Matlab® fmincon) as follow:

$\begin{align*}
\text{minimising} & \quad f(F) = \sum_{j=1}^{n} \left( \frac{P_{j}}{PCSA_{j}} \right)^{2} \\
\text{under constraints} & \quad F_{j} \geq 0 \\
& \quad g(F, f, c) = 0 \\
& \quad F_{j} \in \mathbb{R}
\end{align*}$

The $PCSA_{j}$ used are the physiological cross section areas published in [4].
The dynamic model which we implemented is assessed by comparing its results with the EMG signals on the one hand, and with literature data related to healthy subjects muscular forces, on the other hand. The sensibility of this model was then estimated with respect to (i) a modification of the femoral antetorsion and (ii) the modeling or not of the transfer of the muscle rectus femoris in post-operative conditions (Figure 1).

RESULTS AND DISCUSSION
In such studies, the validation of the accuracy of the computed forces remains difficult; nevertheless, the muscular forces computed for healthy subjects showed good agreement with the EMG signals on the one hand, and with literature data. The modification of femoral torsion induces modifications of the calculated muscle forces, especially for muscles having an insertion on the thighbone. For example, the psoas presents a maximal force during gait of 480N (Torsion 10°) or of 730N (Torsion 40°). There are also dynamic modifications for the distant muscles such as the soleus, which have a stance phase pick of 562N or 416N in the same conditions. The modification of the rectus femoris insertion induces small changes on the computed forces of this muscle, but dynamic modifications happen on other agonist or antagonist muscles and also on distant muscles. Figure 2 presents some of those modifications.

CONCLUSIONS
Healthy subject results showed that the proposed model is able to compute muscular forces for the whole lower limb while presenting some limitations. The sensitivity of the calculations of muscular forces to the geometrical parameters highlights the need for a high degree of fidelity of the geometrical model. This also shows that the employed dynamic model is sensitive enough to focus on the development of researches concerning the optimization, by dynamic simulation, of the musculoskeletal geometry with the purpose to supply, qualitative and quantitative optimal surgical indications.

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