Influence of muscle recruitment criteria on joint reaction forces during human gait

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Abstract

Determination of muscle forces during gait (or any other exercise) is of great interest to extract the principles of the central nervous system (CNS) control (assessment of pathological gait from muscular activation abnormalities, diagnosis of neuromuscular disorders), or to estimate the loads on bones and joints (prevention of injuries in sports, surgical planning to reconstruct diseased joints). The invasive character of *in vivo* experimental measurements, and the uncertain relation between muscle force and EMG, makes computer modeling and simulation a useful substitutive approach.

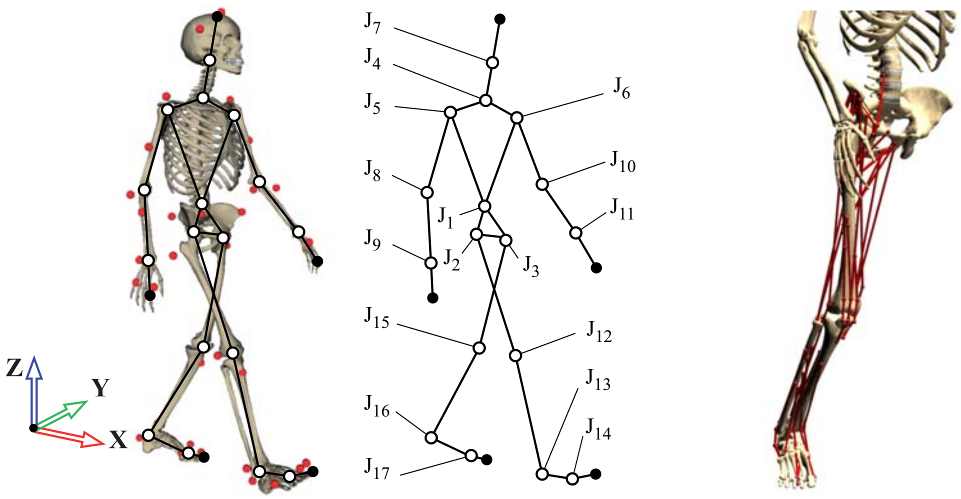

Figure 1: 3D human model and detail of muscles on the right leg.

The fundamental problem is that there are more muscles serving each degree of freedom of the system than those strictly necessary from the mechanical point of view, which implies that, in principle, an infinite number of recruitment patterns are acceptable. This problem is often referred to as the redundancy problem of the muscle recruitment or the force-sharing problem. Experimental studies and EMG collections suggest that a specific strategy of muscle coordination is chosen by the CNS to perform a given motor task.

A popular mathematical approach for solving the muscle recruitment problem is the optimization method, which can be associated to inverse or forward dynamics. These methods minimize or maximize some criterion (objective function or cost function) which reflects the mechanism used by the CNS to recruit muscles for the movement considered. The proper cost function is not known a priori, so the adequacy of the chosen function must be validated according to the obtained results. Many criteria have been proposed in the literature to predict muscle forces. However, according to Daniel [1], the choice of the optimization criterion does not influence the hip reaction force in the inverse dynamic analysis.

In this work, the gait of a female subject of 50 kg weight and 1.67 m height has been captured (along with the ground contact forces) and used, after signal processing, to animate an 18-segment three-dimensional model with 57 degrees of freedom (Figure 1, left and center). In the right leg of the model, 43 muscles have been considered (Figure 1, right), their properties taken from [2]. Inverse dynamic analysis has been applied to the acquired motion in order to obtain the joint drive torques. Then, the following optimization problem has been stated,

$$\begin{aligned} & \min \ C \\ & \text{subject to} \quad \mathbf{J}^{\mathrm{T}}\mathbf{F} = \mathbf{Q} \\ & \qquad F_{i,\min} \le F_i \le F_{i,\max} \quad i = 1, 2, \ldots, m \end{aligned} \tag{1}$$

where C is the cost function, $\mathbf{Q}$ is the vector of joint drive torques at the right leg (where the force-sharing problem is addressed), $\mathbf{F}$ is the vector of muscle forces, $\mathbf{J}$ is the Jacobian whose transpose projects the muscle forces into the joint drive torques space, and $F_{i,\min}$, $F_{i,\max}$ are the lower and upper limits of muscle force F_i, with m the number of muscles (in this case, 43).

Both the static ($F_{i,\min} = 0$, $F_{i,\max} = F_{i,0}$, with $F_{i,0}$ maximum isometric force) and physiological approaches ($F_{i,\min}$ and $F_{i,\max}$ based on muscle dynamics and previous muscle state) have been applied. Regarding the cost function C, four cases have been considered and compared in the static approach, whose mathematical formulations are shown in Table 1, along with that of the physiological case:

I) Sum of the squares of muscle forces,

II) Sum of the squares of proportional muscle forces,

III) Sum of muscle stresses, with A_i the cross sectional area of muscle i,

IV) Largest relative muscle force.

Table 1: The compared muscle recruitment criteria.

I	II	III	IV	Physiological
$\sum_{i=1}^{m} F_i^2$	$\sum_{i=1}^{m} \left(\frac{F_i}{F_{i,0}} \right)^2$	$\sum_{i=1}^{m} \left(\frac{F_i}{A_i} \right)^2$	$\max \left\{ \frac{F_i}{F_{i,0}} \right\} \quad i = 1, 2, \ldots, m$	$\sum_{i=1}^{m} \left(\frac{F_i}{F_{i,\max}} \right)^2$

Conversely to what was suggested by Daniel, results show that different criteria lead to notably different values of the joint forces, as illustrated in Figure 2, where the obtained hip, knee and ankle joint forces are plotted for the static (four criteria) and physiological approaches, respectively.

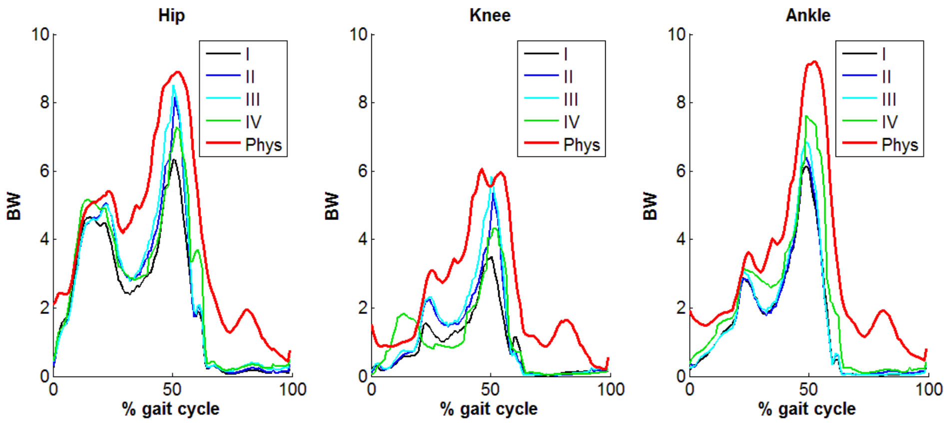

Figure 2: Joint reaction forces at hip, knee and ankle for different muscle recruitment criteria.

References

[1] M. Daniel. Mathematical modelling of the hip joint loading. Bulletin of Applied Mechanics, Vol. 3, pp. 201-215, 2004.

[2] S.L. Delp, F.C. Anderson, A.S. Arnold, P. Loan, A. Habib, C.T. John, E. Guendelman, D.G. Thelen. OpenSim: Open-source software to create and analyze dynamic simulations of movement. IEEE Transactions on Biomedical Engineering, Vol. 54, No. 11, pp. 1940-1950, 2007.