CAN ENERGY-RELATED OPTIMALITY CRITERIA EXPLAIN STANCE PHASE KNEE FLEXION IN GAIT?

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INTRODUCTION

Predictive simulations of gait can help uncover underlying principles of neuromuscular coordination and have potential applications in predicting patient responses to surgical interventions and to prosthetic devices. The optimal neuromuscular control problem requires the definition of a cost function, which is assumed to represent the underlying physiological criteria that govern muscle coordination [1].

Minimal metabolic energy expenditure has generally been used as a criterion in predictive simulation of gait [2]. Minimization of metabolic energy is observed in many experimental studies (e.g. [3]), but those results might also be consistent with other explanations, such as minimal muscle fatigue [1]. Fatigue-related cost functions have generally been used in inverse dynamics studies to solve the muscle force distribution problem [4].

This study investigates the influence of different cost functions on gait patterns predicted by means of computational simulations. In particular, it focuses on the knee flexion in the weight acceptance phase which is observed in normal gait and may be inconsistent with minimal energy criteria as it requires activation of the large Quadriceps to prevent knee collapse.

METHODS

The musculoskeletal system model used in this study is planar and consists of seven rigid body segments, trunk, 2 thighs, 2 shanks and 2 feet, actuated by 16 Hill-type muscle groups which incorporate activation and contraction dynamics [5]. The foot-ground contact was modeled by 10 elements uniformly distributed along each foot sole with nonlinear spring-damper properties and Coulomb friction at each contact point. This musculoskeletal model is characterized by a total of 50 state variables and 16 control variables (muscle stimulation signals).

In order to study the influence of the cost function on the predicted gait patterns a family of cost functions was used as

\[
J = \frac{1}{\sum_{i} w_i} \frac{1}{T} \sum_{i=1}^{m} w_i \int_{0}^{T} a_i^p(t) dt,
\]

where \( m \) is the number of muscles (\( m=16 \)), \( T \) is the duration of half a gait cycle which is optimized, and \( a_i \) is the activation of muscle \( i \). The exponent \( p \) is set to 1, 2, 3 or 10 and the weighting factors \( w_i \) are either 1 or equal to the muscle volume \( V_i \). Optimizations were performed using each one of the eight different cost functions arising from the combinations of exponents and weighting factors.

Direct Collocation was used to transform the optimal control problem into a Nonlinear Programming Problem (NLP) by means of discretization in time [1,6]. Bilateral symmetry was assumed, and a speed of 1.1 m/s was prescribed. Half a gait cycle was discretized by the backwards Euler differentiation formula using 50 time nodes and the resulting NLP was solved using SNOPT (tommopt.com/tomlab/). Solutions were typically obtained in less than one hour. Accuracy of the solutions was verified by successive mesh refinement and traditional forward dynamic simulation with variable step size.

RESULTS AND DISCUSSION

The choice of cost function had a noticeable effect on predicted gait patterns. Normal gait has a peak knee flexion in stance of about 20° and this was correctly predicted with higher powers \( p \) and \( w_i = 1 \). Such cost functions are related to minimal fatigue, as muscle size is disregarded and high activations dominate the cost (Table 1 and Figure 1). Conversely, lower powers \( p \) and \( w_i = V_i \) led to a straight knee in weight acceptance, and high impact forces. Such cost functions are more related to energy consumption as muscle size is taken into account and small and large activations are more equally weighted.

Table 1: Peak knee flexion and peak activation of the Vasti muscle group during stance, for each of the cost functions.

<table>
<thead>
<tr>
<th>( w_i )</th>
<th>( p=1 )</th>
<th>( p=2 )</th>
<th>( p=3 )</th>
<th>( p=10 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_i )</td>
<td>45°/0.55</td>
<td>33°/0.42</td>
<td>26°/0.30</td>
<td></td>
</tr>
<tr>
<td>( V_i )</td>
<td>1°/0.10</td>
<td>1°/0.08</td>
<td>20°/0.26</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1: Predicted gait patterns with \( p=2 \) and \( w_i = V_i \) (left), and \( p=3 \) and \( w_i = 1 \) (right).

As illustrated by the strong correlation between Vasti peak activation and peak knee flexion (Table 1), knee flexion during stance requires activation of the large knee extensors, which in this model leads to greater energy consumption but
less fatigue. These results suggest that energy minimization does not govern all aspects of muscle coordination during gait and indicate the necessity of further experimental and computational investigations on appropriate optimality criteria for human movement simulation.

CONCLUSIONS
The simulation results suggest that the knee flexion observed in the weight acceptance phase of normal walking is not consistent with minimal energy criteria. In fact, it was shown that knee flexion in the model was correlated with activation of the large Vasti muscle group, a phenomenon more compatible with minimization of muscle fatigue. These observations show the importance of further computational and experimental investigations on appropriate optimality criteria for predictive simulations of gait.

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REFERENCES