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Activation dynamics in the optimization of targeted movements

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ABSTRACT

Human movements, and their underlying muscular recruitment strategies, can be studied in several ways. In order to increase the understanding of human movement planning strategies, the movement problem is here seen as a boundary value problem for a mechanism with prescribed initial and final configurations. The time variations of a set of control actuator forces are supposed to fulfil some optimality criterion while creating this motion. The boundary value problem is discretized by temporal finite element interpolation, where the discrete variables are seen in an optimization context. The present work focusses on the introduction of the activation dynamics of the actuators, introducing a delay in the force production from the stimulation variables. The choice of interpolations of the variables is discussed in the light of the optimization setting. Examples show aspects of the results obtained for different assumptions. It is concluded that the formulation gives a good basis for further improvement of muscular force production models in an optimal movement setting.

1. Introduction

Human movements are commonly assumed to consist of an adaptation of partially pre-programmed movement sequences, and a real-time error-correction strategy. The pre-programmed movement sequences are assumed to be related to the capacities and restrictions of the individual. Very complex movements can be performed under neural control, but causes computational difficulties when attempts are made to simulate the behavior [1–3]. The exact functioning of the control system is not fully known, but a common approach is to assume that the muscular forces are chosen from some optimization rule: minimum forces, nominal efforts, activation, energy consumption, or maximum smoothness [4–7]. For quasi-static situations, i.e., slow movements or postures, a static optimization can be assumed to give reasonable distributions of forces on muscles [8] but this requires a static view on muscular force production [9–13].

A computational model of the musculoskeletal system is normally based on a set of rigid, un-deformable links, connected at perfect hinges and affected by more or less simplified muscle models. These create a highly redundant force system [14], with high numbers of alternative components over most joints. This is emphasized by simplified models, in which the kinematics and kinetics are not fully resolved. One particular aspect of the redundant system is that both static equilibrium and movements can be based on an equilibrium between antagonistic muscles, i.e., by a coordinated activation of counteracting muscle actuators, for instance by two equal forces equilibrating each other. The human body commonly uses this type of action both for improved stability and as a preparation for a movement.

In movement simulations, inverse dynamics approaches [15,16] use accurate measurements of external forces and body motions to deduce the forces needed to create a recorded movement. Forward dynamics approaches formulate an initial value problem, and attempt to induce the movement for a set of forces. These can be previously recorded [17] and the simulated movement is compared to the registered movement. The forces can, however, be a priori unknown, and iteratively sought to produce a specified movement. The movement to match can then be known as just the initial and final configurations, with the movement between these as the answer. Depending on the setting of the problem, there can exist a number of possible movements, and the movement problem is thereby 'dynamically redundant'. Among the possible solutions, an optimal one can be sought, where the term 'optimal' is, however, far from obvious [18,19].

A wider concept, an 'inverse optimization', is used in e.g., [20,21], where recorded movements are used in order to deduce the neural motor control strategy, parameterizing the cost function.

Previous work by the authors [22–24] has discussed optimal movement plans, with human musculo-skeletal movements as the primary application. In particular, the optimal targeted movement from an initial to a final configuration has been considered. The work has been aimed at methods which can be used to increase the understanding of human movement planning, in

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particular for movements close to the individual maximum capacities, relevant for sports movements as well as in a clinical context. With this aim, the formulation in [24] is based on two restrictive assumptions, the first being that the movement will take place in a specified time interval. A 'free-time' formulation has recently been presented [25] where time interval lengths for parts of a movement were seen as independent optimization variables.

Another important restriction is related to the timing aspects, as control forces have been assumed to be infinitely quickly regulated. Activation timing is, however, a key aspect in simulations of human movements, where the muscles always act with a delay, and thereby give smoothly varying forces with a memory effect. The present work studies the effects from activation timing on the resulting optimal movements. The aim of the work is to develop a computational formulation which is capable of considering these timing aspects, and to give at least qualitative information on the effects from activation delays. The hypothesis for the work is that timing aspects of muscular force activation is of importance in the simulation of human movements, and in particular when dealing with extreme movements close to the individual capacity.

In the present work, the muscular forces are therefore seen as dependent on activation variables, formulated from first-order processes of the neural stimulation, an assumption which comes closer to the muscular force production, and allows the inclusion of effects from, e.g., length, stretch velocity and work history [26]. The work thereby gives a foundation for including improved muscle models in the forward simulation, a need which has been emphasized in literature [1,27,28, and many others].

The optimization setting is thereby based on three sets of time-varying variables: stimulation and force values for the muscle actuators, together with the displacement coordinates of the mechanical system. Each set is interpolated through a temporal finite element discretization; the sets are connected through the activation dynamics and the dynamic force equilibrium equations. General expressions are used in the formulation of the cost function in the numerical optimization.

The paper first gives a basic formulation of the dynamic equilibrium of a mechanism, and casts it in an optimization context. The main discussion is concerned with the representation and formulation of the activation dynamics. Key issues are the representation of both control variables and displacements over time, and the inclusion of the governing equations in the optimization setting. A simple example is used to show the properties of the solutions obtained. Some conclusions are drawn regarding the computational formulation of the activation dynamics, but also regarding the necessity to include the timing aspects in a simulation of human movements.

2. Basic formulation

The movement problem is seen as a boundary value problem, with prescribed initial and final configurations. It further considers a set of control actuators, the time variations of which can be chosen to fulfil the boundary configurations. The optimal variations of these controls, with respect to a chosen optimality criterion, is part of the solution to the problem. The developed temporal finite element ('FE') representation uses independent discretizations for the unknown displacements and control variables. Low order Lagrange interpolation of all quantities considered, and a weak equilibrium formulation lead to robust and efficient simulations.

The main formulation is thereby concerned with the solution of a discretized dynamic equilibrium problem, where the necessary requirement for a solution can be written as a set of equilibrium equations:

$$\boldsymbol{E}(\boldsymbol{x},\boldsymbol{P}) = \boldsymbol{0} \tag{1}$$

with the solution vector $\boldsymbol{x} = [\boldsymbol{Q}^{\mathrm{T}},\boldsymbol{C}^{\mathrm{T}}]^{\mathrm{T}}$ containing discretized descriptions of both displacement coordinates, $\boldsymbol{Q}$, and control variables, $\boldsymbol{C}$, whereas $\boldsymbol{P}$ represents the prescribed external loading over the interval considered. The number of equations is dependent on the formulation of the simulation problem, as further discussed below.

The displacement vector $\boldsymbol{Q}$ contains a representation of the kinematic behavior over a fixed time interval $0 \leqslant t \leqslant T$. At a time instance t, the configuration is described by a set of N_d coordinates:

$$\boldsymbol{q}(t) = \begin{pmatrix} q_1(t) \\ \vdots \\ q_{N_d}(t) \end{pmatrix} \tag{2}$$

As further discussed below, this configuration is interpolated from the vector $\boldsymbol{Q}$, formally as:

$$\boldsymbol{q}(t) = \mathbb{N}(t)\boldsymbol{Q} \tag{3}$$

with, preferably, a local definition of the interpolation functions in $\mathbb{N}(t)$.

The N_c control variables at a time instance t are similarly interpolated as:

$$\boldsymbol{c}(t) = \mathbb{N}_c(t)\boldsymbol{C} \tag{4}$$

where the vector $\boldsymbol{C}$ contains the discretized descriptions of the control variables over the interval $0 \leqslant t \leqslant T$. Suitable interpolations of both $\boldsymbol{Q}$ and $\boldsymbol{C}$ are dependent on the problem formulation, in particular the equilibrium equations connecting the two vectors. In the present work, the control variables in $\boldsymbol{c}(t)$ and $\boldsymbol{C}$ are more complex, as both the activation and stimulation variables are represented, rather than only the forces.

2.1. Dynamic equilibrium expressions

The basic mechanical formulation uses the kinetic and potential energies of the system in motion, formulating the Lagrangian function at time t:

$$\mathcal{L}(t) = \mathcal{T}(t) - \mathcal{V}(t) \tag{5}$$

where $\mathcal{T}(t) = \mathcal{T}(\boldsymbol{q}(t),\dot{\boldsymbol{q}}(t))$ and $\mathcal{V}(t) = \mathcal{V}(\boldsymbol{q}(t),\boldsymbol{c}(t),\boldsymbol{p}(t))$ are the kinetic and potential energies of the system at time t. Here, a superposed dot indicates a time differential, and $\boldsymbol{p}(t)$ are the external forces at time t.

The Lagrange function is used to obtain a set of weak dynamic equilibrium equations:

$$\int_0^T \left(\frac{\partial\mathcal{L}}{\partial q_i}\delta q_i + \frac{\partial\mathcal{L}}{\partial\dot{q}_i}\delta\dot{q}_i\right)dt + m_i^0\delta q_i(0) - m_i^T\delta q_i(T) = 0 \tag{6}$$

The boundary conditions are:

$$m_i(0) = m_i^0, \quad m_i(T) = m_i^T \tag{7}$$

with $m_i(t)$ the generalized momenta in the coordinates:

$$m_i(t) = \frac{\partial\mathcal{L}}{\partial\dot{q}_i}(t) \tag{8}$$

Obviously, the two last terms of Eq. (6) disappear when a system in initial and final rest is considered.

2.2. Activation variables

The equilibrium equations (6) contain the actuator forces. In previous work, these were directly represented in the vector $\boldsymbol{c}(t)$, but they are now indirectly represented through activation and stimulation variables. The basic formulation thereby uses two variables for each muscle activator at a time instance. The whole vector