Development of a Multibody-Based Methodology for Motion Simulation of Biomechanical Systems using Natural Coordinates

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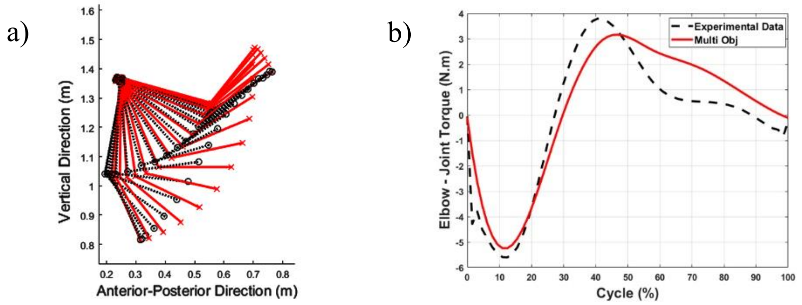
Methodologies based on motion simulation have been successfully applied in the area of clinical biomechanics and gait analysis, particularly in the study of the mechanical and physiological mechanisms underlying human movement [1], predicting the outcome of surgical procedures [2], design new rehabilitation protocols and medical devices [3,4], among other applications. Its success comes from the possibility of testing new variables and conditions *in silico*, before advancing to experimental studies. However, simulating intricate mechanical systems with a large number of degrees-of-freedom is still an issue today due to the complexity of the problem to solve. Within the different methodologies available to solve it, multibody dynamics formulations stand out, as they allow the efficient modelling and simulation of complex structural systems, such as the human body [5]. When applied alongside with musculotendon models and optimization methods, multibody-based methodologies allow also the study of muscle activation and contraction dynamics for the movement in study [6].

The present work aims the development of a methodology based on a multibody dynamics formulation with natural coordinates to be applied in the three-dimensional (3D) simulation of human movement. For that purpose, a predicative approach, based on optimal control, is considered. This type of methodologies presents the advantage of simulate simultaneously the kinematics and dynamics of the system, while minimizes an optimization cost function based on physiological criteria. The present study will focus also on the analysis of different optimization strategies, as well as different cost functions, in order to understand its influence in the simulated movement, aiming its application both in the study of non-pathological and pathological movements.

The first step of the methodology comprehends the definition of the mechanical system and its relation with the optimal control problem (OCP) to solve. Both the state ($\mathbf{y}$) and control ($\mathbf{u}$) variables, which represent respectively the generalized coordinates of the biomechanical system ($\mathbf{q}$) and the internal forces ($\mathbf{f}_{int}$) and joint torques ($\boldsymbol{\tau}$), are treated as variables to optimize during the simulation ($\mathbf{x}$). In order to decrease the complexity of the problem, the OCP is translated into a nonlinear programming problem (NLP) by considering a discretization step. The variables are also interpolated using B-Splines and its coefficients ($\mathbf{C}$) used as the variables to optimize ($\mathbf{X}$). The proposed methodology considers also the substitution of the state variables ($\mathbf{Y}$) by the system drivers, namely angular and translational drivers, instead of optimizing directly the generalized coordinates. This step allows to reduce significantly the number of variables, as the number of DOFs is considerably lower than the number of coordinates. The generalized coordinates ($\mathbf{q}$), velocities ($\dot{\mathbf{q}}$) and accelerations ($\ddot{\mathbf{q}}$) are posteriorly computed during the simulation by performing a kinematic analysis for each optimization step. On the other hand, the control variables ($\mathbf{U}$) will represent directly the Lagrange Multipliers ($\boldsymbol{\lambda}$). The equations of motion (EOM) for a constrained system, as well as other path constraints, will be treated as equality or inequality constrains of the optimization problem. Finally, the last step considers the definition of the optimization inputs, namely the number of nodes, time vector ($\mathbf{t}$), initial and final state of the mechanical system ($\mathbf{q}_0$, $\dot{\mathbf{q}}_0$, $\mathbf{q}_T$, $\dot{\mathbf{q}}_T$), boundaries for the state and control variables ($\mathbf{X}_{LB}$ and $\mathbf{X}_{UB}$) and initial approximation ($\mathbf{X}_0$).

The assessment of the methodology will be made by applying it to the study of two different biomechanical models, a simplified arm model with 7 DOFs and a full-body model. The first model will be used to evaluate the applicability of the methodology in a simple model, by studying different arm movements and comparing it with experimental data. It will be also used to analyze the influence of the different optimization strategies (simple, weighted and multi-objective), weights and cost functions (dynamic effort, mechanical energy, trajectory control, feasible solution, etc.) considered in this study. The second model will be used to assess the methodology while simulating complex models with larger number of DOFs. For running the simulation, two different software are considered. *Apollo,* an in-house 3D multibody dynamics software with natural coordinates, will be used to model the biomechanical system from a multibody perspective and to evaluate the EOM [7]. The optimization problem will be solved recurring to the optimization library available in the MATLAB software.

Preliminary results obtained for the arm simplified model indicate that the methodology can depict with success the movement in study, allowing simultaneously the computation of the internal forces and joint torques. The comparison with results obtained experimentally allows to observe a similar pattern both for the kinematic and dynamics patterns (see fig. 1). The system allow to converge for an optimal solution for the simple, weighted and multi-objective functions, varying slightly in the number of iterations and computational times. The results indicate also that objective functions based on dynamic effort criteria produce good predictions, especially when applied in the study of human movement, as suggested in [8].



Fig, 1: Simulation of the catch an object movement for the simplified arm model, considering a multi-objective strategy with a dynamic effort criteria and trajectory control (experimental – black, simulation – red): a) Coordinates along the time; b) Torque at the elbow.

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