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Influence of the controller design on the accuracy of a forward dynamic simulation of human gait

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ABSTRACT

The analysis of a captured motion can be addressed by means of forward or inverse dynamics approaches. For this purpose, a 12 segment 2D model with 14 degrees of freedom is developed and both methods are implemented using multibody dynamics techniques. The inverse dynamic analysis uses the experimentally captured motion to calculate the joint torques produced by the musculoskeletal system during the movement. This information is then used as input data for a forward dynamic analysis without any control design. This approach is able to reach the desired pattern within half cycle. In order to achieve the simulation of the complete gait cycle two different control strategies are implemented to stabilize all degrees of freedom: a proportional derivative (PD) control and a computed torque control (CTC). The selection of the control parameters is presented in this work: a kinematic perturbation is used for tuning PD gains, and pole placement techniques are used in order to determine the CTC parameters. A performance evaluation of the two controllers is done in order to quantify the accuracy of the simulated motion and the control torques needed when using one or the other control approach to track a known human walking pattern.

1. Introduction

Human gait dynamics has been amply studied using multibody dynamics techniques. Depending on the purpose of the study, these techniques can be used either to analyze a known motion using inverse dynamics or to simulate the motion from joint or muscle forces through forward dynamics [1]. More precisely, the inverse dynamic analysis (IDA) is used to calculate internal joint forces and torques using acquired kinematic and kinetic data, and estimated body segment parameters. On the other hand, the forward dynamic analysis (FDA) is used to obtain the motion of the musculoskeletal system as a consequence of the applied forces and torques, and given initial conditions. One advantage of the FDA is that it allows the simulation or prediction of the actual behavior of the system from a given set of input actuations (at the muscle or joint

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level) and system parameters. Therefore, this tool might serve to anticipate, e.g., the subject's motion after a surgery or when assistive devices are used.

In an ideal case, if the results of the IDA are used as inputs of the FDA, the motion obtained through the forward simulation should match the original captured motion: as long as the inverse and forward models are the same, the results should be close to each other. However, since the forward simulation requires a numerical integration procedure, some differences appear between the captured kinematics (input of the IDA) and the simulated motion (output of the FDA). This discrepancy can be related to the integration approach and the time steps used, the interpolation schemes (needed in variable time-step algorithms), the kinematic constraint stabilization method (if it is present) or the method used to solve the differential–algebraic equations system [2]. Therefore, the use of control algorithms is necessary to ensure stability and robustness in human gait forward dynamics simulation.

In recent years, new methods for efficient control of the musculoskeletal system dynamics using optimal control methodologies have been presented [3–5]. Moreover, a growing interest in motion prediction has appeared [6,7]. In these approaches, the basic idea is to use optimization methods to identify both force and kinematic histories based on the available information of the dynamic system. A nonlinear optimization is formulated based on the physics of the motion (dynamic equations of motion), where the objective function includes terms related to the physiology of muscle actuation and might include terms related to the aesthetics of the predicted motion as well. This function is minimized subject to some constraints; for example, dynamic equations of the musculoskeletal system, task or motion constraints, etc.

Using this type of techniques often implies a trial-and-error process, in which selecting the variables defining the motion and the drive efforts, the cost function terms (and their associated weight factors), and the appropriate physiological criteria represents a great challenge. Moreover, the use of such optimization algorithms requires several function evaluations; and, in the case of forward dynamics-based optimization, each evaluation requires the forward simulation of the complete motion. Those techniques need an appropriate controller to stabilize the simulation and, therefore, the control approach used must be robust to perturbations and efficient in terms of computational simulation time. This paper analyzes the influence of two control strategies on the accuracy of the forward simulation of human walking, without focusing on their implementation in optimization approaches.

When the FDA of a captured motion is carried out, a dynamic inconsistency between experimental ground reaction forces and model kinematics, obtained from experimental markers, appears. Usually researchers have attempted to avoid this problem using controls on the system in order to stabilize the dynamics [8]. Those controls represent a set of non-physical forces accounting for the mentioned inconsistency, which are usually referred to as residual wrench (force and torque). This wrench is composed by linear and rotational actuators that control the absolute degrees of freedom of the model base body (pelvis or trunk in most cases).

Investigation of the real control mechanisms of muscles, that apply to reflexes or controlled motion by the central nervous system, is still a wide open subject of research in biomechanics and neurophysiology. An appropriate control to generate a forward dynamic simulation consistent with the locomotor task has not been clarified yet [2]. In the literature, there are two main approaches to face this challenging problem: following an underactuated methodology or using fully controlled biomechanical models, in which all degrees of freedom are actuated.

The first approach is based on the principle that the human body is not a fully actuated system, but an underactuated one. Using this methodology, the actuators can only be associated to human joints and, therefore, a control on the six degrees of freedom of the base body cannot be applied. In order to represent the foot–ground interaction researchers use a force model or a constraint methodology. This is a challenging area of research and studies following this approach employ very simple models based on passive dynamic walking to explore the natural dynamics of two-legged mechanisms (compass walker, 3-segment model, etc.) [9–11]. Another example using underactuation can be found in [12] for a jumping exercise.

In contrast, when a complex full-body model is required, authors usually propose the use of fully controlled biomechanical models, in which all degrees of freedom are actuated. For example, the Residual Reduction Algorithm (RRA) proposed in [8] is a form of forward dynamics simulation that utilizes a controller to track model kinematics (obtained experimentally) with the aim of reducing the residual wrench (usually defined between the pelvis and the ground) to the absolute minimum that is necessary to closely follow the desired kinematics. Therefore, the external force and torque are reduced, but not eliminated, and the system is fully actuated. Moreover, the authors of [2] proposed the use of a PD control to overcome the lack of correlation between forward and inverse dynamic analyses. In this work, all the degrees of freedom are controlled as well, and the base segment is the pelvis. A similar approach was used in [13] with the purpose of demonstrating a computationally efficient, three-dimensional, torque actuated and forward-dynamics based model of gait, that had the potential of predicting functional outcomes of orthopedic surgeries to the musculoskeletal system. Finally, the authors of [14] proposed to combine a PD controller for each body joint together with a balanced gait controller achieved by externally manipulating the pitch of the HAT (head, arms and trunk) segment.

In the present work, the fully controlled approach is used and the controllers driving the absolute position and orientation of the trunk are associated to the above-mentioned residual wrench. According to [14], if the model is not supported or balanced by any artificial means, poorly chosen trajectories can overwhelm the balance controller, causing the model to fall.

In the robotics field, experimental results show that the computed torque controller has very good performance characteristics and it is becoming increasingly popular [15]. However, the PD control is by far the most common control