Forward dynamics of human gait based on control techniques

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Abstract

The prediction of human motion through computer simulation is a tool that can be useful to anticipate the result of surgery or to assist the mechanical design and control of prosthetic or orthotic devices. The latter is the main motivation of a research project that is being developed by the authors, whose main objective is the design of an innovative active stance-control knee-ankle-foot orthosis (SCKAFO) aimed at assisting the gait of incomplete spinal cord-injured subjects [1].

The problem of human gait prediction is in general approached through optimization methods. Different approaches can be found in the literature depending on the selected cost function and design variable, which can be the motion, the actuation or both (hybrid approach) [4]. Nevertheless, regardless of the approach used, the implementation of such methods raises great difficulties, both from the convergence and the computational efficiency points of view, besides the inherent uncertainty when proposing the most adequate cost function.

Due to the mentioned difficulties, the authors have decided to approach first the analysis of a known human gait motion through forward dynamics. That problem presents less uncertainty and can serve as an intermediate step towards the prediction problem, since it requires dynamics consistency as well, but does not suffer from the same high amount of uncertainty.

A systematic state-of-the-art study of the existing alternatives to obtain, using forward dynamics, the joint efforts that produce a certain known motion has been done. This problem can be approached using optimization algorithms or control techniques. The latter have been chosen due to their higher efficiency, their lower complexity and their simpler applicability to the prediction problem.

The human body is modelled as a 3D multibody system formed by rigid bodies. The biomechanical model used consists of 18 anatomical segments (2 hindfeet, 2 forefeet, 2 shanks, 2 thighs, pelvis, torso, neck, head, 2 arms, 2 forearms and 2 hands). The segments are linked by spherical joints and, therefore, the system has a total of 57 degrees of freedom (DOF). The subject selected to perform the experiments is a healthy adult male, 27 years old, mass 80 kg and height 1.75 m. He walks on a walkway that encloses two force plates (AMTI AccuGait sampling at 100 Hz). The motion is recorded by 12 optical cameras (NaturalPoint OptiTrack FLEX:V100 also sampling at 100 Hz), that compute the position of the 37 passive markers attached to the subject, Figure 1(a).

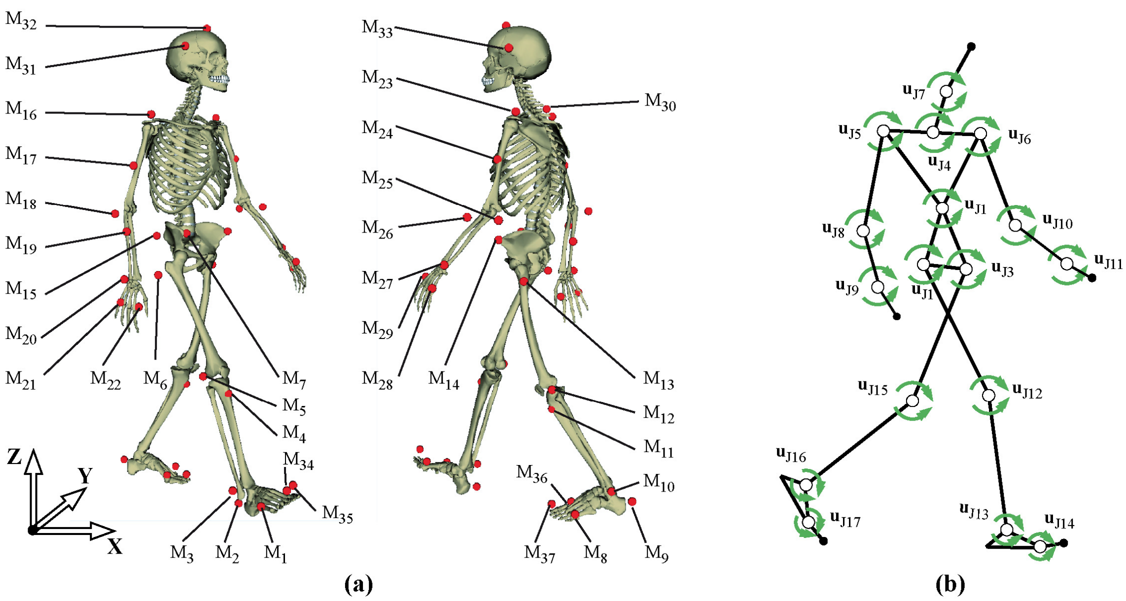

Figure 1: (a) Markers used to capture de motion. (b) Actuation torques applied to the biomechanical multibody system.

Initially, the authors have assumed that all the 57 DOF of the computational model of the subject, whose motion has been recorded, can be actuated. Based on this hypothesis, the following forward dynamics approaches have been implemented [2]: a) apply as actuation efforts those calculated by means of inverse dynamics (computed feedforward); b) use a PD control with computed feedforward; c) use a computed torque control (CTC).

In the next step, the authors have considered that only the 51 DOF corresponding to the subject joints can be actuated (Figure 1(b)), that is, the 6 DOF of the base segment (usually the pelvis or the stance foot) cannot be actuated, as it happens in reality. This involves the use of a foot-ground contact model to characterize the body-ground interaction. In this case, the multibody system is underactuated [3] and a CTC-like technique has been applied to control the motion.

The equations of motion using a minimum number of coordinates **z** can be written as:

$$\mathbf{M}\ddot{\mathbf{z}} = \mathbf{Q} + \mathbf{B}\mathbf{u} \tag{1}$$

where **M** is the mass matrix of the system, **Q** is the generalized force vector associated to the independent coordinates, **u** are the actuation efforts applied to the joints, and **B** projects these actuations to the 57 coordinates **z**. The 51 driven coordinates **y** are selected from vector **z**. The relation between **y** and **z** can be expressed using the constant matrix **H**:

$$\mathbf{y} = \mathbf{H}\mathbf{z} \tag{2}$$

Then, from Eqs. (1) and (2):

$$\ddot{\mathbf{y}} = \mathbf{H}\mathbf{M}^{-1}\left(\mathbf{Q} + \mathbf{B}\mathbf{u}\right) = \mathbf{H}\mathbf{M}^{-1}\mathbf{Q} + \mathbf{H}\mathbf{M}^{-1}\mathbf{B}\mathbf{u} \tag{3}$$

Therefore, vector **u** can be obtained as:

$$\mathbf{u} = \left(\mathbf{H}\mathbf{M}^{-1}\mathbf{B}\right)^{-1}\left(\ddot{\mathbf{y}} - \mathbf{H}\mathbf{M}^{-1}\mathbf{Q}\right) \tag{4}$$

In this work, a CTC-like method is used to control the system. The control scheme can be expressed as:

$$\ddot{\mathbf{y}} = \ddot{\mathbf{y}}_{\text{ref}} + \mathbf{C}_1\left(\dot{\mathbf{y}}_{\text{ref}} - \dot{\mathbf{y}}\right) + \mathbf{C}_2\left(\mathbf{y}_{\text{ref}} - \mathbf{y}\right) \tag{5}$$

where $\mathbf{y}_{\text{ref}}$, $\dot{\mathbf{y}}_{\text{ref}}$ and $\ddot{\mathbf{y}}_{\text{ref}}$ are the reference position, velocity and acceleration vectors, $\mathbf{C}_1$ is a velocity gain matrix and $\mathbf{C}_2$ is a position gain matrix. Combining Eqs. (4) and (5), the control actuation can be determined as:

$$\mathbf{u} = \mathbf{P}^{-1}\left(\ddot{\mathbf{y}}_{\text{ref}} + \mathbf{C}_1\left(\dot{\mathbf{y}}_{\text{ref}} - \dot{\mathbf{y}}\right) + \mathbf{C}_2\left(\mathbf{y}_{\text{ref}} - \mathbf{y}\right) - \mathbf{H}\mathbf{M}^{-1}\mathbf{Q}\right) \tag{6}$$

where $\mathbf{P} = \mathbf{H}\mathbf{M}^{-1}\mathbf{B}$. The driven coordinates are properly selected from **z** to obtain a nonsingular **P** matrix. Moreover, in order to avoid instabilities spring-damper elements are added to the free coordinates (non-driven coordinates). This model-based control method has been implemented and, as a validation, the obtained motion has been compared with the one captured in the laboratory.

References

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