Modeling and computational issues in the inverse dynamics simulation of human movements

Wojciech Blajer, Krzysztof Dziewiecki and Zenon Mazur*

Institute of Applied Mechanics and Power Engineering, Faculty of Mechanical Engineering, Technical University of Radom
ul. Krasickiego 54, 26-600 Radom, Poland
e-mails: w.blajer@pr.radom.pl; krzysztof.dziewiecki@pr.radom.pl; z.mazur@pr.radom.pl

Abstract

With reference to a planar human body model composed of 14 rigid segments connected by 13 hinge joints, branching from the hip joint in the open loop linkages, the modeling and computational issues related to the inverse dynamics simulation of sagittal plane movements like running, walking and jumping are discussed. Two models of control are considered: a determinate one with joint torques as control parameters that represent the muscle action in the joints, and an indeterminate one with a mix set of muscle stresses as controls in the lower extremity joints and the joint torques in the upper part of the body. Using the dynamic equations of motion derived either in absolute or independent coordinates, a discussion is provided on possible solutions to the inverse dynamics analysis. Determination of reaction forces in the lower extremity joints, which involves the influence of muscle forces and external reactions from the ground, are also discussed.

Keywords: biomechanics, multibody dynamics, inverse problems, numerical analysis

1. Introduction

Inverse dynamics simulation is the prevailing non-invasive method for assessment of muscle forces and joint internal loads during human movements, based on human body models and measured kinematic characteristics. Depending on the expected exactitude and scopes of the analysis, the human body (or its part) can be modeled using different methodologies and ranges of approximation of its very complex mechanical structure and actuation, and numerous computational tools for the inverse dynamics simulation can be applied [1-4]. In this contribution we discuss these issues with reference to a planar model seen in Fig. 1, aimed at the determination of muscle forces and joint reactions in lower limbs during sagittal plane movements such as running and jumping. The model consists of $N = 14$ segments connected by $k = 13$ ideal hinge joins. Considered the model as a *flier*, its number of degrees of freedom is $r = 3 + k = 16$. The *flier* can then contact the ground, which yields external (reaction) forces on the system.

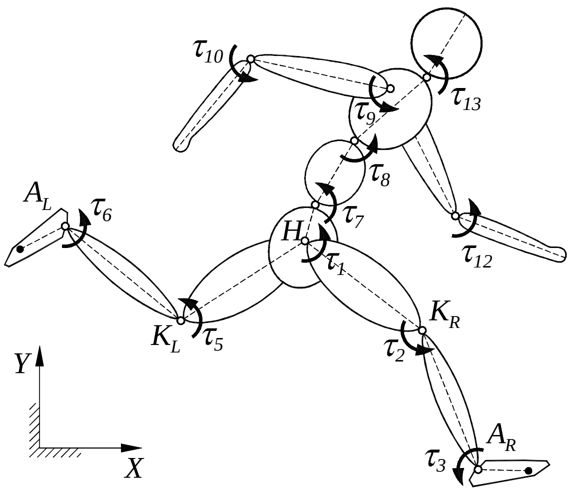

Figure 1: The torque-actuated human model

2. Modeling issues

An important feature of the present modeling methodology is that a unified formulation for the inverse dynamics study can be developed, which holds irrespectively of the system flies or contacts the ground. The other relevant modeling issues are the following.

2.1. Dynamic equations

Dynamic equations of the *flier* can be introduced either in $3N = 42$ absolute coordinates that specify locations of the mass centers and orientations of the segments with respect to an inertial frame or in $n = 16$ independent coordinates. The first (maximal-dimension) formulation, though conceptually simpler when modeling, involves $l = 26$ reaction forces due to the joint kinematical constraints. The (reduced-dimension) formulation in independent coordinates is free from the constraint reactions. It is mathematically more involved, however. Advantages and disadvantages of these two formulations will be discussed.

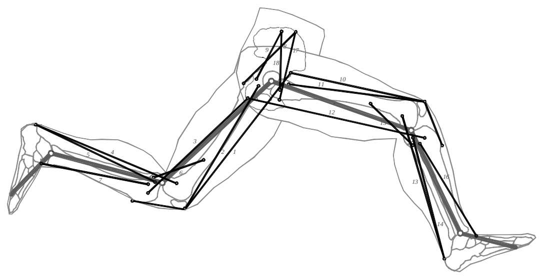

Figure 2: Muscles in the lower limbs

2.2. Models of actuation

Two models of actuation are considered: by means of $k = 13$ torques that represent the resultant muscle action in the joints (Fig.1), and by means of a mix set of $m_\sigma = 18$ muscle stresses in the lower limbs (Fig. 2) and $m_\tau = 7$ control torques in the upper body joints, $m = m_\sigma + m_\tau = 25$, which was first

*The work was financed in part from the government support of scientific research for years 2010-2012, under grant No. N N501 156438.

introduced in [5]. In the latter case of actuation, the attention is focused on more detailed analysis of internal loads in lower limbs, while retrieving the dynamic interaction between the upper body and the locomotion apparatus.

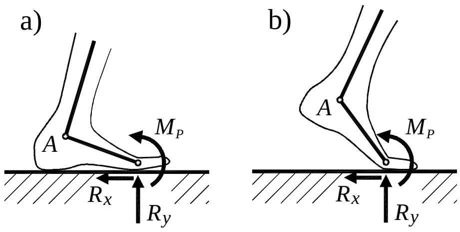

Figure 3: Reactions from the ground

2.3. External reactions

The external reaction components exerted on a foot in contact with the ground are modeled by 3 components, R_x, R_y and M_P, reduced to point P as seen in Fig. 3. Respective (appropriately modeled) generalized constraint force vectors must then be added in the dynamic equations of the *flier*. The provided generic formulation comprises possible flight phases (no contact with the ground, and vanishing reactions from the ground) as well as single and double support phases.

3. Computational issues

The developed human body model, after identification of its inertial and geometric (anthropometric) parameters, can be used for the inverse dynamics simulation of different sagittal plane movements such as walking, running and jumping. The input data to the simulation are measured kinematic characteristics of the analyzed movement. Depending on the model of actuation, the problem appears either determinate or indeterminate.

3.1. Determinate inverse dynamics problem

It relates to the actuation model by means of resultant muscle torques. Applying the prescribed motion characteristics, from $3N = 42$ dynamic equations in absolute coordinates one can explicitly determine the involved $k = 13$ muscle torques, $l = 26$ joint reactions, and 3 external reactions. Seemingly, from $n = 16$ dynamic equations in independent coordinates, the muscle torques and external reactions are available, and the joint reactions can afterwards be found. Evidently, in the flying phase the determined ground reactions should vanish, which can be treated as a criterion for accuracy of the input data used and correctness of the developed human model and its parameters identification. Then, in the double support phase, if happened, some relationships between the external reaction forces on the two feet or additional dynamic input data from measurements are required to keep the problem determinate.

3.2. Indeterminate inverse dynamics problem

It is also called a redundant problem in biomechanics [1-4], and relates to control overactuation in the joints if muscle forces are introduced as independent actuators. The problem is usually solved using appropriate optimization techniques that apply some predetermined criteria to share the muscular joint torques into the individual muscle efforts. For the present mixed model of actuation, the redundancy is limited to lower limb joints only, which yields some modeling peculiarities reported previously in [5]. An improved formulation of this type is motivated in this contribution, and some computational issues are discussed.

3.3. Determination of joint reactions

The joint reaction forces obtained from the determinate inverse dynamics analysis are not reliable since, by applying the resultant muscle torques instead of muscle forces, the contribution of tensile muscle forces to the internal loads is lost. An effective computational schemes are introduced which allow one for the determination of corrected joint reactions selectively in the lower limb joints.

4. Concluding remarks

In the full paper, precise mathematical formulations that involve the above modeling issues will be developed and discussed from the viewpoint of effectiveness and correctness of the inverse dynamics simulation. Some results of numerical simulations will be reported to illustrate the theoretical considerations.

Many further modeling issues can also be pointed out, yielding appropriate modifications in the mathematical formulations. For example, a model composed of two legs attached to a base body (whose motion is specified) can also be introduced. In that case, however, the ground reactions on the feet must be either known (measured) or set to zero (in the flying phase). Of fundamental importance is also modeling of muscles and tendons, related to their paths and attachment points as well as the passive and active properties (the way the tensile forces are generated) [6]. The extreme complex mechanical structure and actuation of human body provide extreme variety of issues for the modeling improvements.

References

[1] Yamaguchi, G.T., *Dynamic Modeling of Musculoskeletal Motion. A Vectorized Approach for Biomechanical Analysis in Three Dimensions*, Kluwer, Dordrecht, 2001.

[2] Pandy, M.G., Computer modeling and simulation of human movement, *Annual Review of Biomedical Engineering*, 3, pp. 245-273, 2001.

[3] Winter, D.A., *Biomechanics and Motor Control of Human Movement*, Wiley, Hoboken, 2005.

[4] da Silva, M.P.T. and Ambrósio, J.A.C., *Human motion analysis using multibody dynamics and optimization tools*. Technical Report IDMEC/CPM – 2004/001, Lisbon, 2004.

[5] Blajer, W., Dziewiecki, K., and Mazur, Z., Multibody modeling of human body for the inverse dynamics analysis of sagittal plane movements, *Multibody System Dynamics*, 18, pp. 217-232, 2007.

[6] Blajer, W., Czaplicki, A., Dziewiecki, K., and Mazur, Z., Influence of selected modeling and computational issues on muscle force estimates, *Multibody System Dynamics*, 24, pp. 473–492, 2010.