Multibody dynamic approaches in modeling and analysis of biomechanical systems for human motion and injury assessment

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Abstract

The construction of the biomechanical models suitable to the human motion analysis requires the use of a formulation to describe their dynamic equilibrium equations. Multibody formulations are suitable for applications to biomechanical modeling as they provide all the required features for the description of the large relative motion between system components and for the dynamic analysis. Due to the limitations on the modeling possibilities associated to different commercial codes the use of biomechanical models for human body motion and for injury assessment are not interchangeable. Examples of this lack of global modeling possibilities are the representation of the anatomical joints by mechanical joints instead of the contact pairs, the muscle actions represented as joint torques instead of the redundant muscle forces, or the point contact between the human segments instead of the distributed contact forces with local compliance between the anatomical surfaces and the environmental surfaces. In this presentation selected methodologies for the analysis of human motion are overviewed with emphasis in the multibody dynamics approaches for the analysis of large motion between moving segments, and finite element procedures for the representation of the local deformations of the physiological structures.

The biomechanical models applied on the study of the human locomotion require that the major anatomical segments of the lower part of the human body are represented by rigid bodies [1]. The anatomical joints are represented either by kinematic joints or by contact joints in the multibody model, depending on the objectives of the analysis [2]. Similarly, the biomechanical models of the upper arm used for the study of manipulation tasks or for the development of shoulder prosthesis, just to name some examples, use the same modeling principles, but do not require that the lower body is modeled [3]. Conversely, in impact biomechanics studies, as those used to design the vehicle interiors

for occupant protection during crash events, the importance of the detailed description of the anatomical joints is limited being more important that the models can handle the whole body dynamic response [4]. In some applications, such as those involving injuries at the spine level, it is important to involve the deformation of some structures such as the intervertebral disks. However, the dynamic coupling between the large rigid body motion of the body structural segments and their structural deformations is negligible and, consequently, the kinetostatic approach can be used for the solution of these cases.

The ligaments and other passive tissues required to provide stability or stiffness to the anatomical joints are typically represented by mechanical elements such as spring-dampers with linear or nonlinear characteristics. The muscles of the locomotion or upper arm apparatus are required in the models used for motion coordination tasks, but not necessarily for impact biomechanics. A Hill type muscle model is applied, being the force produced by the muscle contractile element calculated as a function of the muscle activation, maximum isometric peak force, muscle length and muscle rate of shortening [1, 3]. It is shown how muscle databases are used to infer on the muscle actions in the human body for both coordination tasks, in which the muscle contraction is voluntary, and on impact, where the muscle contraction is reflexive, or involuntary. It is shown that the former problem involves the solution of an indeterminate muscle force sharing problem in which the unknown muscle forces are evaluated based on an optimization problem where the objective is to minimize a given physiological criteria, such as energy or stability [1, 3]. It is also shown that in the later problem, due to the speed at which impact occurs, no voluntary muscle contractions are possible and only the reflexive muscle contraction is used by the body defense mechanism to stiffen the kinematic joints of the human body. In any of the cases, the muscle data and the anatomical segments characteristics are collected in a general database and scaled for the subject dimensions and total body mass.

In the case of human coordination tasks, the biomechanical model is driven through an acquired motion by two different types of kinematic constraints: joint actuators, that drive the degrees-of-freedom of the biomechanical model associated with joints, and muscle actuators that drive the degrees-of-freedom of the joints crossed by the muscles. Typically, inverse dynamic approaches are used to address muscle coordination tasks. When the aim of the analysis is to calculate net moments-of-force of particular joints only the joint actuators need to be used and the solution to the dynamics problem is unique and non-redundant. When the aim is to evaluate the muscle forces it is required the use of muscle actuators in the biomechanical models and the system becomes redundant. In the case of impact dynamics the typical approaches are based on forward dynamic analysis, in which the interaction forces and the internal stimulus on the muscles drive the motion of the biomechanical model.

Based on the typical applications of multibody and finite element modeling of human motion biomechanical models several challenges are identified. The description of the contact between the internal structures of the human body, as in the anatomical joints, or between the anatomical segments and the environment, such as the feet contact with the ground, pose some of the interesting problems in biomechanics [2]. Not only the predictability of the models influences the evaluation of the intersegment forces and stresses but they also condition the appraisal of the muscle forces. The identification of the objectives of the human motion that can be used in motion coordination analysis, such as in gait, is still an open issue. Although criteria base on minimal energy are widely used it is recognized that often the minimization of pain or the maximization of stability are important criteria. In impact studies not only the minimal requirements for representative models of the human body are still being discussed but also the criteria for injury assessment is dependent on the type of application, although the human body is the same. Many issues concerning the influence of the internal active structures of the human body, such as the muscle actions, are still topics of discussion in what concerns the correct level of modeling required by representative biomechanical models.

Keywords: Muscle forces, joint reaction forces, shoulder model, locomotion apparatus model, gait analysis.

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