A DYNAMIC CAUSAL SYSTEM SIMULATION APPROACH FOR ANATOMIC JOINTS

Ruth Leskovar

E101 – Institute of Analysis and Scientific Computing

MOTIVATION AND INTRODUCTION

This contribution presents a closed simulation loop for biomechanical models. This is an interdisciplinary task, since first a biomechanical model is formulated and afterwards this model is represented as dynamic system. Modelling and simulation is an important method in the field of biomechanics to analyse interactions in the human body. The knowledge of the influence of individual parts of the musculoskeletal system is necessary for treatment of diseases. Furthermore, mathematical models of parts of the human body are indispensable in the development of prostheses. Among several methods exist to model a biomechanical system, mainly two modelling approaches are used to describe these systems mathematically, partial differential equations (PDEs) and multibody models which are based on ordinary differential equations (ODEs). Both descriptions can be formulated as dynamic systems which allows to design closed simulation loops for biomechanical models. This extends possible applications and usage fields for biomechanical models as well as their influence in technology and research.

CASE STUDY – THE HUMAN KNEE JOINT

As case study, the human knee joint is a suitable starting point due to its complex structure which is a result of the interaction between rigid components as bones and soft tissues as ligaments, tendons as well as cartilage. A simplified simulation model for the flexion of the human knee joint was implemented using Simscape, the multibody library in Simulink, and COMSOL Multiphysics. The conceptual model is based on the work of Guess, Bloemker et al. [1], [2], [3].

The model contains the three main bones of the human knee, the femur, the tibia and the patella. The bones are implemented as rigid bodies and linked by two revolute joints. The patellar tendon, which attaches the patella to the femur, is implemented as linear spring-damper element. The input for the knee model is the acting force at the tibia which results in the flexion of the tibia and patella in relation to the femur. The output of the model is the angle between femur and tibia. The motion between the bodies resulting from an external force F can be described with a second order ODE [4]:

$$M\ddot{x} + J_x^T \lambda = F. \tag{1}$$

Here, M describes the mass matrix of the system, the vector x denotes the system coordinates, the matrix J_x is the Jacobian matrix of the system coordinates and λ represents the vector holding the Lagrange multipliers.

Although both simulation models are implemented using the same conceptual model, the solution is calculated in Simulink using ODE solver and in COMSOL using the finite element method. This leads to the question if both models can be described as dynamic systems. The states x in dynamic systems can be described by an ODE, dependent on time t, acting inputs u, parameters p and initial values x_0:

$$\dot{x}(t) = f(t, u(t), x(t), p), \quad x(0) = x_0. \tag{2}$$

The investigation of both simulation models as dynamic systems allows the design of closed simulation loops. This allows a flexible handling of the biomechanical models to different applications on the one hand and a comparison between different mathematical descriptions of biomechanical models on the other hand. As it is illustrated in Figure 1, a closed simulation loop with one degree of freedom is designed for both simulation models as plant. The simulation loop is implemented in Simulink which gives the opportunity to use its powerful control tools.

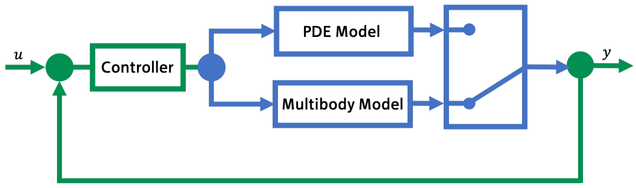

Figure 1: Design of a closed simulation loop for different biomechanical models.

Due to the structure of the multibody model in Simscape, it is possible to define it as subsystem in Simulink and to design suitable closed loops without additional reformulations. The simulation model in COMSOL needs restrictions before it is possible to use as plant in Simulink. The dependency on time and space as well of the solution of the COMSOL simulation model requires to investigate the solution on specific points only. Ultimately, this gives various possibilities of extracting state-space representations of the COMSOL model [5].

CONCLUSION AND OUTLOOK

This work shows possibilities of representing biomechanical models as dynamic systems. This allows to use simulation models of anatomic joints as plants in closed simulation loops. Finally, it was possible to describe both models using the state space representation which allowed to use the same design of closed simulation loops. Nevertheless, disparate behaviour of the simulation models in the closed loop can be observed which is a result from their different mathematical description.
Further work will focus on the specification of the biomechanical model, e.g. ligaments will be included as non-linear spring damper elements to analyse more complex system behaviour. Moreover, the already established loop design focuses on constant reference signals. More sophisticated reference signals, the definition of a trajectory e.g., allows to simulate more realistic motion behaviour and can apply this work for gait analysis.

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