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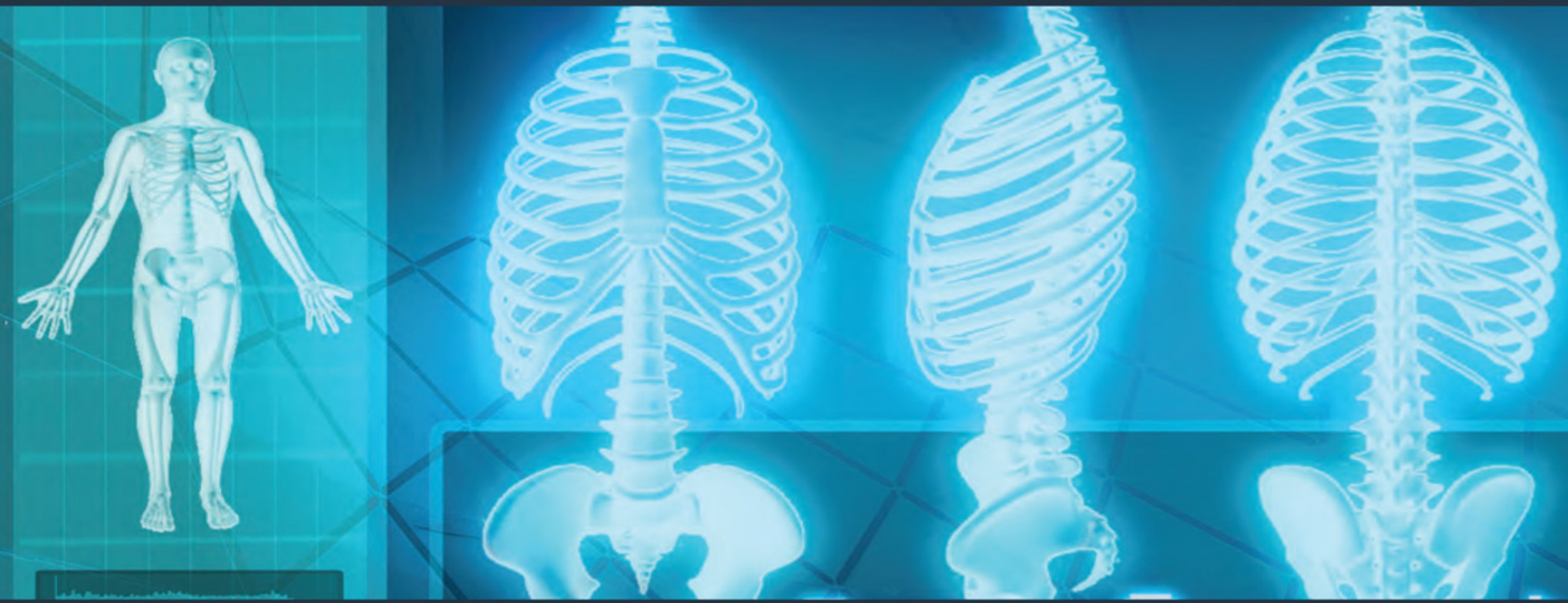

Biomechanics of the Musculoskeletal System

Modeling of Data Uncertainty and Knowledge

Tien Tuan Dao
Marie-Christine Ho Ba Tho

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Preface

Biomechanics of the musculoskeletal system covers a large range of research topics using experimental and numerical approaches. *In silico* numerical models have usually been developed to describe the mechanical behavior of the musculoskeletal system under internal and external loadings. Such models allow us to better understand the mechanical behavior of the different components of the musculoskeletal system (joints, organs, tissue, etc.) and their interaction. Moreover, knowledge obtained from *in silico* model analysis and simulation could be used to help clinicians and/or engineers in their decision-making process for diagnosis, treatments, follow-ups as well as technology development for health care and bioengineering.

However, biomechanical data, used as input data of *in silico* models, are subject to uncertainties due to subject variability, technical protocol assessing experimental data and subsequently numerical processing methods. As a result, this book provides comprehensive and clear contents of the modeling of data uncertainty and knowledge of the biomechanics of the musculoskeletal system. This book is especially aimed at engineers and medical students interested in the biomedical field.

This book is divided into five chapters. Chapter 1 provides an overview of *in silico* rigid multi-bodies musculoskeletal model. Chapter 2 introduces one of the main topics of this book, the modeling of data uncertainty. Chapter 3 focuses on the knowledge modeling of the musculoskeletal system. Chapter 4 addresses some clinical applications of biomechanical and knowledge-based models for orthopedic disorders. Chapter 5 presents some practical software and tools for knowledge modeling and reasoning purposes.

Tien Tuan DAO
Marie-Christine HO BA THO
February 2014

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Biomechanics of the Musculoskeletal System

The musculoskeletal system plays an essential role in the equilibrium and motion of the human body. Biomechanics of the musculoskeletal system uses physical laws and engineering methods to describe the mechanical behavior of the musculoskeletal system during motion. In this chapter, first, the introduction of biomechanics and related applications is presented. Second, the state of the art of knowledge in biomechanics of the musculoskeletal system, in particular the development of *in silico* rigid multi-body musculoskeletal models and their perspectives, is addressed.

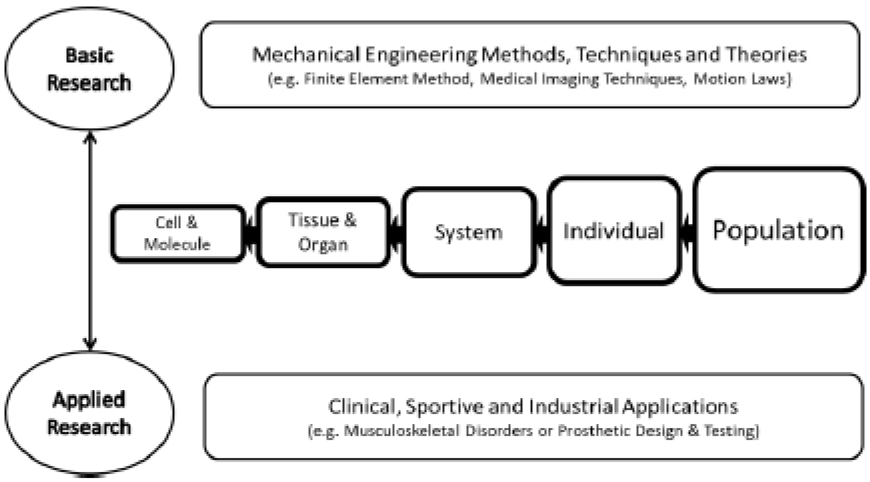
1.1. Biomechanics and its applications

1.1.1. *Introduction*

Biomechanics is a research field which aims to solve biomedical or biological problems by using mechanical engineering methods, techniques and theories [HAT 74, WIN 11]. Living systems such as human musculoskeletal system or cardiovascular system are the main objects of biomechanics research study. Engineering methods range from experimental to numerical approaches. Experimental studies [KEY 65, SHA 01] aim to observe qualitatively and quantitatively the changes of biological tissues (e.g. bone, muscle, cartilage and ligament) or structures (e.g. knee) under normal and abnormal conditions. Experimental studies could be performed *in vivo* and *ex vivo* or *in vitro* conditions. *In vivo* experimentation relates to the study of whole living subject in natural environment. *Ex vivo* or *in vitro* experimentations deal with the testing of tissues isolated outside its biological surroundings of the living organism. Such experimentations are commonly performed in a culture environment. It is important to note that the characteristics and behaviors of a biological tissue/structure *in vivo* condition are completely different from those of the same tissue/structure *in vitro* or *ex vivo* conditions. Moreover, *in silico* numerical studies [REI 02, KIT 02, VEN 06] aim to model and simulate living systems to provide unobservable information of the tissue or structure under investigation such as bone stress under body loading or muscle force during motion. Moreover, numerical studies could be used to test the impact of a clinical treatment procedure (e.g. surgery or functional rehabilitation) or the impact of an implanted device (e.g. prosthesis or orthotic) on the living tissues or structures.

A biomechanics study is commonly performed in response to a basic research question or to depict its potential application for a specific case (e.g. clinical case and industrial case) as illustrated in Figure 1.1. An example of a basic research question could be how to determine the pathophysiological processes of musculoskeletal disorders. Such a basic research question allows us to better understand the functional behavior of tissues and structure. An example of an applied research study could be the application of the finite element method to predict the femoral bone stress when a femoral prosthesis is implanted to optimize the design and fabrication of the investigated prosthesis. In fact, such basic or applied research problems could be solved by using mechanical engineering methods, techniques and theories. Moreover, a biomechanics study relates to single-scale object of study (i.e. cell and molecule, tissue and organ, system, or individual or population) or multi-scale object of study.

Figure 1.1. *Overview of biomechanics field of study*



1.1.2. *Applications in biomechanics*

Biomechanics studies could lead to clinical, sportive and industrial applications. A non-exhaustive list of potential applications is provided below:

– *Virtual muscle-tendon surgeries*: computer-aided modeling using *in silico* rigid multi-body dynamics could allow optimal treatment procedures to be simulated, analyzed and assessed [DEL 97]. An example of such an application is the simulation of the effect of tendon transfer on the joint behavior [RIE 97] or the muscle behavior [ASA 02].

– *Optimal design of biomedical materials and devices*: computer modeling using medical imaging and finite element method could be applied to perform the optimal design of orthopedic, dental and cardiovascular biomaterials [SLO 98]. Moreover, the effect of implanted devices (e.g. braces and prostheses) could also be assessed [PER 02]. Bioartificial devices (e.g. a liver device and a kidney device) could be designed and developed [CAR 09].

– *Assessment of gait abnormalities*: musculoskeletal disorders, such as children with cerebral palsy, have abnormal locomotion functions (e.g. stiff knee flexion). Musculoskeletal models have become customized tools to assess these abnormal functions both qualitatively and quantitatively, leading to the proposal of optimal treatment planning [ARN 01, ARN 04, ARN 05].

– *Computer-aided orbital and maxillofacial surgery*: the outcomes of facial surgery could be predicted using a patient-specific finite element model [LUB 05]. Another example is the simulation of the consequence of a surgical procedure [BUC 07].

– *Detection and prediction of preterm deliveries*: uterine electromyography (EMG) and the data mining method could be used to detect and predict the preterm deliveries, leading to a reduction in the risk of death and disabilities/impairment for premature babies [DIA 09, HAS 10].

– *Performance sportive analysis*: using different biomechanics techniques (e.g. three-dimensional (3D) motion capture, force plates, and surface electromyography), qualitative and quantitative assessments of sportive activities or exercises could be performed in order to improve the performance or prevent the risk of injury for non-professional and professional athletes [CHA 97, SPE 05, BUR 06].

– *Electrical energy harvesting*: a walking model was developed to control a wearable, knee-mounted energy harvester device to produce electrical energy with minimal user effort [KUO 05, DON 08].

– *Early diagnosis of degenerated intervertebral discs (IVD)*: lower back pain is one of the most chronic musculoskeletal disorders. Degenerated IVD is one of the possible causes of this disease. Its early diagnosis could make it possible for a better clinical outcome. Advanced medical imaging (e.g. T2 mapping and diffusion-based magnetic resonance imaging (MRI)) and image processing techniques could be used to analyze and depict the IVD changes at the tissue level, leading to early detection of the degeneration state [HAU 04, DAO 13].

1.2. Biomechanics of the musculoskeletal system: current knowledge

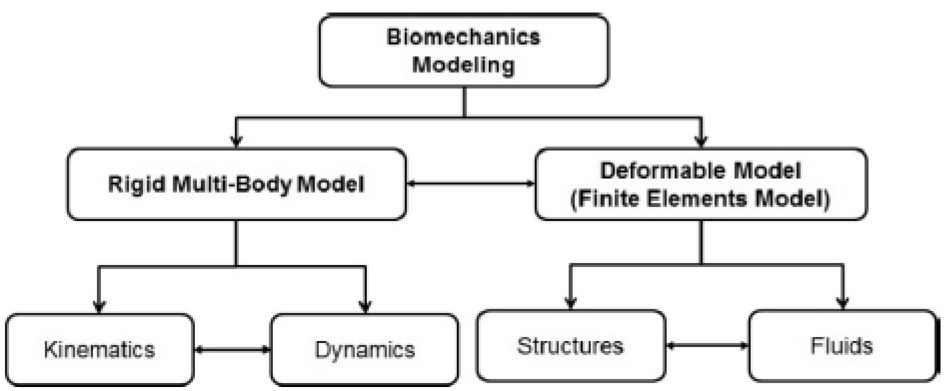
1.2.1. *Introduction*

Biomechanics of the musculoskeletal system is a specific branch of biomechanics, which focuses on the studies of the behavior of isolated tissues and structures (e.g. bones and segments, muscles and tendons, ligaments, cartilage, nerves and joints) as well as on the interaction between these tissues to create stability and motion functions. The objective of such a study is to provide substantial insights into the physiological and pathophysiological processes of the musculoskeletal system in the normal and pathological cases, respectively.

This section aims to describe the current knowledge extracted from basic or applied research studies on the interaction of tissues using mechanical engineering methods, techniques and theories.

Musculoskeletal models are commonly used to study the interaction of tissues. From a mechanical engineering point of view, there are two approaches for developing a musculoskeletal model as illustrated in Figure 1.2. The first approach relates to the rigid multi-body dynamics using tissue properties and Newton's laws of motion to describe the kinematic and dynamic behavior of the musculoskeletal system. The second approach deals with deformable modeling using tissue properties and finite element methods to study the structure interaction with and without fluid consideration under normal and abnormal loading conditions. In this chapter, we focus only on the rigid multi-body modeling. Current knowledge of this modeling approach is addressed in the following section.

Figure 1.2. *Overview of musculoskeletal models and their interaction*



1.2.2. *Rigid multi-body musculoskeletal modeling*

In the framework of rigid multi-body dynamics, a 3D musculoskeletal model could be a generic parameterized model or a patient-specific model. The generic parameterized model uses an available model provided by musculoskeletal modeling software to scale and calibrate all properties for a specific subject. This approach reduces significantly the development time and effort. The patient-specific model uses common medical images to create individualized geometries and properties of the subject/patient under investigation, leading to more accurate simulation results. In fact, the development of a 3D musculoskeletal model requires advanced modeling knowledge and skills. Moreover, this development process is very time-consuming. For these reasons, the use of musculoskeletal modeling software is an efficient solution, especially in the case of clinical application where the decision-making needs to be performed quickly and with minimum effort. The next section addresses commonly used rigid multi-body musculoskeletal modeling software in the scientific community.

1.2.2.1. *Modeling software*

There are many pieces of modeling pieces of software, which could be used to develop generic parameterized or patient-specific musculoskeletal models. The main characteristics of commercial musculoskeletal modeling software are given in Table 1.1. There are three pieces of commercial software (AnyBody, LifeMod and software for interactive musculoskeletal modeling (SIMM)). All these pieces of software allow 3D musculoskeletal models to be developed and analyzed. The setup process of each model could be done through specific scripting language (AnyScript) or graphical user interfaces. Kinematics, kinetics and muscle forces could be computed and analyzed. Only SIMM software allows the real-time simulation to be performed using a motion analysis system. User-specific routines could be developed using automatic dynamic analysis of mechanical systems (ADAMS) script for LifeMod software.

Table 1.1. *Commercial musculoskeletal modeling software*

Characteristics	AnyBody[1]	LifeMod[2]	SIMM[3]
Type	Commercial	Commercial	Commercial
Society	AnyBody Technology (Denmark)	BRG (USA)	MusculoGraphics (USA)
Analysis	3D	3D	3D
Model setup	AnyScript	Graphical user interface	Graphical user interface
Kinematics	Inverse kinematics (skin-based markers)	Inverse kinematics (skin-based markers)	Inverse kinematics (skin-based markers, joint angles)
Kinetics	Inverse dynamics	Inverse dynamics	Inverse dynamics
Muscle model	Hill-based	Closer loop Hill-based	Hill-based
Muscle forces	Static optimization	Static optimization	Static optimization
Real time			Motion Analysis
Individualized model		Bone geometries (CT, MRI)	Bone geometries (CT, MRI)
User routine		ADAMS script	

The main characteristics of open-source musculoskeletal modeling software are given in Table 1.2. These software tools provide two-dimensional (2D) and 3D analysis of the musculoskeletal system. One of the most widely used pieces of open-source software is the OpenSIM. This piece of software provides all programmable libraries and a graphical user interface to develop, simulate and analyze musculoskeletal models during motion. User-specific