UNICUSANO
ROME

Italian code: ING-IND/34 **Credits: 9**
Course: Biomechanical Modelling and Simulation
Main language of instruction: Italian
Other language of instruction: English

Head instructor

Professor Marco GERMANOTTA - marco.germanotta@unicusano.it

Objectives

The course aims to provide students with the expertise to understand and analyze biomechanical models applied to human movement. It focuses on the mathematical tools necessary to study human motion from both kinematic and dynamic perspectives. Additionally, the course covers the fundamental measurement tools essential for capturing key biomechanical variables and introduces effective methodologies for data analysis. Complementing these theoretical aspects, the course incorporates *Etivities* aimed at developing practical skills in formulating and solving biomechanical problems through computational tools and real-world datasets.
Specifically, the course on Biomechanical Modeling and Simulation has the following learning objectives:

a. Illustrate the main data acquisition techniques for human movement analysis
b. Explain clinical nomenclature and key issues related to human movement analysis
c. Demonstrate data analysis techniques using optoelectronic motion analysis systems
d. Explain electromyographic signal generation and surface electromyography signal processing techniques
e. Present key models for human movement simulation
f. Implement codes for solving biomechanical problems.

Course structure

- Introduction to Biomechanics
- Human Movement Representation
- Kinematics
- Localization of Rigid Bodies from Experimental Measurements
- Dynamics

- Gait Analysis and Posturography
- Surface Electromyography
- EMG-Driven Models

Competencies

Expected Learning Outcomes

- Knowledge and Understanding: by the end of the course, students will demonstrate familiarity with both engineering and clinical terminology used in biomechanics, will understand the primary measurement tools and variables in human movement and posture analysis, and will be able to use the main mathematical techniques for processing biomechanical data.

- Application of Knowledge: students will be able to analyze data within a motion analysis lab using the mathematical tools acquired during the course, ensuring accurate biomechanical problem analysis. Through the Etivities, students will apply theoretical problems addressed in lectures to real-world cases using scripts in the Octave environment and real-life data.

- Communication Skills: students will develop a correct and comprehensible scientific language, enabling them to clearly and unambiguously convey the technical knowledge acquired in biomechanics.

- Learning Skills: students will gain the ability to model a biomechanical problem mathematically and solve it.

Syllabus

Module 1 – Introduction to Biomechanics

Topics:

- Introduction to biomechanics
- Measurement tools used in biomechanics
- Recap of vectors: magnitude and unit vector, vector addition and subtraction, scalar multiplication of a vector, dot product, cross product, right-hand rule
- Recap of matrix calculus: addition and subtraction of matrices, transposed matrices, scalar multiplication of a matrix, matrix multiplication, determinants of square matrices, inverse matrices

Module 2 – Human Movement Representation

Topics:

- Anatomical planes
- Classification of joints
- Joint movements: locating a point in space, coordinate transformations, rotation matrices, interpreting rotation matrices
- Representing orientation: rotations around moving axes, Euler/Cardano angles, relationship between Euler/Cardano angles and rotation matrices
- Representing movement: rotations around fixed axes, Roll-Pitch-Yaw angles, relationship between Roll-Pitch-Yaw angles and rotation matrices
- Inverse problem: from rotation matrix to Euler/Cardano angles
- Gimbal Lock
- Quaternions: quaternion algebra, representing rotations with quaternions, relationship between quaternions and Euler/Cardano angles
- Homogeneous transformations, rotation-translation matrices

Module 3 – Kinematics
Topics:

- Kinematic analysis
- Introduction to direct and inverse kinematics
- Direct kinematics: examples
- Inverse kinematics: examples
- Differential kinematics: linear velocities and accelerations, relationships with rotation matrices
- Differential kinematics: angular velocity and relationships with rotation matrices
- Minimal representations of orientation and angular velocity
- Derivatives of Euler sequences
- Minimal representations of orientation and angular velocity: examples

Module 4 – Localization of Rigid Bodies from Experimental Measurements
Topics:

- Acquisition procedures in gait analysis
- Defining local reference systems
- Identifying rigid bodies
- Associating reference systems with rigid bodies
- Localizing a rigid body in space: non-optimal localization (examples)
- Localizing a rigid body in space: optimal localization (examples)
- Standardization proposals in biomechanics for body localization

Module 5 – Dynamics
Topics:

- Introduction to dynamics
- Static analysis: example of elbow equilibrium
- Inverse dynamics: introduction to the problem, Newton-Euler equations
- Direct dynamics: introduction to the problem, Lagrange equations (overview)

Module 6 – Gait Analysis and Posturography
Topics:

- Gait analysis
- The gait cycle
- Measurements obtained during a gait analysis exam: spatial parameters, temporal parameters, joint range of motion, moments, and powers
- Acquisition protocols (overview): Davis, Plug In Gait, CAST
- Posturography
- Sensorimotor system
- Postural stability control
- Posturographic parameters: Center of Pressure (CoP), Center of Mass (CoM), Center of Gravity (CoG), Stabilogram, and Statokinesigram
- Pressure matrix and confidence ellipse

Module 7 – Surface Electromyography
Topics:

- Introduction to electromyography
- Structure of muscles
- Muscle contraction and excitation mechanisms
- Generation of muscle signals
- Signal acquisition: needle and surface electrodes
- Electrical schematization of the electrode-skin complex
- Electrode placement
- Cross-talk and co-contractions
- Artifacts
- Characteristics of the EMG signal
- Differential acquisition of signals (examples)
- Signal processing: pre- and post-processing, normalization
- Parameters derived from the EMG signal: amplitude, frequency, and temporal parameters

Module 8 – EMG-Driven Models

Topics:

- Introduction to Musculoskeletal Models
- Hill model
- Basics of musculoskeletal models
- 2D static problem examples and challenges
- Optimization methods
- EMG-driven models

Evaluation system and criteria

The exam consists of:
(a) a written test and
(b) five activities (Etivities) completed during the course.

Written Test: the written test includes two open-ended questions and three exercises, each divided into multiple sections. Each of the two questions can be graded from 0 to 2 points. The maximum score for the exercises is 24 points, with the distribution of points among the exercises and their sections varying from exam to exam. The maximum points for each section are specified in the exam text. A significantly poor result on any exercise may prevent passing the exam, regardless of the scores obtained on other questions or exercises.

Etivities: only the fifth Etivity contributes to the final score, offering up to 4 points. However, completing all the Etivities is mandatory to access the final test.

Final Grade: the final grade will be calculated by summing the score obtained in the written test with the score from the Etivity. To achieve distinction (*cum laude*), the total score must exceed 30 points.

Bibliography and resources

1. *Materials to consult*
   Notes written by the instructor are available in Italian (part of the notes are also available in English).

2. *Recommended bibliography*
   Suggested readings are:

- Di Prampero, Pietro Enrico, Angelo Cappello, and Aurelio Cappozzo, eds. Bioingegneria della postura e del movimento. Patron, 2003.

- Winter, David A. Biomechanics and motor control of human movement. John Wiley & Sons, 2009.
- Robertson, D. G. E., Caldwell, G. E., Hamill, J., Kamen, G., & Whittlesey, S. Research methods in biomechanics. Human kinetics, 2013.