Biomedical Engineering

Degrees Offered

Doctor of Philosophy*

*In partnership with Marquette University

Program Description

Biomedical Engineering (BME) is an interdisciplinary field that is based on the application of engineering principles and experimental and analytical techniques to the development of biologics, materials, devices, implants, processes and systems that advance biology and medicine and improve medical practice and health care.

The Doctor of Philosophy (PhD) degree in BME is a research degree that is intended to provide the graduate with the breadth and depth of knowledge in one area of specialization within BME, as well as the scientific research training needed for successful careers in academia, biomedical industry, or government. The research training process begins with the student working closely with his or her Dissertation Director and participating in his or her research program. Building on these experiences, the student begins to conduct independent research that eventually leads to an original contribution to the BME field.

Program Admissions Requirements

*In addition to the general **Graduate School admission requirements**, this program has additional specific requirements.*

Graduates of accredited colleges or universities with a Bachelor's or Master's degree in various engineering, physical science, or life science disciplines or equivalent are eligible for admission to the joint MU-MCW PhD Program in BME.

Students who do not have a BME degree are admitted into the PhD program on a conditional status based on successful completion (grade of B or better) of a sequence of leveling courses. These courses will provide them with fundamental engineering principles and analytical skills needed for successful completion of the PhD degree in Biomedical Engineering. See the **Handbook of MU-MCW PhD Program in BME** for details.

Fields of Research

- **Bioinstrumentation**
- **Biomechanics**
- **Biomedical Imaging**

- **Cellular and Molecular Engineering**
- **Computational Biology and Bioinformatics**
- **Rehabilitation Bioengineering**

Program Degree Requirements*

The Doctor of Philosophy degree is conferred in recognition of marked ability and high attainment in the advancement of knowledge and pursuit of truth. The comprehensive knowledge expected of the student in his or her major field is such that the requirements for the degree usually take no less than four years of full-time work, or the equivalent, beyond the baccalaureate degree.

Upon enrolling in the doctoral program in BME, a student selects his or her area of specialization. Faculty will design a curriculum and research program to address the specific goals of each student. Programs will include course work in engineering, biology, mathematics and medicine, all of which will be integrated with research laboratory experience.

The Doctoral Candidacy Examination consists of both written and oral components. Students entering the doctoral program with a master's degree are required to take the written portion within two terms after entering the program. Students entering the doctoral program with a bachelor's degree are required to take the written portion before or at completion of 30 graduate credit hours or completion of the master's degree, whichever comes first. Each student is expected to complete the oral portion by the end of the third year.

A minimum of 60 graduate credits are required to complete the PhD degree in BME. For someone entering with a BS degree, this constitutes 36 credits in didactic coursework, 9 credits in dissertation, and a minimum of 15 credits in reading and research. For those entering with an MS degree or with Graduate credits (see Transfer of Credits Policy), they are required to complete a minimum of 18 credits in didactic coursework, 9 credits in dissertation, and a minimum of 33 credits in reading and research. Pre-requisite courses for applicants who do not have a BME degree are not counted as graduate credits. Reading and research credits can be earned by registering and attending a seminar series, workshop, conference, journal club, or simply carrying dissertation-related activities. A student can register for up to 9 credits of reading and research per semester during fall and spring semesters and up to 6 credits during the summer. Students should register for dissertation credits in the semester they intend to defend their dissertation.

- **Core course requirements** (17 credits): All doctoral students must complete courses that satisfy the following competencies:

  - Systems physiology (3 credits) (e.g. BIOL 5703, BIEN 5700, BIEN 5720, BIEN 6391, MCW Physiol 08204)
  - Biostatistical methods (3 credits) (e.g. MSCS 5720, MSCS 5740, MCW courses: BioStat 04224, BioStat 04231, BioStat 04232, BioStat 04233, BioStat 04363, BioStat 04365)
  - Biomedical signal processing (3 credits) (e.g. BIEN 5510, BIEN 6200, BIEN 6210, BIEN 6220, MCW Biophys 03240)
  - Bioethics (2 credits) (MCW BIOETHICS 10222, MCW BIOETHICS 10444). Both courses (1 credit each) are required for all doctoral students.
  - Advanced engineering mathematics (3 credits) (e.g. EECE 6010, MEEN 6101, BIEN 6500)
  - Computational and simulation methods (3 credits) (e.g. BIEN 5710, BIEN 6620, MCW BIOM 35284, MCW BIOM 35285)

- **Specialization-specific courses** (19 credits): Selected in consultation with the student's Dissertation Director.

PhD students in the BME Department are also required to register for the BME Department seminar series for the duration of their study (BIEN 6953, which counts for 1 credit/semester of reading and research). For a given semester, students are expected to attend at least two thirds of the seminars.

***Please see Biomedical Engineering Handbook for more detailed information**

Overall Courses

BIEN 5220. Embedded Biomedical Instrumentation. *3 credits.*
Fundamentals of digital circuit design and analysis and the application to embedded biomedical instrumentation. Topics include microprocessor principles and programming and system design constraints for medical electronics. Laboratory provides applications of concepts introduced in class.

BIEN 5320. Biomedical Instrumentation Design. *3 credits.*

Problems in instrumentation relating to physiological measurements in the laboratory and clinic. Electronic devices for stimulus as well as measurement of physiological quantities. Design of actual instruments. Features include mechanical design, accessory design and safety requirements.

BIEN 5400. Transport Phenomena. *3 credits.*

Applications of mass, momentum, and mechanical energy balances to biomedical fluid systems. Study of physiological phenomena with an emphasis on cardiovascular systems and blood rheology.

BIEN 5420. Biomaterials Science and Engineering. *3 credits.*

Designed to introduce the uses of materials in the human body for the purposes of healing, correcting deformities and restoring lost function. The science aspect of the course encompasses topics including: characterization of material properties, biocompatibility and past and current uses of materials for novel devices that are both biocompatible and functional for the life of the implanted device. Projects allow students to focus and gain knowledge in an area of biomaterials engineering in which they are interested. Prereq: MEEN 2460 or cons. of instr.

BIEN 5500. Medical Imaging Physics. *3 credits.*

Examines how light, X-rays, radiopharmaceuticals, ultrasound, magnetic fields, and other energy probes are generated and how they interact with tissues and detectors to produce useful image contrast. Addresses practical issues such as beam generation, dose limitations, patient motion, spatial resolution and dynamic range limitations, and cost-effectiveness. Emphasizes diagnostic radiological imaging physics, including the planar X-ray, digital subtraction angiography mammography, computed tomography, nuclear medicine, ultrasound, and magnetic resonance imaging modalities.

BIEN 5510. Image Processing for the Biomedical Sciences. *3 credits.*

Introduces biomedical image processing. Topics explored include: the human visual system, spatial sampling and digitization, image transforms, spatial filtering, Fourier analysis, image enhancement and restoration, nonlinear and adaptive filters, color image processing, geometrical operations and morphological filtering, image coding and compression image segmentation, feature extraction and object classification. Applications in diagnostic medicine, biology and biomedical research are emphasized and presented as illustrative examples.

BIEN 5600. Neural Engineering. *3 credits.*

Basic principles of neural engineering, properties of excitable tissues, quantitative models used to examine the mechanisms of natural and artificial stimulation. Basic concepts for the design of neuroprosthetic

devices for sensory, motor and therapeutic applications. Design issues including electrode type, biomaterials, tissue response to stimulating electrodes and stimulus parameters for electrical stimulation and artificial control. Examples of how engineering interfaces with neural tissue show increasing promise in the rehabilitation of individuals of neural impairment.

BIEN 5640. Bioengineering of Living Actuators. *3 credits.*
Overview of muscle tissue as a living actuator from the perspective of engineering design, systems biology, muscle modeling and adaptive control. Prereq: BIEN 4700/5700.

BIEN 5700. Systems Physiology. *3 credits.*
Analyses of the underlying physiologic and bioengineering aspects of the major cell and organ systems of the human from an engineer's point of view. Classic physiologic approaches used to introduce topics including cell functions, nervous system, nerve, muscle, heart, circulation, respiratory system, kidney, reproduction and biomechanics. Design problems including models of cell-organ-system function and problems in biomechanics illuminate topics covered. Computer techniques and relevant instrumentation are incorporated. Experts on related topics are invited to speak as they are available.

BIEN 5710. Analysis of Physiological Models. *3 credits.*
Development of continuous (compartmental) and distributed-in-space-and-time mathematical models of physiological systems and molecular events. Analytical and numerical methods for solving differential equations of the initial and boundary value types. Simulation of model response, and estimation of model parameters using linear and nonlinear regression analysis.

BIEN 5931. Topics in Biomedical Engineering. *1-3 credit(s).*
Course content announced prior to each term. Students may enroll in the course more than once as subject matter changes. Possible topics include biomechanics, experimental methods, neuroanatomy, telemetry, etc.

BIEN 6120. Introduction to the Finite Element Method. *3 credits.*
Introduces finite element analysis as applied to linear, static problems. Application to problems in plane strain, plane stress, and axisymmetry. Development of shape functions and element stiffness matrices. Although primarily structural analysis, also considers problems in heat transfer and fluid mechanics. Use of user-written and packaged software. Prereq: GEEN 2130; and matrix/linear algebra or equiv.

BIEN 6200. Biomedical Signal Processing. *3 credits.*
Introduces students to statistical processing of biomedical data. Topics include: data acquisition, probability and estimation, signal averaging, power spectrum analysis, windowing, digital filters and data compression. Students complete several computer projects which

apply these processing methods to physiologic signals.
Prereq: MATH 2451; and proficiency in C or FORTRAN.

BIEN 6210. Advanced Biomedical Signal Processing. *3 credits.*
Covers modern methods of signal processing encountered in the biomedical field including parametric modeling, modern spectral estimation, multivariate analysis, adaptive signal processing, decimation/interpolation, and two-dimensional signal analysis. Students complete several computer projects which apply these modern techniques to physiologic data. Prereq: BIEN 6200 or equiv.; knowledge of C or FORTRAN.

BIEN 6391 Special Topics: Advanced Systems Physiology for Biomedical Engineers. *3 credits.*
This course takes a disease-based approach to understanding systems physiology when those systems go wrong. Examples will be taken from diseases of the cardiovascular, respiratory, endocrine and immune systems. Course material will span systems ranging from cellular and molecular to whole organ and organism. Students will work in teams to develop disease-based models that capture the multiscale, complex behavior underlying human disease.

BIEN 6440. Biomedical Engineering Analysis of Trauma. *3 credits.*
An engineering analysis of the physiological changes following impact to the head, spinal cord, and limbs, and electrical events and effects on tissues are treated.

BIEN 6450. Musculoskeletal Biomechanics 1. *3 credits.*
Emphasizes the interrelationship of force and motion as related to anatomic structure and function. Examines the forces and motions acting in the skeletal system and the various techniques used to describe them. Highlights current concepts as revealed in the recent scientific and engineering literature. Topics include: bone mechanics, joint mechanics, gait kinematics, instrumentation and measurement of biomechanical phenomena, and computer modeling of the musculoskeletal system. Prereq: GEEN 2120 and GEEN 2130.

BIEN 6451. Musculoskeletal Biomechanics 2. *3 credits.*
Advanced concepts of kinematics and mechanics as they apply to the fields of biomechanics and rehabilitation. Covers aspects of gait, bone and joint surgery, and soft tissue surgery. Detailed study of joint mechanics, implant applications and mobility device function is performed. Includes advanced analysis and modeling as well as laboratory-based final project. Prereq: BIEN 6450.

BIEN 6500. Mathematics of Medical Imaging. *3 credits.*
Begins with an overview of the application of linear systems theory to radiographic imaging (pinhole imaging, transmission and emission tomography), and covers the mathematics of computed tomography

including the analytic theory of reconstructing from projections and extensions to emission computed tomography and magnetic resonance imaging. Topics may also include three-dimensional imaging, noise analysis and image quality, and optimization. Contains advanced mathematical content.

BIEN 6600. Neuromotor Control. *3 credits.*

Overview of current issues in neuromotor control and movement biomechanics. Special emphasis on the study of normal and impaired human movement. Topics include: muscle mechanics, biomechanics of movement, neural circuitry, strategies for the neural control of movement (including a discussion of adaptation and motor learning) and potential applications of biomedical engineering techniques to the study and improvement of impaired motor function.
Prereq: BIEN 3300 which may be taken concurrently or equiv.; or cons. of instr.

BIEN 6610. Rehabilitative Biosystems. *3 credits.*

Examines the plastic changes in biological systems that occur in response to targeted stimuli. These processes involve responses by cells to chemical, mechanical, or electrical stimuli (which may be related), which may be influenced or directed using engineering techniques. Examines the homeostasis of physiologic systems and their response to pathologic and rehabilitative stimuli. Examines engineering applications involving the diagnosis and rehabilitation of musculoskeletal, neurologic and cardiopulmonary biosystems in the context of the underlying cellular mechanisms.
Prereq: BIEN 5700 which may be taken concurrently; and PHYS 1004.

BIEN 6620. Modeling Rehabilitative Biosystems. *3 credits.*

Introduction to large-scale mathematical models of various physiological systems of interest in rehabilitation (e.g., cardiovascular, pulmonary, musculoskeletal, etc.). Discusses mathematical modeling, a widely used tool for testing hypotheses regarding the underlying mechanisms of complex systems such as physiological systems in health, disease and recovery. For each, simulation is used to further our understanding of the adaptive processes of these systems in response to physiological/pathophysiological stresses and rehabilitative interventions. Prereq: BIEN 5710 and BIEN 5700.

BIEN 6710. Cellular and Molecular Bioengineering. *3 credits.*

Main topics include: cellular biomechanics with an emphasis on the cardiovascular system, molecular bioengineering, biotransport phenomena, and tissue engineering with focus on artificial internal organs. Cellular biomechanics topics covered are biomechanics of the endothelium, endothelial-immune cell interactions, and blood cell structural biomechanics. Topics in molecular bioengineering include chemotaxis and chemokinesis, and modeling of receptor-mediated

endocytosis. Biotransport and tissue engineering topics include bioreactor design and the analysis and development of artificial internal organs like the liver and pancreas.

BIEN 6931. Topics in Biomedical Engineering. *3 credits.*

Subject matter variable as determined by needs of biomedical graduate students. Students may enroll more than once as the subject matter changes. Possible topics: biostatistics, experimental methods, neuro-anatomy, etc.

BIEN 6947. Medical College of Wisconsin/Joint Degree. *1-8 credit(s).*

Graduate-level course in selected areas of the life sciences offered at the Medical College of Wisconsin. May be taken by doctorate BIEN students at Marquette University. Prereq: Cons. of dept. ch.

BIEN 6953. Seminar in Biomedical Engineering. *0 credits.*

Scholarly presentations on current topics in biomedical engineering and related areas by visiting professors, resident faculty and graduate students. Attendance is required of all full-time graduate students. SNC/UNC grade assessment. Mandatory for all full-time BIEN graduate students.

BIEN 6995. Independent Study in Biomedical Engineering. *1-3 credit(s).*

Prereq: Cons. of instr. and cons. of dept. ch.

BIEN 8995. Independent Study in Biomedical Engineering. *1-3 credit(s).*

In-depth research on a topic or subject matter usually not offered in the established curriculum with faculty and independent of the classroom setting. Prereq: Cons. of instr. and cons. of dept. ch.

BIOM 35284. Medical College of Wisconsin/Joint Degree. Computational Methods for Biomedical Research. *3 credits.*

This course focuses on modeling and computational techniques for simulation and analysis of biological systems, developed largely through application-driven examples. Examples will be developed to a depth at which models will be used to analyze real biological or physiological data. To accomplish this, the important details of the underlying biological systems must be described along with a complete step-by-step development of model assumptions, the resulting equations, and (when necessary) computer code.

BIOM 35285. Medical College of Wisconsin/Joint Degree. Mathematical Biology. *3 credits.*

This course teaches the students how to express physiological problems in equations and how to solve such equations. Emphasis on physiological problem solving methods rather than mathematical theory. Topics include the application of matrices, differential

equations, and numerical analysis to problems in bioelectricity, biomechanics, and optics.

BIOL 5703. Exercise Physiology. *3 credits.*

Study of the effects of acute and chronic exercise on selected organ systems. Particular emphasis will be placed on muscle, cardiovascular, respiratory, and environmental physiology.

BIOM 35284. Computational Methods in Biomedical Research. 3 credits.

EECE 6010. Advanced Engineering Mathematics. *3 credits.*

Prerequisite: MATH 2451 or equivalent and proficiency in computer programming. Linear algebra and matrix theory, ordinary differential equations, partial differential equations, and complex variables emphasizing both theoretical and numerical aspects as well as engineering applications.

MSCS 5720. Statistical Methods. *3 credits.*

Probability, discrete and continuous distributions. Treatment of data, point and interval estimation, hypothesis testing. Large and small sample method, regression, non-parametric methods. An introduction to the basic understanding of statistical methods. Applications-oriented.

MSCS 5740. Biostatistical Methods and Models. *3 credits.*

Introduction to the statistics of life science and the use of mathematical models in biology. Data analysis and presentation, regression, analysis of variance, correlation, parameter estimation and curve fitting. Biological sequence analysis, discrete and continuous mathematical models and simulation.

MEEN 6101. Advanced Engineering Analysis I. *3 credits.*

Matrices and linear algebra with applications. Tensor analysis and applications. Calculus of variation. Green's function techniques. Complex variable theory and applications. Topics in ordinary and partial differential equations.