

DEPARTMENT OF
**BIOMEDICAL
ENGINEERING**



SENIOR DESIGN PROJECTS 2018

industry sponsors

2017-2018

Mortara Instruments, Milwaukee, WI
3M, Minneapolis, MN
GE Healthcare, Waukesha, WI

2016-2017

Siemens Medical Solutions USA Inc., Hoffman Estates, IL
Safe Place Bedding, LLC, Conesville, OH
9 Degrees of Human, Milwaukee, WI

2015-2016

Medtronic USA Inc., Minneapolis, MN
Trek Bicycle Corporation, Waterloo, WI
Cardiac Profiles Inc., Franklin, TN
Zimmer Biomet, Warsaw, IN

2014-2015

GE Healthcare, Waukesha, WI
Medtronic USA Inc., Minneapolis, MN
Rowheels, Fitchburg, WI

2013-2014

Cytophil, Inc., East Troy, WI
DesignWise Medical, Loretto, MN
GE Healthcare, Waukesha, WI
Siemens Healthcare, Hoffman Estates, IL
Medtronic USA Inc., Minneapolis, MN

2012-2013

NeoCoil, LLC, Pewaukee, WI
Gauthier Biomedical, Grafton, WI
3M, Minneapolis, MN

ON THE COVER:

A 4-year-old boy living with congenital amputation of his lower limbs and forearms uses his new assistive eating device designed by a student team. See page 15 for more information.

2011-2012

GE Healthcare, Waukesha, WI
Medtronic USA Inc., Minneapolis, MN
Innovator of Disability Equipment
and Adaptations, LLC, Pewaukee, WI

2010-2011

Cardiac Science Corporation, Deerfield, WI
DePuy Orthopedics, Inc. Warsaw, IN
GE Healthcare, Waukesha, WI
Medtronic USA Inc., Minneapolis, MN

2009-2010

DePuy Orthopedics, Inc. Warsaw, IN
GE Healthcare, Waukesha, WI
3M, St. Paul, MN

2008-2009

DePuy Orthopedics, Inc., Warsaw, IN
Siemens Medical Solutions, Hoffman Estates, IL
GE Healthcare, Waukesha, WI
ACTRA Rehabilitation Associates, Brookfield, WI
Gauthier Biomedical Inc., Grafton, WI
Stevenson Industries, Simi Valley, CA

2007-2008

3M, Saint Paul, MN
Siemens Medical Solutions, Hoffman Estates, IL
Baxter Healthcare, Deerfield, IL

2006-2007

Medtronic USA Inc., Minneapolis, MN
DePuy Orthopedics, Inc., Warsaw, IN
Siemens Medical Solutions, Hoffman Estates, IL
GE Healthcare, Waukesha, WI

to our industry partners

We are pleased to present the Biomedical Engineering Senior Design Projects completed during the 2017-2018 academic year with the new joint department between Marquette University and the Medical College of Wisconsin.

The Department of Biomedical Engineering at Marquette University is dedicated to preparing students for their professional and personal lives after graduation. Undergraduate students can specialize in biomechanical, bioelectrical, or biocomputer engineering. In addition to courses in engineering, mathematics, and the life sciences, students are required to complete several design challenges in the freshman year and a year-long project-based capstone design course in the senior year. Students develop their teamwork skills, learn about the product development process used in industry, and are made aware of the unique requirements and constraints of medical device design. They consider legal and regulatory issues, use standards where applicable, conduct economic analyses, and learn about packaging, sterilization, and testing of medical devices. Several project deliverables, similar to those used in industry, are required. This capstone design experience provides students with the knowledge base and skill sets needed to be effective contributing members of a medical device company, clinical engineering department, or academic research laboratory, and create value for their customers.

This was the second year of our new joint Department of Biomedical Engineering between Marquette University and the Medical College of Wisconsin. This year we continued our 13-year collaboration with the Milwaukee Institute of Art and Design (MIAD). Six of our project teams collaborated with industrial design students from MIAD during the spring semester. This was the seventh year of external funding for service learning, assistive technology, and other projects. We appreciate this support made possible by R25 EB013070 from the National Institute of Biomedical Imaging and Bioengineering and the Marquette University Strategic Innovation Fund.

In our Biomedical Engineering Department, students may enhance their design experience and preparation for careers in the engineering profession through work experience. At the Les Aspin Center for Government Studies, students can work as interns for the US Food and Drug Administration and learn first-hand how the FDA functions and what is required to market a regulated medical device. Students participating in our highly popular and nationally recognized Cooperative Education Program gain work experience at medical device companies prior to graduation.

As you read through this report and learn of the benefits of industry sponsorship of senior design projects, please consider becoming a sponsor. We recognize the value to our students and program of strong ties to industry, and we are interested in working with additional companies to help us prepare our students for careers in biomedical engineering.

Respectfully,

Jay R. Goldberg, Ph.D., P.E.
Clinical Professor of Biomedical Engineering,
Senior Design Course Instructor

Lars Olson, Ph.D.
Associate Professor and Interim Chair,
Department of Biomedical Engineering

industry sponsorship

Senior Design Course Sequence:

At Marquette University, all senior biomedical engineering students are required to successfully complete a set of project-based capstone design courses (BIEN 4920, Principles of Design, and BIEN 4998, Senior Design).

At the end of these courses, students will demonstrate:

- The ability to connect and apply the knowledge and skills developed in previous engineering (and other) courses towards a design solution (to a specific problem) that creates value for a customer
- The ability to plan and produce a product or service that will meet customer needs
- The ability to work effectively in teams
- Written technical and oral communication skills

Senior Design Project:

The major component of the course is a design project that is managed by a multidisciplinary team of three to five students for an entire academic year. During the year, project teams identify customer needs, develop potential designs, construct and test prototypes, and deliver a design and/or working prototype to their industry sponsors. Project teams develop project schedules, maintain project notebooks, conduct economic and risk analyses of their design solutions, and develop and present written and oral project proposals and final reports.

Many of the projects are industry sponsored and provide students with an opportunity to learn about the needs of the medical device market and the operations of a company. Experience gained from industry sponsored projects helps prepare students for careers in the medical device industry. Teams are advised by a biomedical engineering faculty member and a representative from the sponsoring company.

Benefits of Sponsorship:

Benefits to companies sponsoring design projects include:

- Additional resources at little cost to company

Three to five senior engineering students will be dedicated to each project for two semesters.

The sponsoring company can specify the composition of the project team (biomedical, electrical, computer, and mechanical engineering students).

This can be very beneficial to companies with limited engineering resources and can allow companies to focus efforts on higher-priority projects.

- Involvement and participation in the training of new engineers and potential employees

- On-campus advertisement of the sponsoring company

Involvement in the senior design project will provide the company access to and a higher profile among graduating engineers.



Benefits to students of industry-sponsored projects:

- Opportunity to work on real-world problems important to industry
- Exposure to the medical device industry and market
- Experience with project management and product development
- Familiarity with requirements and constraints of medical device design

Requirements for Industry Sponsorship:

Personnel: Sponsoring companies must identify at least one company representative to act as an industry advisor to the project team. The industry advisor would be the company contact for the project team, advise students on issues involving customer needs, provide technical expertise and advice, and approve design concepts and prototypes. Faculty advisors will be responsible for administrative issues (grading, meeting deadlines, monitoring progress of teams, dealing with team personnel issues, etc.) and providing guidance to the team.

Time: At a minimum, industry advisors must be available to discuss project requirements, customer needs, and potential designs. Communications can be in-person or by phone, e-mail or video conference. The advisor determines the frequency of communications.

Travel: The sponsoring company determines the need for travel.

Funding: Depending upon the needs and expectations of the sponsor, a fund of \$1000–\$1500 may be necessary to pay for prototypes and testing.

Other: Students have access to Marquette University's computer network, libraries, Discovery Learning Laboratory (machine shop, collaboration space, 3D

printers, prototyping resources), faculty expertise, and engineering laboratories. Sponsors may want to provide additional resources (prototyping facilities and/or personnel, laboratories, etc.) to their project teams if desired.

Types of Projects Appropriate for a Senior Design Project:

- Lower priority projects for which the company lacks resources
- Projects that can be completed in nine months or less
- New products (hardware or software)
- Product improvements (new features, packaging, materials, etc.)
- Process improvements
- Development of test procedures and/or test equipment

Protection of Proprietary Information:

Sponsors can request that members of their project teams sign non-disclosure agreements to protect confidential and trade secret information.

To Sponsor a Biomedical Engineering Senior Design Project:

If you have any questions about our senior design program or if you are interested in sponsoring a senior design project please contact Dr. Jay Goldberg at (414) 288-6059 or jay.goldberg@mu.edu.

We look forward to working with you.

projects

ECG SIMULATOR

Project Team: Tyler Brackeen
David Dembo
Kasia Mysliwiec
Collin Shale

Faculty Advisor: Dr. Guilherme Garcia

Sponsor: Jeff Westcott
Mortara Instrument

An electrocardiogram (ECG) simulator is used to simulate either artificial or real patient ECG data. Having a device that can playback ECG data without having a real patient connected is crucial for R&D purposes, especially for Verification and Validation (V&V) teams. It also allows user flexibility in terms of testing location, ECG waveform selection, and testing duration without the concerns of patient comfort and safety. Using an ECG simulator also confirms that the software on ECG products recognizes and produces the correct algorithm statements that are correctly displayed on the user interface. ECG simulators are also used to evaluate the signal acquisition and processing done by ECG products, including filtering and artifact reduction.

The purpose of this project was to develop an ECG simulator to meet the developing needs of the Mortara V&V team. The device was required to be adaptable to multiple test environments, have upgrade capabilities



for future iterations, be durable to hold up in a testing environment, and accommodate a variety of user workflow patterns. ECGsim uses digital-analog converters to convert waveform data files saved on the device into analog signals that are injected into several lead posts to simulate individual electrode connections. These waveforms are accessible by a touchscreen user interface on the device. The combination of these features eliminates test setup time, allows for faster waveform selection, and provides a strong base for development into an integral part of the Mortara V&V cycle.

Hardware testing verified that the simulator provides the electrical functionality needed to complete testing and a long service life due to component redundancy and durable design. However, further software development is required by the Mortara software team for complete functionality.

AUTOMATED TEST FIXTURE FOR 3M™ TRUE DEFINITION SCANNER

Project Team:	Justin Prom Matthew Messina Justin Riebe Matthew Tenuto Lisa Vlach
Faculty Advisor:	Dr. Taly Gilat-Schmidt
Sponsor:	Amanda Kastanek 3M

The objective of this project was to develop and implement a repeatable test protocol for the 3M™ True Definition Intraoral Scanner capable of assessing scanner accuracy and variability. The True Definition Intraoral Scanner is a portable 3D scanning system designed to create digital dental impressions. The current test methods in place to evaluate and compare scanner performance are time consuming and do not offer a repeatable, relevant scan path. The True Definition Scanner Team at 3M requested a repeatable evaluation method to assess wand performance, a reduction of the number of wands returned due to scan performance, and

increased customer satisfaction.

Customer needs were determined through weekly meetings with the True Definition Scanner Team. The automated test fixture was then designed and fabricated with these needs in mind. Iterative design principles were adopted to ensure the prototype functioned as desired through all phases of the design process.

Two Zaber motors were connected in series to provide the two degrees of freedom necessary to complete the relevant scan section. A custom script was then created to drive the motors as necessary. Design verification results indicated that the automated test fixture operated as expected during all possible scan configurations.

The end goal of this automated test fixture was to allow 3M to streamline the research and development process of the True Definition Scanner wands. The automated test fixture accomplished this goal by providing a method to assess current wands that is faster and more repeatable than manual methods. This will save 3M engineering time and provide valuable data for assessing wand performance. It will also provide a framework for validating future iterations of the True Definition Scanner.



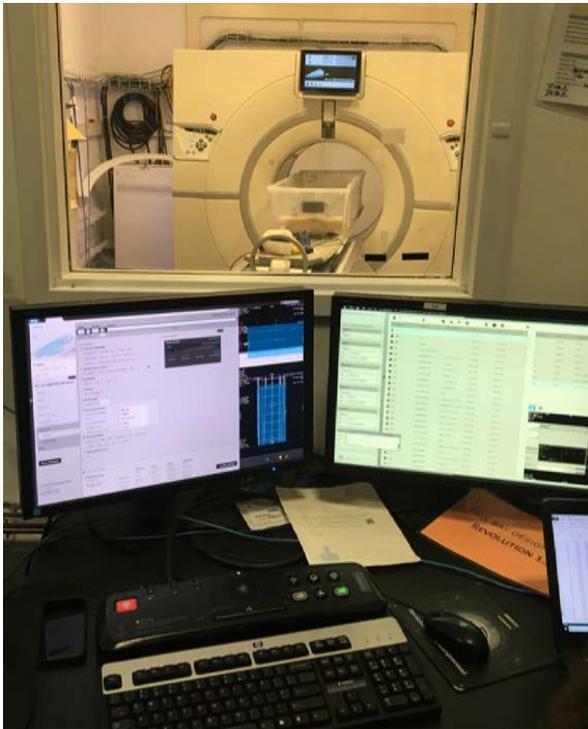
CT CONTRAST PHANTOM

Project Team: Anthony Amore
Kevin Driscoll
Lauren Ernst
Teagan Jessup
Chandler North

Faculty Advisor: Dr. Taly Gilat-Schmidt

Sponsor: Christine Hammond
GE Healthcare, CT
Systems Team

Computerized Tomography (CT) scanning is an advanced imaging technology used by healthcare professionals for a multitude of applications. The imaging of contrast agent during CT scanning is a specific and valuable tool for clinicians. Contrast imaging is a tool used for enhancing



structures within the body for clinical research and diagnosis. A specific scan that is performed using contrast fluid is a full body scan, clinically known as an angiography, to map the full venous system of the patient from the chest to the feet by tracking a “clump” of contrast, defined as a bolus, through IV injection.

Unfortunately, due to the changing anatomy within patients’ venous systems from the chest to the feet, the bolus is frequently outrun by the CT scanner causing the exam to be repeated. Repeated exams require injecting more contrast fluid into the patient. For efficiency and health purposes, the inability of the system to dynamically track the bolus and subsequently necessitate a re-run of the scan is a limitation GE Healthcare is actively working to eliminate.

The purpose of this project was to collaborate with the CT Systems Team at GE Healthcare to develop a dynamic contrast phantom for design testing and verification. For GE to develop a system capable of dynamically tracking the bolus, it is necessary for all test conditions to mimic a patient scan with repeatable scan outputs. The phantom design chosen by the team had strict design parameters as each component was required to mimic patient anatomy in the output image. The speed range of the motors, density of the materials used to create the “venous system” in the phantom, and the precision of the control of the hardware in the phantom were the driving components of the project and the completed design.

The final design incorporated a casing, bolus speed range, and speed accuracy allowing the CT Systems Team at GE to run verification tests simulating a realistic angiography scan. The motors, pulleys, and timing belts that were implemented into the design ensured the accuracy of the bolus travel speed, while the use of outlet power, lightweight materials, and USB communication allowed for automation and efficiency of testing.

HAMSTRING MONITORING DEVICE

Project Team:	Adam Hunter Blake Golliday Dana Morgan Mason Rather Mitchell Kwapick
MIAD Partners:	Jade Akim Alexandra Upadhyaya
Faculty Advisor:	Dr. Brian Stemper
Sponsor:	Dan Kant-Hull Marquette Track and Field

Hamstring injuries are some of the most common injuries in athletes and can significantly limit participation in training and competition activities. Injury is a naturally occurring part of athletics, but the risk of injury can be reduced with proper training and activity monitoring. In recent years, hamstring injuries have plagued Marquette athletic teams and prevented teams from achieving their athletic goals. Currently, there is no way to quantifiably measure the hamstring strength and activity of athletes other than through the observation of an improvement or decrease in amount of weight lifted. Unfortunately, this method often allows injuries to go unnoticed until they are severe and can allow for right/left muscle imbalances to flourish. Hamstring imbalance is a leading cause of hamstring injury in athletes. Early identification of these imbalances can allow trainers and athletes to properly manage training to reduce the risk of injury.

The purpose of this project was to design and build a machine that could aid in tracking and monitoring hamstring strength, with the goal of using quantitative data to reduce the severity and number of

injuries. The device needed to measure, record, and store data on the individual hamstring strengths and activities of athletes. The Hamstring Monitoring Device features the combination of a mechanical device and the Trackstar application. The two load cells in the device measure a voltage that each hamstring is creating during the Nordic curl exercise, and this voltage signal is amplified, filtered, and converted to a force measurement. This value is transmitted via Bluetooth to the iPad application for the athlete or trainer to view live, and the data is stored for further analysis of each athlete. The application includes both athlete and trainer accounts with different information displayed based on the user type.

Verification testing proved that this device was able to provide live feedback as well as a stored log of data for athletes ranging from 112 lbs. to 228 lbs., with evidence to support the accurate testing of all athletes. Further verification and repeatability testing and analysis of measurement data will need to be completed before commercialization or routine use of this product by the Marquette athletic teams.



This project was supported by R25 EB013070 from the National Institute of Biomedical Imaging and Bioengineering.

LOW-COST, BATTERY-POWERED VENTILATOR FOR DEVELOPING COUNTRIES

Project Team: Joseph Aculado
Jack Bralick
Patrick Connelly
Jonathan Hjelmgren
Ricardo Vega
Jason Wallenfang

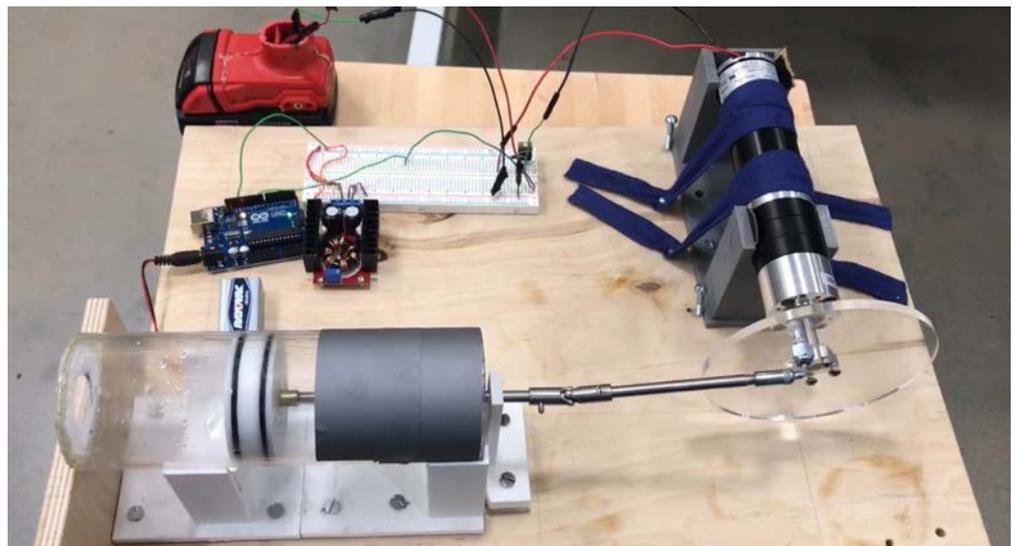
Faculty Advisor: Dr. Lars Olson

The cost of purchasing and maintaining commercial ventilators can be crippling for hospital care units with very limited budgets. The average commercial ventilator costs approximately \$34,000 while daily maintenance and upkeep can cost between \$600 and \$1,500. These costs far exceed reasonable budget limitations for hospitals in developing countries. Furthermore, existing commercial ventilators typically have very little support for transportability making the idea of transferring ventilators between hospitals unrealistic. Finally, power sources in developing countries can often be inconsistent which is a significant concern

when that power is allowing the reliable function of devices that help people live. Countries such as the Philippines are plagued with sporadic power outages causing self-sustainability to be a necessary design requirement.

The focus of the low-cost ventilator is to consider all problems mentioned above and develop a working prototype that solves these problems. The cost of the ventilator was maintained by using low-cost components to reduce the cost of the product. Physical design choices were made with compactness and portability in mind to ensure the ventilator could easily be moved from place to place. Finally, all electrical components were designed to be powered off a single 18 Volt Lithium Battery and reliably run for several hours.

The ventilator was thoroughly tested, verifying that 250 mL of air could be provided at 10 beats per minute on a fully charged battery for 6 hours. A solid foundation for the development of this ventilator has been established, allowing future teams to enhance the design and produce a fully functional device.



CONNECTIVE PIECE FOR FEEDING TUBE

Project Team: Will Clawson
Sean Green
Kelli Moyle

Faculty Advisor: Dr. Jay Goldberg

Clinical Advisor: Dr. Christine Schindler

A gastrostomy tube (G-tube) is a tube that is inserted into the stomach through a stoma button and connects to a feeding bag. Currently, over 344,000 Americans have a feeding tube, and many of them are children. Many times, when there is a sudden movement, especially when sleeping, the tubes connected to the feeding bag and the stoma button become disconnected. This can be a problem for both patients and caretakers. When the tubing becomes disconnected, food continues to flow out of the bag until there is nothing left, creating a mess. This is inconvenient to the caretaker as they must take extra time to reconnect the patient to a new feeding bag and clean up the mess on the floor or sheets. Patients do not receive the nutrients they need from the food, and there is a chance that the stoma button can be dislodged from the stoma. This can cause discomfort for the patient, lead to infection, and may require an additional surgical procedure to reattach the stoma button.

The purpose of this project was to design a device that would prevent the leakage of feeding solution while also preventing the stoma button from being dislodged. The device must be able to stop the flow of food when disconnection occurs and must not pull



the stoma button out of the patient. The final design is a connective piece that is composed of a dome and funnel. When activated, the dome collapses on to the funnel by friction, stopping the flow of food. This also causes the tubing connected to the funnel to become disconnected to relieve stress on the stoma button and prevent dislodging. Design verification results proved that the device was able to disconnect before dislodging the stoma button.

FINGER INDIVIDUATION DEVICE

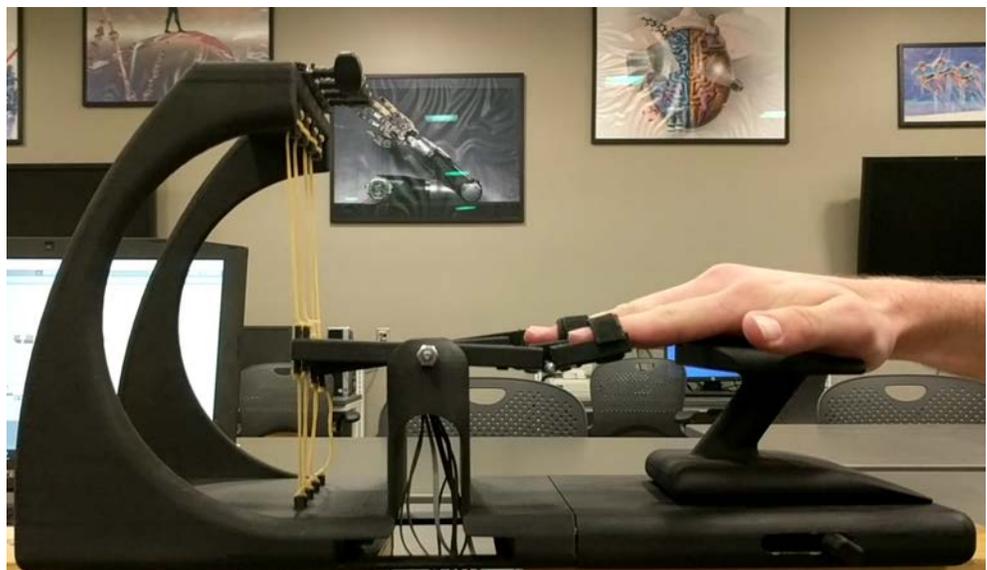
- Project Team:** Nathan Gregg
Lara Riem
Mary O'Connor
Audra Riem
Bridget Moffett
- MIAD Partners:** Samuel Joseph
Clay Quinn
- Faculty Advisor:** Dr. Brian Schmit
- Clinical Advisor:** Dr. Brian Robertson-Dick

For individuals who are neurologically impaired, the most common shared trait is hand dysfunction, or peripheral weakness. This can be characterized by grasp weakness, movement fatigue, response latency, poor coordination, and low ability to individuate peripheral muscles. These tasks are largely controlled by the nervous and motor systems to initiate, coordinate, and utilize hand and finger motions to complete a goal. While there are tests that can provide a clinical score for some characteristics of this dysfunction, they are not comprehensive of the entire problem.

The purpose of this project was to combine a direct clinical assessment of finger individuation with rehabilitation

activity to provide a comprehensive understanding of a patient’s hand function. The device was required to provide a metric for individuation, be comfortable for patient use, and provide user feedback to a clinician. The Finger Individuation Device contains four major components: accelerometers, a user interface, hinged keys, and a hand rest. The accelerometers are used to provide a metric for finger individuation which is sent to the user interface for use by the clinician. The hinged keys provide comfort and sustained contact for the patient’s fingers to remain on the keys. The hand rest provides adjustability to accommodate a range of hand sizes for all patients.

Verification testing confirmed that performance requirements were met for individuation and use as a diagnostic tool. The adjustability of the device provides comfort and accommodates a wide range of users. Additionally, the user interface creates an interactive environment for the patient and clinician while using the device. It is anticipated that the device will be used as a diagnostic tool by the sponsor or further developed by a future engineering team.



This project was supported by R25 EB013070 from the National Institute of Biomedical Imaging and Bioengineering.

IMPROVEMENTS TO LAPAROSCOPIC SURGICAL PROCEDURES

Project Team: Matthew Coughlin
Jonathon Frigo
Brandon Kwak
Ryan O'Toole
Mitchell Rawson
Devin Wozniak

Faculty Advisor: Dr. Bing Yu

Clinical Advisor: Dr. Rana Higgins

Upon observation of numerous surgical procedures, particularly laparoscopic procedures, a common issue was identified. A congestion of cables, instruments, and accompanying surgical staff caused inefficiencies detrimental to the Operating Room (OR) work flow. Specifically, the cables within the sterile field impeded desired range of motion of the surgeon(s) and caused confusion and miscommunication regarding the use of surgical instruments. Furthermore, laparoscopic surgical equipment presents a unique level of severity as these instruments are powered by long cables which must remain in the sterile field throughout the duration of the surgery. When interviewing surgeons and supporting medical staff, their most common complaint was cable mismanagement and the effects it had on their ability to perform their jobs. Currently, there are no commercial products that are specifically designed for cable management in the OR.



The purpose of this project was to provide a solution to cable mismanagement within the OR that aimed to make laparoscopic surgical procedures more efficient while maintaining a minimal footprint. Initial development of a solution included functions which would provide an avenue for removing and returning cables from the surgeon's point of focus. Further development of the solution led to decreases in surgical suite setup time through the integration of a modular cable organizer, which also better communicated the status of instruments. In addition, designing the device to be vertically adjustable in its hospital bed fixation method allows surgeons to customize their surgical experiences. The final product is named the Cable Doctor. Design verification and validation confirmed that customer needs and performance requirements were met.

This project was supported by a Marquette University Strategic Innovation Fund grant.

NIGHTTIME LEG EXTENSION DEVICE

Project Team: Madison Olesen
Ben Rappaport
Brittany Scaglione
McKenna Stillings
Andrew Walker

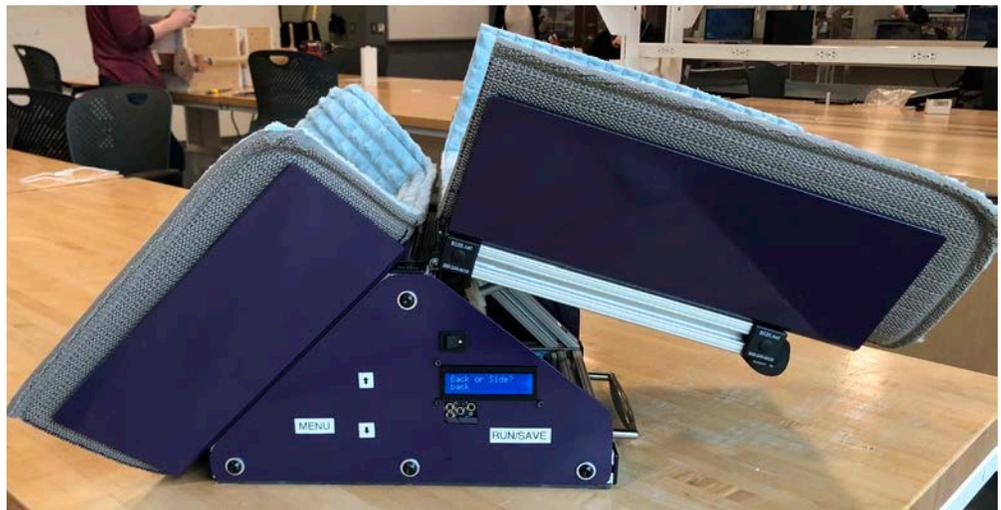
MIAD Partners: Samantha Bruening
Trever Krueger

Faculty Advisor: Dr. Jay Goldberg

Spinal muscular atrophy (SMA) is a disease that can cause patients to lose the ability to walk, eat, or breathe without assistance, by affecting motor nerve cells in the spinal cord due to a gene mutation. Our client is a 12-year-old girl with SMA type I. She can sit up but has no control of the muscles in her legs. However, she still has feeling in her legs and therefore gets uncomfortable after sitting or lying still for 20-30 minutes. The lack of movement in her legs causes reduced circulation in her legs leading to pain, swelling, and stiffness, as well as an increased risk of pressure sores and blood clots. Stretching her legs increases leg circulation and maintains her current range of motion, allowing her to feel more comfortable.

Our client's wheelchair has been fitted with a device to extend and flex her legs during waking hours at her control. However, there is no equivalent device that she can use in bed during the night or while lounging around. Currently, the client and her parents must wake up periodically throughout the night to stretch her legs to prevent the pain, swelling, and other negative effects that come from stationary sleeping.

The purpose of this device was to assist in leg extension and flexion throughout the night in a safe and non-interruptive manner, while remaining compatible with the client's bed and surroundings. The Nighttime Leg Extension Device allows the client and her family to adjust the angle to which her legs are stretched, how often her legs are stretched throughout the night, and how long her legs are stretched for each time. The device also allows the client to independently stretch her legs in between the set intervals should she need an extra stretch.



DEVICE TO ASSIST WITH FEEDING ACTIVITIES

Project Team: Maleah Brody
Molly Erickson
Ashley Galarneau
Cody Hanson
Maeve McDonald
Ashley Sillin

MIAD Partners: Tess Powers
Pedro Carranza

Faculty Advisor: Dr. Benjamin McHenry

The goal of this project was to design and develop an assistive eating device for a 4-year-old boy living with congenital amputation of his lower limbs and forearms. A congenital amputation is defined as the absence of a fetal limb or fetal part at birth. For individuals with congenital amputations, some activities of daily living (ADL) may prove to be a challenge, limiting independence and requiring adapted methods for completing these activities. For the client, one of these challenges is eating. The current method that he uses to eat is to fasten a spoon to his right residual limb using a hair tie, while rotating the spoon to his mouth with his left arm. This method limits the types of food he can independently eat as he is only able to use a spoon. Twisting and turning of the utensil may also occur, causing spillage of food and frustration while eating.

The team was tasked with designing an assistive device which would allow the client to feed himself independently. This includes the ability to apply pressure with a utensil, allowing him to stab with a fork. Customer needs were identified by interviewing



the client and his parents and observing the client as he engaged in ADLs. The team needed to design a comfortable device that could be easily attached to the client's arm, while also resisting rotation with applied pressure.

The team designed a 3D-printed watch face that enables the rotation of a utensil within a desired range. When pressure is applied to the utensil, a locking mechanism secures the utensil in place. Upon release of pressure, a spring restores the utensil to its original position, enabling rotation. An off-the-shelf utensil holder was modified and secured to the top of the watch face via Dual Lock. The silicone utensil holder contains a slot that allows the client to use and interchange a variety of utensils. An elastic armband was constructed to secure the watch face to the client's arm. A Velcro strap and buckle allow for the circumference of the armband to be adjusted to fit the client's arm as he grows. Through use of the device, he is now able to feed himself independently.

This project was supported by a Marquette University Strategic Innovation Fund grant.

DEVICE TO AID IN TABLETOP PERSONAL INDEPENDENCE AND SOCIAL INTERACTIONS

Project Team:	Casey Anderson Michelle Boehm David Doherty Tim Fitzpatrick Alex Sherman Samantha Winther
MIAD Partner:	Taylor Schaut
Project Advisor:	Dr. Jay Goldberg
Clinical Advisor:	Dr. Stacey Stibb Dr. Kim Zvara

The client for this project was a three-year-old boy with Arthrogryposis Multiplex Congenita (AMC). This disorder is characterized by joint contractures affecting two or more areas of the body. The client lacked the muscle strength to lift his arms to a tabletop height and maintain his arms at a resting position on a table. This was a detriment to his ability to participate and interact socially with his peers in preschool. The goal of this project was to improve his quality of social interaction and personal independence by developing a device that would allow him to raise and lower his arms.

To resolve this issue the team developed a backpack with two inflatable wings that can be worn by the client to provide support and lift to his arms. The backpack design allows the device to blend into the classroom, minimizing any distraction. The inflatable wings were chosen to provide the lift as they are the safest and most gentle way

to provide lift to the client's delicate arms. Two micro-pumps, two normally closed solenoid valves, and two chin activated buttons compose most of the electrical system used to power the inflatables. Micro pumps minimize the overall weight of the device while two simple color-coded buttons provide a user interface appropriate for use by a three-year-old.

Design verification confirmed the device to be within an acceptable noise range (under 80Db), provide quick but gentle lift to the arms (within 10-12 seconds), maintain comfort, and be intuitive to use. The device was also validated by the client who overwhelmingly approved of the design. The lift provided by the inflatable wings will allow the client more independence to interact with peers in the classroom.



This project was supported by a Marquette University Strategic Innovation Fund grant.

MODIFIED SPORTS WHEELCHAIR

Project Team: Nicholas Burke
Scott Crawford
Ford Ellis
Rushi Patel
Ryan Sheard

Faculty Advisor: Dr. Barbara Silver-Thorn

Clinical Advisor: Dr. Christine Schindler

The client for this project has two significant medical conditions—femoral hypoplasia and arthrogryptic teratologic clubfoot syndrome. Together these conditions necessitated the design of a modified sport wheelchair for her continued participation in wheelchair basketball and other activities. Femoral hypoplasia is a rare condition, defined by underdevelopment of the femur. The resultant shortened lower limbs and altered center of gravity warrant a custom wheelchair design for comfort and stability. Further, arthrogryptic teratologic clubfoot syndrome results in fixed joints; the client’s left knee is fixed in extension, her right knee is locked in flexion. While some modifications are available for non-sport wheelchairs, such accommodations are not readily found with sport wheelchairs. Custom sport wheelchairs often cost twice as much as high priced standard sport wheelchairs.

The purpose of this project was to provide a custom sport wheelchair that could be used by the client, providing sufficient protection for her lower limbs. The wheelchair was required to protect her (and her teammates) from injury, provide maneuverability needed for sports activity,



and provide comfort while seated and during propulsion. The wheelchair contains three primary features: an extended leg rest, a protective leg guard, and an extended custom cushion. The extended leg rest and custom cushion provide adequate leg support for comfortable seating. The leg guard provides protection for her legs, minimizing injury risk from chair-to-chair impact, common during gameplay. The custom cushion and frame also provide adjustability to accommodate future growth.

The wheelchair design was verified and validated through customer and coach surveys, finite element analysis, and maneuverability drills. These results confirmed that the device provides the desired comfort, protection, and maneuverability.

EMERGENCY HYPOTHERMIA BLANKET

Project Team: Anthony Tufano
 Brien Irving
 William Spingola
 Alexander Valente
 Robert Smith

Faculty Advisor: Dr. Said Audi

Sponsor: Dr. Kevin Weidman

One of the most serious challenges that the United States military faces in any of its conflicts involves the maintenance of homeostasis when a soldier is wounded. More specifically, when a soldier is struck by a bullet, it only takes a few minutes for the critically wounded body to drop its core temperature at an alarming rate. Hypothermia, or low body temperature, is a very real threat when it comes to wounded soldiers, regardless of the temperature of the ambient environment. Often, injuries of wounded soldiers are sustained miles away from any medical clinics. It is imperative to the soldier's survival that body temperature is kept as close to 37 °C (normal body temperature) for as long as possible so that the soldier can be airlifted to an immediate care center for appropriate medical treatment.

Currently, there is not a practical solution to this problem. Heated blankets can be bulky and not durable enough to withstand the rigors of the battlefield.

The objective of this project was to create a durable, lightweight, compact, and thermodynamically efficient emergency hypothermia blanket that can survive a battlefield environment. This was achieved by using premium materials to make the blanket, including 1) a high-quality spacer mesh material as the interior layer, 2) primaloft ONE insulation, and 3) a Gore-tex outer layer. Furthermore, the blanket utilizes a carbon fiber heating tape electrical heating source that is powered by a lithium ion battery.

Upon testing the final prototype, it was found that the blanket met all customer needs by warming a simulation mannequin while being lightweight, compact, and durable. Although studies have not yet been conducted on human subjects the team expects the prototype to perform as required in the battlefield environment.



ALIVE

Project Team: Alex Barrington
Michael Barrowclift
Colleen Pawlicki
Tim Pawlicki

Faculty Advisor: Dr. John LaDisa

Lack of mobility is a serious issue for anyone who is injured, hospitalized, or entering the assisted living community. Isolation, depression, and a loss of freedom are all potential concerns for these more sedentary people. The project team sought to provide a solution to the loss of freedom experienced by the less able-bodied with the Assisted Living Immersive Virtual Environment (ALIVE) system.

ALIVE is a safe, user-friendly, portable, individual, and panoramic virtual environment where users can move through a scene of their choice. It can use real video footage to create the most realistic experience possible. By using 3D video instead of computerized graphics, ALIVE can bring the world to those who cannot get out and see it for themselves. The small-footprint system can be set up in an hour and taken down in twenty minutes. The portability of the system allows it to be brought to many different locations. The system incorporates a recumbent bicycle that the user rides. The pedaling speed determines the playback speed of the video, thus enhancing the immersive quality of the experience. The ALIVE system allows users to experience real world locations through high-quality 3D video and provides both fitness and therapeutic benefits.

True confirmation of the success of this project is only possible upon the execution of its purpose—the delivery of a virtual outdoor experience to an assisted living facility or nursing home—which has not yet been accomplished. A minimum viable product will need to deliver longer and more stable footage than is currently used, while providing a variety of interesting locations. To bring the system to a facility, a means of transportation would have to be provided. A transport van and several custom carts would be needed to ensure the safe, quick, and compact transportation of the various parts of the system to the facility. It is critical to have a good first impression when delivering a product in a new market segment, especially when the product likely would be classified as a non-critical entertainment purchase by a program or activities department. A significant number of target specifications were met to show that the system could be taken to assisted living facilities once a means of transportation and source of high quality video content are obtained.



This project was supported by a Marquette University Strategic Innovation Fund grant.

HOME THERAPLAY

Project Team: Ben Mol
Mark Gotthelf
Lucas Connelly
Charles Manchester
Katherine Ramos-Delgado

MIAD Partner: James Harding

Faculty Advisor: Dr. Scott Beardsley

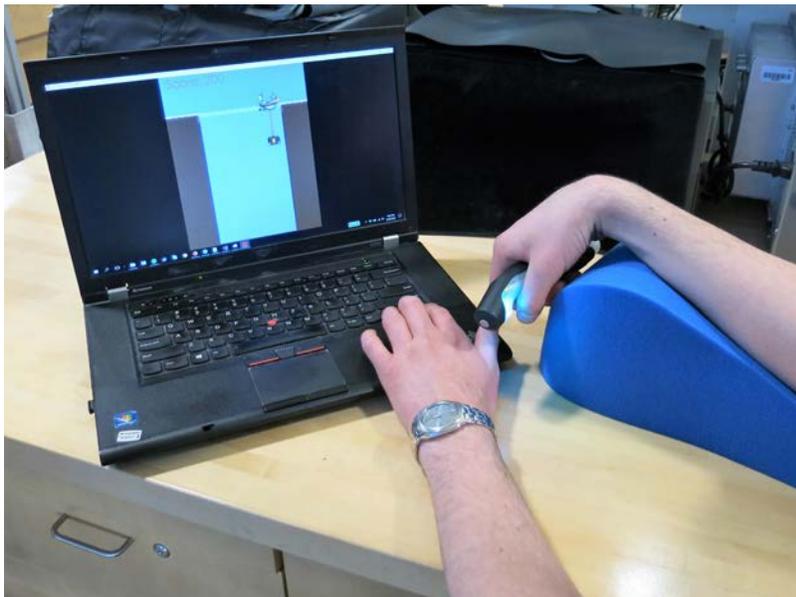
Cerebral palsy (CP) is a disorder affecting many people across the world which constitutes impaired movement and posture development caused by problems with the development of the brain. The effects of the disorder can vary, but most patients depend in some way on others for assistance in tasks of daily living, and nearly all require physical therapy for most of their lives, to ensure that their muscles remain strong and flexible enough to support them and their bodies.

Physical therapists (PT) experience many challenges when treating patients with CP. Because the therapy can take a long time to see limited improvement, many patients, and especially children, begin to feel discouraged with the treatment and stop exercising at home between sessions with the therapist. This effect is complicated by the tendency for patients to exaggerate to the doctor what they have done at home, resulting in the PT not knowing what progress had been made at home in the past week.

Home TheraPlay is a product which engages patients and encourages them to complete their therapy at home and reports the results of the at-home practice to the therapist each week. The product was required to accurately capture degrees of motion of wrist flexion/extension and forearm pronation/supination, as well as the amount of grip force exerted on it. Home TheraPlay achieves this through the implementation of a six-degree-of-freedom accelerometer/gyroscope and a force-sensing-resistor.

Via Bluetooth communication, the hardware portion of Home TheraPlay communicates to a software package, which was developed in-house and implements different game modes into the therapy exercises recommended

by physical therapists for children with CP. These games give feedback to the patient when they perform the exercises correctly and provide added motivation for completing the at home therapy sessions. The software package also allows the therapist to adjust several parameters for each exercise, allowing for a fully customizable therapy program specialized for each patient. Extensive hardware and software tests have been completed on this project with very positive results, but clinical trials would likely be necessary prior to commercialization.



MEDICAL ASSISTIVE DRONE

Project Team: Max Cahill
Charles Fennig
Dutchess Lejman
Luke O'Donnell
Rebecca Streit
Joseph Zanfardino

Faculty Advisor: Dr. Jay Goldberg

The team was tasked to build a piloted unmanned aerial vehicle to serve as a viable assistive device, capable of delivering emergency supplies until paramedics can arrive on scene. The drone was designed to meet a carrying capacity of 3 pounds, total device weight of less than 55 pounds, an operational temperature of between 20° and 30° Celsius, fluid resistance for rain-like conditions, an operation range of up to 2 miles, and a functional audio/visual link. The team needed to build a drone that complied with all FAA regulations and accomplished the task of decreasing first responder response time to improve patient outcome.

Customer needs were determined by interviewing several first responders and medical professionals. These interviews led the team to design a drone that would decrease first responder response time, bring medical



aid without direct human assistance, and provide the necessary medical supplies while using a live audio/visual link between the first responder and patient. A six-propeller drone was assembled from a kit and a camera system was added. An attachment rail and medical kit were also fabricated. A thin aluminum sheet was machined into the rail and PLA plastic was used to 3-D print the case in its entirety. After assembly, flight tests were completed. These tested the carrying capacity, flight time, flight speed, maneuverability, and audio/visual link on the drone. In addition, the kit was tested for water resistance and damage to contents, to ensure no damage to medical supplies would occur during flight. The drone was able to meet each target specification.

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Biomedical Engineering is a discipline that advances knowledge in engineering, biology and medicine to improve human health.

Students in biomedical engineering participate in cross-disciplinary activities that integrate the engineering sciences with the biomedical sciences and clinical practice. Biomedical engineers develop strategies to effectively solve challenging problems in medicine and biology.

Most graduates secure employment working in the medical device/biotechnology industry. Some graduates use our “renaissance” training as a stepping stone for careers in fields such as medicine, law, healthcare management, and academics.

Distinctive Features of Biomedical Engineering at Marquette University and the Medical College of Wisconsin

Marquette University has the largest engineering school at a Jesuit University. The new joint department formalizes the long-standing relationships with the Medical College of Wisconsin and the Zablocki Veteran’s Administration Medical Center. We also have strong ties to the Rehabilitation Institute of Chicago, and manage a number of Centers including the Orthopaedic Rehabilitation and Engineering Center (OREC), the Falk Neurorehabilitation Engineering Research Center and the Rehabilitation Engineering Research Center on Accessible Medical Instrumentation.

The department has unique laboratory capabilities including CT and SPECT microfocal imaging, biotelemetry, implantable devices, telerehabilitation, and neurorehabilitation robots, in areas including neurorehabilitation, imaging systems, and cardiovascular technologies.

The joint Biomedical Engineering department offers degrees at the bachelors, masters and doctorate levels.

Co-op and Internship Program

Marquette University has developed one of the leading co-op/internship programs among Biomedical Engineering Departments in the nation. More than half of the undergraduate biomedical engineers gain co-op or internship experience before graduation. The Biomedical Engineering department has forged partnerships with many major medical device companies in the Midwest who rely on the excellent reputation established by our students as co-ops, interns and permanent employees. The Co-op and Internship Program offers students the opportunity to gain meaningful practical and professional experiences in the health care industry, in addition to their on-campus educational experiences.

Marquette University began its Engineering Co-op Program in 1919. Students usually enter the Co-op program at the end of their sophomore year and complete three to four terms of off-campus employment.



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The employment experience is alternated with semesters of on-campus study, extending graduation by only one year. Internships, in comparison, are summer-only engineering experiences.

Les Aspin Center for Government (FDA Internships)

The Les Aspin Center for Government at Marquette University and the Department of Biomedical Engineering offer internships on biomedical research and regulatory issues. The Les Aspin/Biomedical Engineering Internships began in 1997 with Biomedical Engineering undergraduates participating in this innovative program in Washington, D.C. To date, more than 100 biomedical engineers have completed Les Aspin Biomedical Internships. The internships are completed at the Food and Drug Administration, Office of Science and Technology in Rockville, MD.

Undergraduate Offerings

Choose from Three Specializations

The Biomedical Engineering Department offers a strong undergraduate education. There are three tracks in the Biomedical Engineering curriculum:

- Bioelectronics
- Biomechanics
- Biocomputing

All undergraduate tracks in Biomedical Engineering are compatible with other programs offered by the Opus College of Engineering. Each track contains the requisite humanities courses, and requires 132 credit hours for graduation. Students automatically earn a minor in biology, and can earn an optional minor in areas such as mathematics, electrical, mechanical, or computer engineering. In addition, all tracks retain most of the core courses of the initial year, which allows the student flexibility to transfer to other curricula if so desired. The Biomedical Engineering curriculum is



interdisciplinary in nature, incorporating courses in biology, chemistry, physics, mathematics, computer science and engineering.

We provide a solid foundation in the mathematical, physical, and life sciences necessary for the engineer to function effectively in a medically or biologically oriented problem solving environment. Social science and humanities courses prepare students to deal with contemporary ethical, cultural, and social issues.

In addition, we prepare biomedical engineers to communicate with life scientists, physicians and other health care providers to describe and model complex biological systems, collect and analyze experimental or clinical data, understand the capabilities and limitations of sophisticated instrumentation, and understand the principles of design. ▶

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Undergraduate Design Curriculum

Biomedical engineering students in our Department learn about design throughout the four year curriculum.

Freshman Year:

Students first gain experience with the design process in the freshman year during BIEN 1100 and 1110 (*Introduction to Biomedical Engineering Methods I and II*). In these courses, they participate in several team design challenges such as:

- Physiological monitoring: Design of an algorithm for analysis of ECG, blood pressure, and other waveforms
- Medical imaging: Design and testing of an imaging phantom
- Entrepreneurship: Semester-long team-based medical device design project including a business plan and elevator speech

These experiences help develop teamwork skills, and teach students about the engineering design process, including technical, legal/ethical, regulatory, and economic design constraints. Students learn to identify customer needs, develop a list of performance requirements and specifications, convert requirements into design concepts, and build and test prototypes.

During BIEN 1110, students learn about basic business concepts and entrepreneurship (as part of their design projects) culminating in a presentation of their new product ideas to students, faculty, and industry representatives at the college-wide Design Day event.

Sophomore and Junior Years:

During the sophomore and junior years of the biomedical engineering curriculum, students take courses that include individual and team-based design projects which allow them to apply what they are learning in the course to the solution of a related problem. This helps them relate theory with practice.



In the junior year, students can take BIEN 3400 *Clinical Issues in Biomedical Engineering Design*, an elective in which students observe procedures in the clinical environment and learn to identify unmet clinical needs and opportunities for new product development. Their final project proposals can serve as the basis of their senior capstone design projects.

Senior Year:

During the senior year, students are required to take BIEN 4920 *Principles of Design* and BIEN 4998 *Senior Design*. These courses require students to apply what they have learned during their previous years of the undergraduate curriculum in a multidisciplinary team-based project experience. They further develop their design, analytical, project management, communication, time management, and teamwork skills. They learn about the product development process and value creation, the medical device industry, testing for safety and efficacy, design validation, standards and regulations, risk management, project scheduling, patent issues, and a variety of design issues.

Students complete a design project from problem definition to design validation (per ISO 9001 and 13485) and gain experience in generating the same project deliverables as required in industry.

Five Year B.S./M.S. Program

This program allows qualified students to receive a Bachelor of Science Degree and a Master of Science Degree in Biomedical Engineering in just five years. Students with qualifying grade point averages apply to the program during their Junior year. They begin their thesis research the summer between their Junior and Senior years, and continue their research during the summer between their Senior and fifth years and throughout their fifth year, culminating in the preparation of a written thesis and defense.

Research in Biomedical Engineering

Biomedical Engineering faculty and students at Marquette and the Medical College of Wisconsin are engaged in a wide range of research activities, with many opportunities available for students at both the graduate and undergraduate levels.

Research-oriented Faculty

More than 60 faculty who are active in research have primary (22), secondary (16), or adjunct (>30) appointments in our department, and are available for supervision or co-supervision of students.

Research Laboratories and Centers

The number of research laboratories and centers within our department has been growing dramatically, with the Biomedical Engineering Department now housing 11 research laboratories and three centers.

Most recently, the NIDRR awarded our department a **Rehabilitation Engineering Research Center on Technologies for Children with Orthopedic Disabilities (TECH4POD)**. Faculty, students, clinicians,

and researchers from six area institutions are developing a national center with a focus on advancing engineering research and development based on innovative technologies addressing children with orthopedic disabilities.

Externally Funded Research

More than \$5 million/year in externally funded research, the largest of any department on campus, flows through the Department of Biomedical Engineering. Research and training grants are managed by Biomedical Engineering core faculty and support research projects for more than 50 graduate students.

Strong Partners

We are a member of the **Clinical and Translational Science Institute of Southeast Wisconsin**. Supported by a \$20M grant from NIH, this consortium of eight Milwaukee institutions is dedicated to transforming biomedical research in southeast Wisconsin, accelerating the translation of research discoveries, and advancing patient care and education. The eight member organizations include the Medical College of Wisconsin, Marquette University, Milwaukee School of Engineering, University of Wisconsin-Milwaukee, BloodCenter of Wisconsin, Children's Hospital and Health System, Froedtert Hospital, and the Clement Zablocki VA Medical Center.

Targeted Areas of National Leadership

While our students and faculty are engaged in many areas of research, three areas of excellence stand out: Functional Imaging, Rehabilitative Bioengineering, Systems Physiology, Cardiovascular Physiology, and Biocomputing.

faculty

Olson, Lars E., Ph.D.

Associate Professor and Interim Chair.

Optical instrumentation, tissue engineering, biological transport and circulation physiology, mathematical modeling of physiological systems, biosensors

Audi, Said H., Ph.D.

Pulmonary mass transfer, tracer kinetics, pulmonary hemodynamics

Beardsley, Scott, Ph.D.

Neuroengineering, computational modeling, perceptual learning, functional imaging

Dash, Ranjan, Ph.D.

Computational biology and bioinformatics

Garcia, Guilherme, Ph.D.

Respiratory fluid mechanics

Gilat-Schmidt, Taly, Ph.D.

Medical imaging, image processing and reconstruction, systems engineering

Goldberg, Jay R., Ph.D., P.E.

Director, Healthcare Technologies Management Program

Medical device design

Greene, Andrew, Ph.D.

Cardiovascular physiology

Harris, Gerald F., Ph.D.

Quantitative assessment of neuromuscular function, human motion analysis, orthopedic biomechanics, data acquisition and control, real time analysis

Hoffmann, Brian R., Ph.D.

Metabolism

Jeutter, Dean C., Ph.D., P.E. (Emeritus)

Implantable transcutaneous radio frequency power transfer, biotelemetry, biomedical instrumentation, radio frequency circuit design and development

Joshi, Amit, Ph.D.

Optical imaging

LaDisa, John F., Jr., Ph.D.

Cardiovascular biomechanics, adult and congenital heart disease, stent design and development

Pintar, Frank, Ph.D.

Biomechanics of traumatic brain and spine injury, motor vehicle crash trauma

Ropella, Kristina M., Ph.D

Professor and OPUS Dean

Signal processing, cardiac and neuro-electrophysiology, functional magnetic resonance imaging

Scheidt, Robert A., Ph.D.

Human motor control, systems identification, rehabilitation engineering, embedded systems, product development

Schmit, Brian D., Ph.D.

Spinal cord injury, human neurophysiology, neurorehabilitation, instrumentation, biomechanics

Shimoyama, Mary E., Ph.D.

Analytics, informatics, software engineering

Silver-Thorn, M. Barbara, Ph.D.

Prosthetic limbs, soft tissue mechanics, rehabilitation engineering, orthopaedic and dental biomechanics

Stemper, Brian, Ph.D.

Biomechanics of traumatic brain and spine injury, biomechanics of the cervical and lumbar spine, automotive safety

Tefft, Brandon J., Ph.D.

Cardiovascular and pulmonary physiology

Winters, Jack M., Ph.D.

Neuromuscular control systems, movement and tissue biomechanics, rehabilitation engineering, telehealth, neurofuzzy computing

Yu, Bing, Ph.D.

Optical imaging

ASSOCIATE FACULTY**Ackman, Jeffrey, M.D.**

Orthopedic surgery

Cariapa, Vikram, Ph.D.

Rapid prototyping, process controls, neural networks, design of experiments

Carroll, Joseph, Ph.D.

Ophthalmology

Clough, Anne V., Ph.D.

Mathematical and computer modeling of biomedical systems, image processing and analysis, modeling of pulmonary hemodynamics, integral equations

Connelly, Jennifer, MD

Neurology

Koch, Kevin, Ph.D.

MR imaging

Krenz, Gary S., Ph.D.

Mathematical modeling of hemodynamic properties of the lung, microangiographic measurements, pulmonary vascular morphogenesis

Kurpad, Shekar, M.D., Ph.D.

Neurosurgery

LaViolette, Peter, Ph.D.

MR imaging, cancer

Liebenthal, Einat, Ph.D.

Functional neuroimaging

Liu, Yu, Ph.D.

Radiology

Marklin, Richard W., Ph.D.

Ergonomics in office and industrial settings, human factors, cumulative trauma disorders

Meier, Timothy, Ph.D.

Neurosurgery

Nagurka, Mark L., Ph.D., P.E.

Biomechanics, vehicle dynamics and controls, and control system design

Nencka, Andrew, Ph.D.

Radiology

Pawela, Christopher, Ph. D.

Anesthesiology

Schminda, Kathleen, Ph.D.

MR imaging, cancer

Stowe, David, Ph.D.

Anesthesiology

Terhune, Scott, Ph.D.

Microbiology, molecular genetics

Toth, Jeffrey, Ph.D.

Biomaterials

Tugan Muftuler, Lutfi, Ph.D.

MR imaging, neurosurgery

Voglewede, Phillip A., Ph.D.

Lower limb prostheses, dynamics, kinematics

Yoganandan, Narayan, Ph.D.

Neurosurgery

opus college of engineering

Since 1908, the Marquette University Opus College of Engineering has been uniquely blending professional engineering preparation with a liberal arts education to provide the world with well-balanced leaders in their profession.

OUR MISSION

The mission of the College is to excel in four critical areas:

- To prepare all students for successful careers based on a strong moral and ethical foundation
- To advance the state-of-the-art in engineering
- To serve our professional and technical communities
- To contribute to our global society

The Opus College of Engineering offers six undergraduate degrees in eleven programs/majors through four departments: Biomedical Engineering; Civil & Environmental Engineering; Electrical and Computer Engineering; and Mechanical Engineering. Marquette also offers a wide range of graduate and doctoral programs.

ACCREDITATION

All undergraduate programs offered by the Marquette University Opus College of Engineering are accredited by the Engineering Accreditation Commission of ABET, 111 Market Place, Suite 1050, Baltimore, MD 21202-4012, 410-347-7700.



THE UNIVERSITY

Founded in 1881 in Milwaukee, Wisconsin, Marquette University has been educating people of faith to be leaders in their professional lives, their communities and in society.

Since the first graduating class of five men were awarded bachelor of arts degrees in the 1880s, Marquette has grown into a modern coed campus of more than 11,000 students who learn and grow through nationally admired undergraduate, graduate and professional programs.



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BE THE DIFFERENCE.

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