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Engineers in Medicine: Foster Innovation by Traversing Boundaries

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ABSTRACT: Engineers play a critical role in the advancement of biomedical science and the development of diagnostic and therapeutic technologies for human well-being. The complexity of medical problems requires the synthesis of diverse knowledge systems and clinical experiences to develop solutions. Therefore, engineers in the healthcare and biomedical industries are interdisciplinary by nature to innovate technical tools in sophisticated clinical settings. In academia, engineering is usually divided into disciplines with dominant characteristics. Since biomedical engineering has been established as an independent curriculum, the term "biomedical engineers" often refers to the population from a specific discipline. In fact, engineers who contribute to medical and healthcare innovations cover a broad range of engineering majors, including electrical engineering, mechanical engineering, chemical engineering, industrial engineering, and computer sciences. This paper provides a comprehensive review of the contributions of different engineering professions to the development of innovative biomedical solutions. We use the term "engineers in medicine" to refer to all talents who integrate the body of engineering knowledge and biological sciences to advance healthcare systems.

KEY WORDS: engineers in medicine, biomedical innovation, interdisciplinary learning, diversity, education for innovation

I. INTRODUCTION

The nature of biomedical innovation is the translation of scientific discoveries and engineering principles into novel and affordable medical treatments and practices, including new drugs, devices, diagnostics, and other medical technologies. The greatest challenge for the success of biomedical innovation is to achieve efficacy, safety, and cost-effectiveness at the same time. Therefore, innovation activities often span the boundaries of specialty and sometimes need radical movements beyond conventional practice. Engineers in medicine play a critical role in the advancement of biomedical science and technologies for the development of transformative solutions for medical problems. They must work closely with healthcare professionals at the intersection of various disciplines to integrate knowledge and skills through synthetic learning for developing novel diagnostic and therapeutic tools. Essentially, they must apply their domain knowledge to analyze and develop novel systems in other knowledge domains and study products and their interactions with the human body.

Driven by the need for healthcare improvement, the growth of engineers in medicine is around the world. Initially, engineers are trained in a specific discipline and later join the biomedical industry to make contributions to human health and well-being. In 1972, the first independent engineering program for biomedicine in the United States was accredited by academia.[1] Since then, the programs have grown explosively to produce over 7000 biomedical engineers per year.[2] The success of independent biomedical engineering programs (BME) does not impede the contributions of other traditional engineering disciplines to healthcare systems. In fact, biomedical innovation has always been an exciting and popular area for almost all engineering disciplines. For example, electrical engineering majors use their core knowledge to develop electronic medical imaging systems, dialysis machines, laser systems, and implantable devices, among others.[3] Mechanical engineers with their understanding of structural statics and dynamics apply their fundamental understandings to study the mechanics of the human musculoskeletal system. This in synergy with human factor engineering helps to develop many products, such as exoskeletal wearable robotic systems to aid manual workers.[4] Computer science majors work closely with electrical and mechanical engineers to develop working software platforms and algorithms for the physical systems developed by engineers in other domains.[5] Furthermore, computer engineers also have many standalone contributions to the healthcare industry by developing everyday digital mobile health apps, developing virtual environments for patient-doctor interaction, virtual surgeon training, etc.[5] Chemical engineering majors apply their domain knowledge to develop drug delivery methods and understand their complex interactions within the human body.[6] Material engineering majors develop new bio-compatible materials for scaffold and self-assembly implants possessing bio-mimetic mechanical and chemical properties.[7]

Today, biomedical innovation and education are beyond the effort of any individual discipline. Collaboration among different engineering majors is the core pillar for the next big leap in diagnostic or therapeutic solutions. While most recent review papers about engineering for healthcare focus on biomedical engineering specifically, this paper provides a comprehensive review of the contributions of different engineering professions to medical innovation and a discussion about the educational strategies for future engineers who aim to foster the development of innovative solutions for diagnosis, treatment, and prevention of disease.

II. BIOMEDICAL ENGINEERING

The modern era of medicine began in the 18th century marked by the discoveries of the smallpox vaccine and bacteria.[8] Engineers were involved in medical field in the first place and contributed to the development of early bioengineering. Notable figures include Poiseuille[9] for the Hagen–Poiseuille equation in fluid dynamics, Fick[10] for the laws of diffusion, Womersley[11] for the fluid dynamics of blood flow, Penne[12] for the bioheat transfer equation, Skalak[13] for the biomechanics of prosthetics, and Fung[14] who was regarded as a founder of modern biomechanics and bioengineering. The first biomedical engineering program in the United States was accredited in 1972[1] while an unaccredited program was started in 1966. According to the definitions from the National Institutes of Health[15] and the Whitaker Foundation,[16] "bioengineering" and "biomedical engineering" are interchangeable terms that refer to a discipline that advances knowledge in engineering, biology, and medicine, and improves human health through cross-disciplinary activities.[17] Sometimes bioengineering emphasizes more on the molecular or cellular levels and the interactions between materials and cells/tissues while biomedical engineering aims at the larger scale that covers biomechanics, instrumentation, modeling, and healthcare systems.[18]

Biomedical engineering requires skills in both engineering and science and the ability to work in a cross-disciplinary or interdisciplinary environment. Biomedical engineering is a versatile domain that combines basic engineering such as mechanical, electrical, chemical, etc. with that of bioengineering.[19] Bioengineering is closely related to biotechnology and genetic engineering that investigates disease diagnosis, vaccine synthesis, protein-surface interaction in biological life forms, enzyme technology, etc.[20] Bronzino defines the role of a biomedical engineer as the "application of electrical, mechanical, chemical, optical, and other engineering principles to understand, modify, or control biological (i.e human and animal) systems as well as design and manufacture products that can monitor physiological functions and assist in the diagnosis and treatment of patients."[20] Biomedical engineering from that perspective is a broad area where knowledge from all engineering domains is necessary along with knowledge in biological sciences to design, construct, improve and sustain both physical products and services for the human healthcare system.

Biomedical engineering is a derived field and thus contributions by engineers in this domain overlap with those in other fundamental engineering fields. For example, biomedical engineers develop new methods to deliver pharmaceutical drugs by combining the concepts from chemical and mechanical engineering. One such example is the radiation-forced liposphere wall disruption where bioactive ingredients encapsulated in bubbles are injected into the body and subsequently triggered to release drugs in localized body parts using ultrasonic radiation.[21] Biomedical engineers use the concepts of biomechanics, statics, and dynamics from mechanical engineering and biomedical sciences to study the biomechanics of cardiovascular, body muscles, bones, tendons, ligaments, etc., and develop new prosthetics and surgical tools.[22–25] They also use fundamental concepts of electrical engineering like circuitry, and signal processing to develop implantable sensors, capsule endoscopy for body imaging, radiological imaging, etc. They often combine different engineering and biological domains to innovate new devices and concepts.[26,27] The mind controllable robotic arm is an under-development biomedical engineering marvel that uses biological concepts like synaptic plasticity and electrical engineering concept like neural circuit spiking.[28] The bone-anchored hearing aid and the cochlear implants (CI) had radical improvements over the years owing to advancements in digital signal processing, medical studies on nerve stimulations, and surgical methods.[29] Biomedical engineering has been bridging the concepts of engineering and medical science to aid this improvement.[29]

Recently, tissue engineering is recognized as a sub-field under biomedical engineering that links cellular biology to engineering.[18] Tissue engineering and cellular-level manipulation require a strong molecular-level understanding of cell biological phenomena. In addition to the engineering perspectives, biomedical engineers are equipped with the requisite knowledge of biological science for connecting medical needs with the engineering tools in tissue engineering.[19] A recent contribution to advances in control over cellular proliferation, propagation, and differentiation through bioelectrical impulses can be traced to biomedical engineering alongside other vital biological fields.[30] Biomedical engineering connects biomechanical compatibility with immunological acceptance in designing synthetic scaffolds, acellular techniques, and self-assembly methods for cellular vascularization.[31] Biomedical engineering is also bringing concepts from material engineering into hard-tissue engineering to develop nanocrystalline calcium phosphate, bioactive glasses, and tricalcium phosphates with improved biocompatibility, fracture toughness, and other biomechanical properties.[32]

Biomedical engineering is making countless contributions in medical imaging, optical systems, device development for treatment and diagnosis, brain-machine interfaces, medical nanotechnology, lab-on-a-chip, cancer therapy, medical software development, etc.[33–35] The field acts as a successful proponent of engineering contributions to healthcare by linking traditional engineering to biological life sciences. Currently, biomedical engineering professionals are playing leadership roles in healthcare innovation by bringing engineering and medical science under a common umbrella.[36,37]

III. CHEMICAL ENGINEERS IN MEDICINE

In the traditional sense it is known that chemical engineers design, improve and maintain the operation of chemical plants, food processing and manufacturing facilities, pharmaceutical facilities, and even biological waste processing facilities. In the recent times, chemical engineering with their foundation in chemical interaction, rheological behaviors, fluid mechanics, mass transport, etc. are greatly contributing to the field of healthcare systems. The kidney dialysis machine is a classic example of the contribution of chemical engineering in the field of healthcare.[38] The principle of solute solvent separation in this so-called “artificial kidney” is responsible for saving millions of lives annually around the world.[39] The solid-liquid interfacial phenomena giving rise to certain macromolecular changes such as absorption or chemical reaction, is a concept used by chemical engineers in the fields of drug delivery, protein classification, and organ failure detection among others.[40,41] Furthermore, chemical engineers have developed and are improving the extracorporeal blood oxygenators based on the principles of liquid-gas interaction, which is a vital life support instrument for patients with cardiac and respiratory conditions.[42,43] Chemical engineers study drug interaction within the human body in a specific sub-branch called pharmacokinetics and aids in the development of better pharmaceutical drugs, food additives, and vitamins.[44] In modern medical science, much emphasis is placed on the development of novel biomaterials for tissue engineering. Chemical engineers study the interaction between material and cell protein to provide insights into the future development of functional scaffolding, drug delivery medium, and devices.[45] Point-care devices like pregnancy test kits, blood glucose monitors, strep tests, and home COVID-19 test kits to name a few, are chemical reaction-based portable devices used in day-to-day life for home medical examinations. Chemical engineers are involved in developing advanced electrochemical biosensors to reduce the market cost and increase the accuracy and efficiency of such test kits. Chemical engineers with their understanding of macro/micro-scale chemical reactions and microfluidic systems are developing complex lab-on-a-chip devices for counting cholesterol, HIV cells, and blood gases for example.[46,47] Organs-on-a-chip is currently a rapidly developing area that mimics the physiology and functionality of a particular human organ.[48,49] This technology is being used in testing disease models, drug delivery, and screening for biomedical applications.[50,51] Chemical engineers in collaboration with other engineering disciplines and biologists are working to model and design more complex Organ-on-a-chip devices. Chemical engineers also work in developing advanced chemical reaction based quantifiable biomarkers that is used to detect certain physiological processes and disease detection within the human body.[52] This is particularly crucial in developing novel techniques for preventing certain diseases.[53]

Chemical engineers work closely with material engineers in developing novel healthcare devices for disease diagnosis and treatment. Material engineering is more focused on the fundamental aspects of the structure and functionality of different materials and their potential application in the real-world spectrum. Material engineers innovate new alloy, ceramic, composite, and polymer structures for implantable support structures for the human skeletal system with regards to proper biocompatibility and biomechanical properties.[54,55] They also study the degradation of such compounds within the human body and look for better alternative materials for better *in vitro* compatibility.[56,57] Different polymers are currently being designed material engineers for kidney membranes, heart valves, and other soft-tissue replacement with negligeable toxicological impact on the body from such implants.[58–60] The future of material engineering in healthcare will promising outcomes with the development of implantable biosensors, drug delivery hydrogels, wound healing patches, tissue augmentation and artificial tissues and muscles.[61]

IV. ELECTRICAL ENGINEERS IN MEDICINE

Electrical engineering is a field that goes beyond power grids and circuits. The fun fact is that the IEEE Engineering in Medicine and Biology Society (EMBS) was founded before the first BME department was established, and now is the largest international member-based society of biomedical engineers.[62] Electrical engineers contribute to the biomedical fields by developing medical electronics and instruments for more accurate diagnosis and treatments. Magnetic resonance imaging (MRI) and computed tomography (CT) machines are currently crucial to take a deeper look inside human bodies and diagnose patients.[63] In addition, a new technique named electromagnetic acoustic imaging (EMAI) is emerging in recent years. This imaging system uses "long-wavelength RF electromagnetic waves to induce ultrasound emission." It is not only portable, but also more accurate, safer and less expensive than MRI and CT.[64–66] Nowadays, medical imaging systems including MRT, CT and EMAI, etc. are powerful assistances for doctors to make medical decisions.

Besides the advanced medical imaging system, the rapid developed electrical technology significantly improved the healthcare efficiency by producing a variety of medical sensors. At the early stage of 1800s, sensors with the capability to measure and record bioelectric activity were invented. In the next decades, the sensitivity and complexity of medical sensors improved rapidly with the development of the electronics technology.[67] The representative examples are wearable medical monitors. They can work effectively and unobtrusively with small, low-power sensors and smart materials together with the wireless communication technology.[68] Wearable health monitors could help to monitor vital signs automatically to cut down on nurses' duties and free them up for more complex patient care.[69]

Whereas wearable health monitors are used to monitor chronic conditions including chronic obstructive pulmonary disease, congestive heart failure and the early diagnosis of Parkinson's disease, etc.[70,71] Furthermore, the wearable chemical "skin-like" monitors can be used for real-time non-invasive analysis of key electrolytes and metabolites,[72] which can help to reduce the frequency of patients entering the hospital for tests to reduce the pressure of the hospital.

Apart from imaging systems and medical sensors, medical robots are another tool that electrical engineers are making efforts to help with the improvement of medical and health systems. Medical robots can help to balance human imperfections to improve the treatment accuracy and replace part of the doctors' work to turn the complicated surgeries easier and lower the cost of patients.[73] The medical robots were firstly used in 1985, and gradually had broad impact on various medical disciplines including laparoscopy, neurosurgery and orthopedic surgery, etc.[74] Laparoscopic robots[75] have been the successful example of medical robots, the applications include radical prostatectomy, radical cystectomy for bladder cancer[76] and rectal cancer resection, etc.[77] Catheters, bronchoscopes, ureteroscopes, and colonoscopes are widely used as continuum robots to help with the manual surgeries.[78] Electrode implantation in the brain and microsurgery inside the eye are usually completed with non-laparoscopic robots to reduce the operation error.[79] Some other medical robots such as soft robots,[80] assistive wearable robots,[81] capsule robots,[82] and therapeutic rehabilitation robots[83] also make great contribrutions to the medical and healthcare field.

V. MECHANICAL ENGINEERS IN MEDICINE

Mechanical engineering in its basic sense deals with the motion and functionality of physical systems. This branch of engineering splits into several subbranches of specialized knowledge such as fluid mechanics, thermal systems, automation, mechatronics, manufacturing, etc. Although, historically mechanical engineering was seen to be more associated with the design and functionality of larger complex machineries that mobilizes the human civilization, recently, it has its fair share of contribution in medicine and healthcare systems. Wheelchairs are perhaps the simplest mechanical system innovated in the early 16th century that aided the mobility of the disabled.[84] In modern times, control engineering coupled with the concepts of dynamic system mechanics is helping innovate multitude of locomotion assisting devices and contraptions. From patient-controlled automatic wheelchairs[85] to wearable light-weight exoskeleton system,[86] mechanical engineers are playing significant role in enabling motion of the disabled patients. Currently, wearable exoskeleton systems are being designed to aid manual workers who are at a risk of suffering from long-term muscular and skeletal system degradation from repeated lifting of heavy loads.[4,87–89]

There is a variety of medical equipment used on a regular basis as a life-saving tool in hospitals and bed-side cares which are the results of innovative ideas from mechanical engineering. The insulin pump is one such modern marvel that allows a diabetic patient to have their regular dosage of insulin at the right time of the day to lead a normal life.[90,91] Nebulizers are mechanical devices widely used for delivering liquid medication in the form of mist to treat and prevent certain pulmonary symptoms and condition in patients.[92,93] Likewise, oxygen concentrators and delivery tanks have also aided many patients deal with certain recurring symptoms asthma, chronic obstructive pulmonary disease (COPD), flu, COVID-19, and other illnesses.[94–97] Day-to-day medical instruments like heart-monitor, blood pressure monitor, body temperature thermometer, patient lifter, etc. are some of the notable examples of mechanical instrument design engineering applied to medical science.[98] Complex life support instruments are also innovated, designed, and fabricated by mechanical engineering professionals. Instruments like the heart-lung machine has enabled crucial surgeries of vital body organs that requires a general anesthesia.[99] Prior to this, many coma-induced surgeries were unthinkable as general anesthesia stalls the normal functionality of the human lung.[100] Medical ventilator is another mechanical marvel like other oxygen devices but with higher delivery pressure.[101] Recently, this technology has proved its worth in the time of a global pandemic (COVID-19) and mechanical engineers are developing scalable versions to be used by serious patients at their homes.[102] Incubator design and improvement are another notable mechanical ingenuity applied to provide suitable conditions for neonatal infants.[103]

Mechanical engineers also make valuable contributions to surgical procedures and the development of implants. Various orthopedic implants and supports, such as the artificial hip and kneecap, have been developed by mechanical engineers in collaboration with surgical specialists.[104–106] Mechanical engineers with their knowledge of material properties, dynamic and static forces, design, and simulation using finite element analysis (FEA) can develop novel and patient-specific implants for the best outcomes. Modern mechanical fabrication techniques like additive manufacturing using new technologies, such as 3D printers, bioprinters, lithography, and electrospinning, has paved new ways to fabricate biocompatible implants and wearable technologies.[107–111]

The advance of computational fluid dynamics (CFD) has enabled mechanical engineers to address complicated problems in capillary-scale flows. Numerous simulation techniques have been developed to quantitatively describe the fluid and solid mechanics of artificial heart valve,[112] red blood cells,[113] and tumor transit.[114] Using advanced CFD tools and imaging technologies, mechanical engineers can develop next-generation artificial heart pumps, detect abnormal heart flow patterns, support the clinical-decision making process of aneurysms,[115] understand complex phenomenon such as brain aneurysms,[116] and elucidate the effects of flow forces on cancer metastasis.[114] Furthermore, interactive multi-physics simulation tools coupled with virtual reality technologies not only facilitate the development of advanced imaging, robotics, and automation tools for accurate diagnosis and surgical procedures, but also provide cost-effective educational strategies to train medical professionals in various scenarios.[117]

VI. INDUSTRIAL ENGINEERS IN MEDICINE

Industrial engineering is primarily associated with industrial process design, improvement, and optimization. Recently, industrial engineers have been making valuable contributions to the healthcare industry through application of their fundamental knowledge and philosophy of system improvement. With their ability to solve large-scale problems related to process optimization, network-flow analysis, production yield, patient scheduling, etc. Certain industrial engineering philosophies such as lean manufacturing, which primarily deals with wastage reduction, is now being applied to reduce variability in radiological process, improving efficiency of the emergency care units by streamlining overcrowded emergency units through process mapping.[64–67] Reduction of treatment costs, medical errors, service bottlenecks, hospitalization time, etc. are carried out using industrial systems engineering tools such as design, measure, analyze, improve, control (DMAIC) and Six Sigma.[68–70]

Operations research, a branch of industrial engineering, investigates crucial parameters in a healthcare system to identify factors that are critical to quality (CTQ).[82] Subsequently, optimization of the process is done either by maximization of a certain parameter, e.g., patient satisfaction or minimization of a factor, such as patient cost.[78] Outpatient appointment scheduling problems, for example, can be better solved by analytical and numerical optimization tools, including a framework that classifies decisions at the strategic, tactical, and operational levels.[118] Industrial engineering also encompasses areas of system reliability using a variety of statistical, mathematical and data analytics tools. This particularly plays a very significant role in the healthcare management systems. Reliability of hospital queuing models are statistically simulated by industrial engineers to test system performance, delays, and robustness.[74–76] Accurate patient information, statistical prediction of fluctuating patient loads, timed and sequential drug/service delivery to complex network of in/out-patients fall under the evolving area of clinical pathway modelling.[77–79] These modelling techniques are designed and implemented by systems and industrial engineering specialists using their knowledge of reliability, systems theory, and statistical simulations.

Ergonomics, also known as human factors, is a discipline under industrial engineering focusing on the interactions among humans and other elements of a system in order to optimize human well-being and overall system performance.[119] Ergonomic engineers address both micro and macro level problems in health care systems, ranging from the best practices for medical procedures or machine operations to organizational management strategies for enhancing occupational safety and efficiency. Their findings became handbooks for occupational safety to reduce rates of accidents and musculoskeletal injuries, such as multi-modal training programs for improving patient handling techniques,[120] guidelines for preventing occupational low back pain,[121] and administrative controls related to sequencing and scheduling breaks of medical examinations.[122] Human factors can be used to inform and improve the usability and performance of healthcare technologies, such as crash cart configuration for responding to cardiac or respiratory arrest emergencies,[123] laboratory simulation systems,[124] and blood administration and cerebrospinal fluid drainage systems[125] by redesigning the user interfaces, device configurations, IT systems, and medical procedures. Ergonomics principles are also applied to medical device development to provide safe and effective clinical care for patients as well as to ensure the health and safety of professional and lay device users.[126] The engineering outcomes are expected to benefit all healthcare workers, including trainees, nurses, physicians, supporting staff, pharmacists, and patients, across various healthcare contexts, including rural settings, acute care hospitals, ambulatory clinics, emergency rooms, and hospital pharmacies.[127]

Prototyping and manufacturing of life sciences-based products, including foods, drugs, cells, and medical devices faces regulatory, environmental, and economic challenges associated with energy and manufacturing demands. Industrial engineers innovate new approaches for a holistic paradigm coupled with continuous improvement of manufacturing processes with a life-cycle approach.[128] In addition to total quality management (TQM) and current good manufacturing practice (cGMP), quality by design (QbD) has been implemented in the pharmaceutical industry. The approach involves a robust control of the consistent process performance, validation and filing of the process, and ongoing monitoring to ensure robust process performance over the life cycle of the product.[129] Risk assessment and management, raw material management, use of statistical approaches and process analytical technology (PAT) provide a foundation for these activities.[130] Lean management was also implemented to pharmaceutical production to eliminate waste, control raw materials and flows, map value stream, and reduce costs. Ten critical steps include understanding, expert lean-team, enterprise evaluation, training program, communication and feedback system, methods and tools, improvement projects, sustaining, performance measurement system and documentation and standardization.[131] At the system level, the integration and automation of intelligent agent services into the existing bio-pharmaceutical workflow systems is challenging. Collaborative and distributed knowledge discovery systems within grid-based computing environments will help to reduce development time and costs, and yield processes that are very productive, robust, resilient, and transferable between locations.[132] Overall, industrial engineers can play a critical role in biomanufacturing optimization to enhance production efficiency, safety, and cost effectiveness.

VII. COMPUTER SCIENTISTS IN MEDICINE

Computer scientists have their contribution rooted at the very foundation of our modern civilization with their contribution to modern healthcare systems no less than other fields of engineering. Computer scientists are involved in the medical industry all the way from developing mobile applications for home healthcare monitoring to writing programs for integrating medical devices with specific disease detection algorithms. Computer scientists are constantly developing new virtual tools that assist medical professionals to have a better assessment of their patients through online consultations.[82–84] One such tool is the development of augmented reality-based software and allows better human-machine interaction to get more in-depth information about the health situations of patients.[85,86] Furthermore, augmented and virtual reality is playing a crucial role in training new surgeons through muscle memory development prior to hands-on experience.[87] Furthermore, these technologies are also helping experienced surgeons to get a better visual of the internal human anatomy during the surgical procedure which is particularly helpful in neuro, cardiac and renal surgeries.[88–90] Computer vision is a recently booming field of research where computer engineers are using complex image recognition algorithms in conjunction with existing technologies such as ultra-sound, X-ray, CT scan, MRI, positron-emission tomography (PET), etc. to detect tumors and cancers in their early stage of development which was previously thought to be undetectable.[91–95] Computer engineers are also playing valuable roles in information technology systems for maintaining patient data. For management of large hospital systems, computer engineers are developing new software for the electronic health record (EHR) to keep records of patient health information, treatments, drug dosage, medical complications, etc.[96,97] This system when integrated with the interconnected network aids multiple in-network care providers to instantly pull up patient records and provide urgent treatments when needed.[97] The implementation of the internet of things (IoT) has given computer programmers an edge to interconnect multiple patient care devices, from smart pacemakers to insulin pumps to provide seamless vitals-monitoring of routine and critically ill patients.[98–101] Computer engineers are also developing applications for wearable smartwatches to monitor heart bits-per-minute (BPM), blood oxygen level, blood pressure, etc. which has proved quite helpful in times of the recent pandemic (COVID-19).[102] Computer engineers also develop algorithms for biological process modelling, organism, and protein detection. Sequence-level investigation software for DNA assembly reconstruction and analysis are being developed to aid genetic engineering experts dig deeper into understanding the genetic information of various organisms.[103–105] Machine-learning, neural network processing, and other advanced computer tools have given birth to artificial intelligence (AI), which is considered the next big leap for human civilization. These advanced computer programs and tools are laying the foundation stones to the development of the Healthcare 4.0 system, where it is anticipated that healthcare will be ever more accessible, high-quality, and cost-effective in the day to come.[106–109]

VIII. CIVIL AND ENVIRONMENTAL ENGINEERS IN MEDICINE

Typically, one would assume that civil and environmental engineering has more to do with structural, roads and highways, landscape design, and other large pieces of infrastructure rather than being relevant to providing healthcare services. As the healthcare system becomes more physically and virtually interconnected, there is a strong need for proper physical structure design and modeling such as hospitals, clinics, pharmaceutical transportation, medical waste disposal, etc. Civil engineers play a dominant role when it comes to physical healthcare facility design. The building information system (BIM) is now being considered a major game-changer for modern healthcare facilities and is very common in civil engineering.[133] The BIM is a digital representation of a physical space that is supported by multiple tools and technologies.[134] For a medical facility design, multiple factors such as patient compartment, surgical theatres, medical equipment storage, emergency evacuation routing, over capacitation during a pandemic, equipment flow, patient waiting zone, etc. Factors can easily be pre-planned to aid swift and efficient medical services.[135–138] Civil structural engineers also work with healthcare systems to ensure that a hospital facility has all the spatial capacity to meet the auxiliary medical needs for power, airflow, backup suppliers, etc. to meet the current and growing demand for medical services.[139]

Although some of the contributions of civil engineering in healthcare systems may not seem as explicit as other engineering branches, the indirect role played are essential for preventive and risk-reduction in the healthcare system. Civil engineering also deals with road and transportation design which also has a role to play in the overall healthcare system. The modern healthcare system is not limited to the services provided within the walls of a care unit such as a clinic or a hospital. Optimal and proper routing design for roads, highways, traffic signals, etc., determines the efficacy of an emergency transportation system such as an ambulance and determines if critical care can be delivered in time.[140] Furthermore, transportation system design also affects the safe handling and disposal of hazardous wastes which may have public health implications.[141] Environmental engineering, a subfield of civil engineering investigates the air and water quality, and the presence of environmental toxicological factors reduces pollutant contamination and ensures structural-level facility sanitation and hygiene through the application of their knowledge of structural engineering and facility design.[142] This is particularly important for healthcare facilities dealing with patients who are sensitive or allergic to certain microbes or inorganic pollutants present in the air and thus reduces any chance of condition deteriorating.

IX. DISCUSSION

The STEM and the healthcare communities have a consensus that employing real-world experiences[143] and interdisciplinary collaborations[144,145] will substantially improve the educational outcomes for preparing future workforce in biomedical innovation. The interdisciplinary team-based learning (ITL), based on the concept of "constructivist learning," has been implemented in various engineering disciplines for decades. This type of learning relies on the student ability to utilize previous knowledge and skills as well as attribute value to the project at hand, thus constructing their own education. Students are more likely to be attracted to and persevere to graduation in STEM if they engage in constructivist learning because they will perceive that they are gaining in knowledge and skills and feel that they actively understand and have internalized core concepts. Students show consistent interest in interdisciplinary curricular activities to obtain rich educational experience and expand their intellectual mobility beyond their disciplines. There is a need for an education framework to provide students with authentic experiences to stimulate their creativity and curiosity, and enable them to gain meta-skills to optimize a target system that can ultimately improve the quality of healthcare.[146]

The interdisciplinary work in medical engineering can be achieved through several models of training and education. MD-PhD majoring in bioengineering is an option that trains individuals in both disciplines. The professional Master programs in clinical sciences and medicine also serve as sources to train scientists at the interface of engineering and medicine. In addition, training teams of engineers and clinicians who develop literacy towards the other culture is another option that enables effective collaborations. For example, the Howard Hughes Medical Institute (HHMI) - National Institute of Biomedical Imaging and Bioengineering (NIBIB) Interfaces Program was a precedent endeavor that inspired cross-department medical engineering programs at several universities. Most currently, some institutions pioneered a new graduate-level medical innovation programs to combine engineering, business, and clinical training to solve real-world medical needs and encourage entrepreneurship, such as Biodesign at Stanford University, Engineering Innovation in Health at the University of Washington, and Medical Innovation at Rice University.

For undergraduate education, however, cross fertilization between realms of medicine and engineering is still in its infancy. Undergraduate research and engaged learning have proven effective in enhancing the students' critical thinking and creativity.[147–149] However, the traditional education for engineers in medicine especially from non-biomedical disciplines (mechanical, electrical, chemical, manufacturing, etc.) often lacks opportunities of active and collaborative learning in a real clinical setting. In engineering, the structured curriculum more than often does not provide the students to take enough electives hours to explore research opportunities in disciplines outside their majors.[150,151] In addition, faculty also find themselves confronted with the problem of finding sufficient resources to train students with necessary skills due to various constraints in schedules, credits, lectures, laboratories, and other inflexibilities.[152,153] Thus, effective media for synthetic learning and interdisciplinary education are needed to better prepare undergraduate students for their careers in biomedical research enterprise.

X. CONCLUSION

The complex nature of medical challenges requires engineers to work closely with healthcare professionals in order to integrate the knowledge and skills from multiple disciplines. Innovations enhancing diagnostic and treatment modalities were often generated by traversing boundaries. Under traditional teaching, the domain knowledge and engineering tools for bioinnovation are taught in separate courses. Enhancing the quality of students' learning and motivation in engineering for medicine is a high priority and has always been a continual improvement process. Foster team–based learning in an interdisciplinary environment is one of the key innovative strategies for advancing both undergraduate and graduate education for engineers in medicine.

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