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Chapter 11: Cross-disciplinary approaches to biomedical engineering and clinical collaboration

11.1. Introduction

Cross-Disciplinary Approaches to Biomedical Engineering and Clinical Collaboration Introduction The continuous development of advanced medical technologies has vastly improved clinical practice and health outcomes in the past decades. Innovative biomedical engineering methods have increased our understanding of biological processes and provided new solutions for improved diagnostics, interventions, and therapy. However, the transfer of innovative technologies into healthcare has turned out to be challenging. Novel technological approaches often require a longer validation and approval process before they can be employed to treat medical conditions. Moreover, the healthcare market is highly competitive, which poses financial risks for many start-ups and innovative research groups developing novel technologies. These challenges question the enforcement of a clear separation of biomedical research for technology exploration and clinical medicine using advanced technologies for treatment. New approaches are required to better combine these fields with the goal to advance healthcare technologies and optimize access to digitalization for improved patients' care. Cross-disciplinary collaboration in terms of technology development and application in a clinical setting can effectively address this challenge. The innovative strength of medical technology research from biomedical engineering can be further supported by a close feedback loop with experts in medicine. A joint expertise facilitates in-depth clinical understanding and enables the development of tailored solutions for patients' advanced care. Successful validation of novel concepts and technologies in clinical studies leads to faster and wider access to cutting-edge diagnosis and treatment options. Moreover, a close and continuous collaboration between technology developers and experts in clinical healthcare creates an enriched environment for youth transfer and advanced learning opportunities for both fields, technology, and clinical research. Such

an immersive learning experience facilitates the emergence of innovative professionals with a blended expertise, enabling future technology progress and patient care (Dubey et al., 2017; Ozdemir & Akan, 2020; Badawy et al., 2024).

All of these disciplines are crucial to the advancement of biomedicine. We discuss some boundaries here to help illustrate the interdisciplinary nature of the field and its associated academic programs. These boundaries are not hard-and-fast, differing among the concentration areas of each specialization. Not are not going to discuss all sub-disciplines of biomedical engineering. Rather, we overview and survey some major areas the field and academia focus on to help orientate the reader (Rehman et al., 2022; Zhang & Yang, 2023).

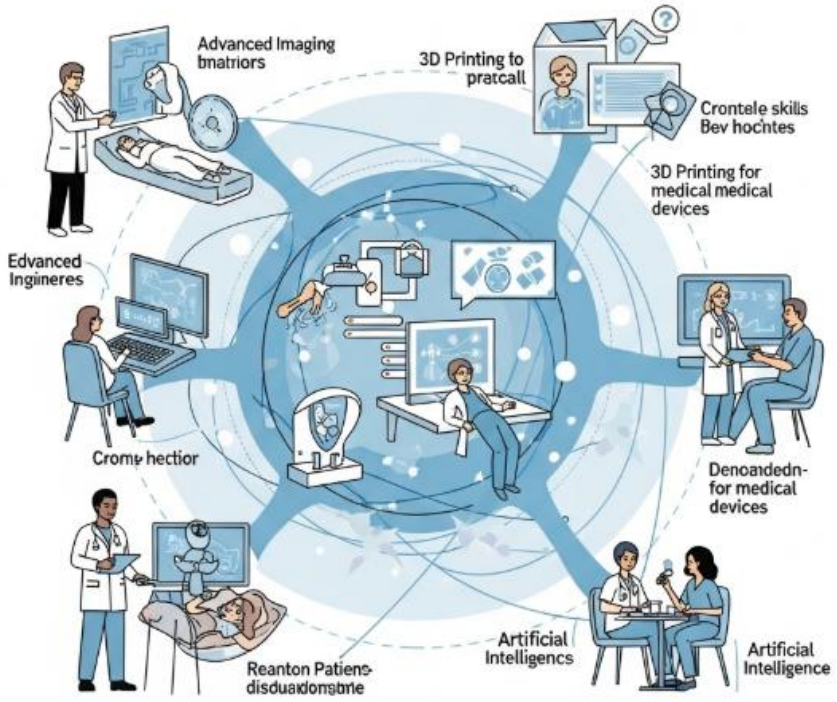

Fig 11.1: Cross-Disciplinary Approaches to Biomedical Engineering and Clinical Collaboration

11.2. Overview of Biomedical Engineering

Because of the breadth and depth of the field, there are many facets of biomedical engineering practice. Biomedical engineering encompasses taking the basic science and engineering concepts from the various disciplines of traditional engineering fields and applying them to life sciences of biology and medicine. Biomedical engineering is at the

basic research interface of engineering and medicine. Often, the goal of the engineer is to either understand the mechanistic basis of biological or pathological processes or make tools, techniques, and instrumentation to better understand biology, whether on the fundamental level of building biological machinery or slab-on-a-chip type systems to understand fundamental cellular processes, or at the clinical level with new types of imaging and analysis, and molecular marker identification for newly recognized diseases or disease processes. There is not a single academic discipline of biomedical engineering, but rather a collection of many, as the priorities of each academic program is tailored to the needs and requests of the academic department hosting the biomedical engineering programs, whether it is mechanical engineering, applied physics, electrical engineering, computer science, chemical engineering, materials science, or bioengineering.

11.3. Importance of Clinical Collaboration

Orthopedic and rehabilitation medicine strives for the restoration of optimal function after injury or disease of the musculoskeletal system. It finds itself in a privileged position in facing one of the medical disciplines most affected by the aging society, patients with mobility restrictions. Current and future generations of rehabilitation specialists are urged to develop new and innovative rehabilitation ideas and concepts to cope with the demographic change and the shortage in the area of care. Future research endeavors will be shaped by a reform of the healthcare system aimed at controlling rehabilitation costs while enhancing the quality of services and ensuring the equal distribution of therapeutic concepts.

In an era emphasizing a better understanding of different scientific disciplines and the importance of collaboration between research and practice, the fields of sports science, sports medicine, and sports rehabilitation are defined by high practical relevance and wide-ranging connections to other disciplines. High-volume acute- and overuse-injury patients create the need for scientific work oriented toward clinical use. However, large prospective clinical studies are often difficult and costly to realize, especially with regard to rehabilitation. Large single-surgeon, cohort studies, and case studies or propensity score matched studies are useful tools for clinical questions, which can be applied well in the demanding area of rehabilitation. This requires not only good collaboration with the clinical partner but a real interest in clinical questions. To follow this direction, Maxillofacial Surgery and the Department of Orthopedic Surgery made a real effort into matters of biomechanics and functionalization.

11.4. Interdisciplinary Models in Biomedical Engineering

Biomedical engineering is a rapidly growing sector that combines various areas of study and application. The expectation within the United States is that, over the next 10 years, approximately 24,000 new jobs will be created, specifically in the development of equipment designed to assist with the problems of aging in society. However, it is critical that these new engineers complete their studies with the competence required of practically any area of applied biomedical technology in the real world. Proposed solutions to meet these growing demands of biomedical engineering and to also fulfill the capabilities of entering students education ranges between diverse types of interdisciplinary collaboration models. Although these considered models are not exclusive, a unique collaboration framework likely will amplify the weaknesses and fail to foster new competencies.

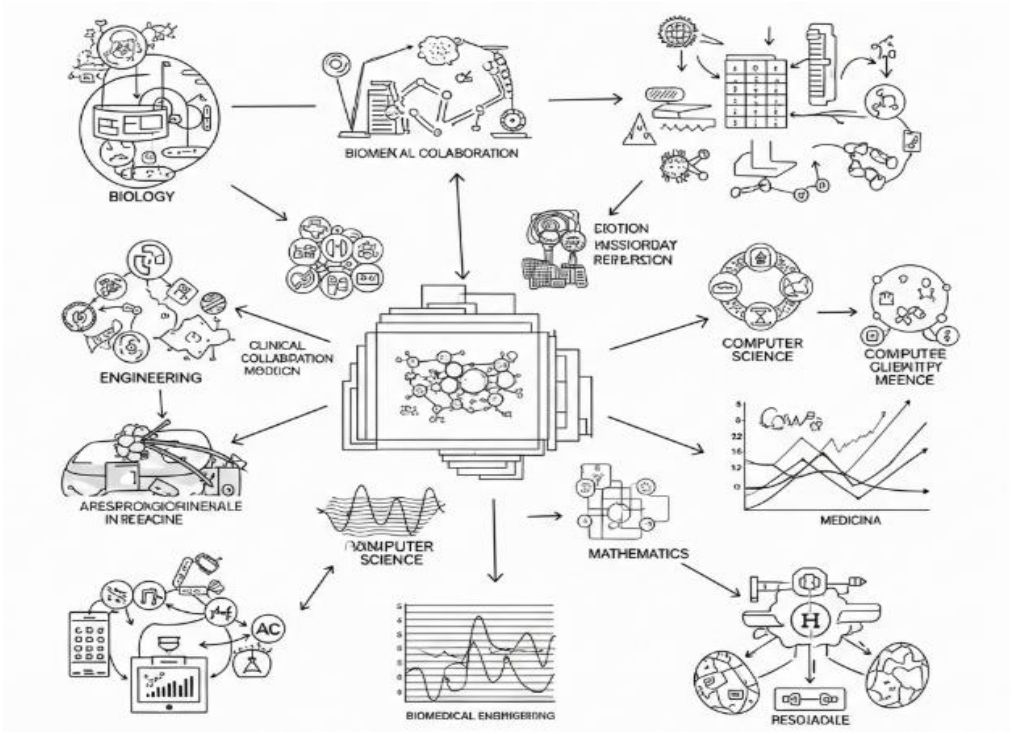

Fig 11.2: Interdisciplinary Models in Biomedical Engineering

Increasing complexity drives sufficiently experienced professionals from different domains into interdisciplinary academic collaboration in order to instruct students in real-life issues pertaining to their discipline and solutions spanning other areas of expertise. In this perspective, the aim is twofold: expose students to the understanding of what it means to work with other types of professionals in a biomedical context, beginning with the courses they take prior to engaging specifically within their major

area in the final years of their program, and address multidisciplinary items by floor, while inspiring students to continue interdisciplinary discussions on these basic items at a senior level. This type of discussion can narrow any knowledge gap between engineering and clinical application domains, sharing the same goal: provide well-structured opportunities for face-to-face unplanned exchanges. Students can benefit from the capacity of experts in an area, to bring out words of knowledge, themselves nourished by healthy discussions that can generate clear SOA for specific questions.

11.4.1. Collaborative Frameworks

The inherent complexity of living systems has forced new medical engineering initiatives to be both cross-disciplinary and multi-disciplinary. Engineering is an ideal partner for the medical community, and investigations accomplished in collaborative research efforts have the potential to improve productivity for all participants. Multi-disciplinary approaches often consist of a collection of experts with little or no coordinated effort, interaction, or truly shared goals. True collaboration creates a creative research culture that encourages and supports multiple and shared perspectives, goals, and methodologies, while fostering informal communication among all participants. Funding from government and/or commercialization efforts often thrive on collaborative and interdisciplinary interaction. For this reason, many sponsors are increasingly active in encouraging and facilitating collaborative research activities at the very root of research, as are the organizations that support these efforts.

Recent initiatives indicate that a focus is on high-risk research using collaborative, team-based systems. There is also a high value placed on interdisciplinary linking projects with real world problems, offering them a funding advantage over single-investigator basic science projects. Opportunities for growth in this arena are plentiful, with many reporting on regional clusters/centers with a focus on technology transfer. Such collaboratives are ripe pools for the reservoirs of talent that keep technology thriving. Partners needed for economic growth are already linked to universities and medical institutions via the supply-chain of products, graduates and intellectual endeavors. As hospitals and universities see the positive contributions of technology development on our wide-ranging biomedical problems, as the economy demands new ideas to sustain growth, and as support finds its way to only those endeavors with proven collaborative merit, the demand for growing partnerships will accentuate "the prime responsibilities of academia and hospitals to teach, care and discover."

11.4.2. Case Studies in Interdisciplinary Teams

Case studies of collaborative partnerships in health systems suggest evidence of better outcomes, high adoption, and influence on practice. Existing models, collaborative practices, and evaluation frameworks presented in this chapter create a foundation upon which health services research can build. Understanding what makes interdisciplinary collaboration most effective requires examination of how, when, and why it works or does not in very specific health practice, teaching, or research contexts.

Researchers undertook a collaborative learning agenda for implementation of an experimental surgery in deaf children, chronic conductive hearing loss, and tympanic membrane reconstruction. This practice provided both evidence of better outcomes, but also evidence of insufficient evidence to influence practice. Three co-chairs participated in quarterly face-to-face meetings during a 2 year period to oversee and implement the project. An academic attending physician, a theater nurse, and an industry advisor were linked with a program support grant. This funding was used to support a graduate student who was part of the interdisciplinary core-working group.

Realizing the benefit in academia for funding industry led interdisciplinary collaborative work, researchers lead a study to identify comparative paradigm benefits in the commercialization of surgical advances for ophthalmology. These comparative team recruitment and remaining challenges led to suggestions for improving success in the commercialization of technology if resources are appropriately designed by governments and institutions. These need time in various environments including clinical, academic, and industry.

11.5. Technological Innovations in Healthcare

Advances in sensing technologies are promoting new innovations in several areas, enabling disruptive business models and addressing issues such as wellbeing, chronic diseases, the accessibility to health solutions, and patients' experience throughout the healthcare process. Wearable sensor-based devices and Mobile Health apps that run on smartphones have become ubiquitous in daily life. Wearable devices help in monitoring several vital signs and biometrics. The sensor data can be interfaced with smartphones and analytics platforms to track everything from steps taken and heart rate to the amount of sleep and blood serum glucose. These advanced systems are helping manage diabetes remotely using machine learning along with caregiver involvement, and have shown significant improvements when it comes to patients sticking to their management goals. Despite enabling individuals to proactively manage their goals and health, and even allowing researchers to collect valuable data, many of the wearables lack the usability and security aspects of traditional medical devices. In addition to sensors in wristbands

and smartphone apps, other biosensors placed on the skin include: the use of Electrocardiogram and Photoplethysmogram for heart monitoring, Hyperhidrosis for sweat detection, and recently developed epidermal microfluidic biosensors for the monitoring of lactate, electrolytes, and glucose among others. Remote-care solutions have been enabled by video conferencing tools, now augmented by chat messaging apps, voice-recording tools, and even robots using Artificial Intelligence to augment providers in reaching out to patients, exchanging information, and enhancing the experience. Telemedicine provides a way for patients and healthcare professionals to communicate and work together using technology, while overcoming geographical limitations.

11.5.1. Wearable Technologies

Wearable technologies are electronic devices worn close to the body, or on the body, which send and receive data. Wearables are most commonly reported in business, entertainment, fitness, health, and mobile computing. The wearable healthcare devices market is expected to exceed USD 174 billion by 2026. The wearable healthcare solutions segment is expected to grow at a CAGR of over 23% during the forecast period. Communicating and receiving data from a wide variety of sensors such as gyroscope, accelerometer, magnetometer, temperature, optical heart rate, galvanic skin response, pressure sensors, bioimpedance sensor, near infrared sensors, laser Doppler vibrometry, and electrocardiogram, wearables are increasingly applied in the healthcare domain for monitoring a wide variety of body functions such as heart rate, heart rhythm, blood pressure, glucose, oxygen saturation, motion tracking, multi-channel impedance cardiography and bioelectrical impedance analysis, identification of sleep apnea events, and providing solutions for sleep quality analysis. Most wearables are smart and connect to the cloud for storage and data analysis using artificial intelligence. Simple wearables use the onboard microcontroller for storing required data. Various smart wearables such as smart watches, wrist bands, and headgear are commercially available for monitoring well-being functions. In applicability, various wearable biomedical and healthcare devices may be deployed on the skin, in the clothing, implanted in the body, or consumed by the body. Such wearable technologies have transformed the era of mobile health and have made abundant and amazing personalized health data available for people and clinicians. However, the general adoption of wearable technologies is still lacking and is majorly attributed to issues related to data accuracy, data security, and regulatory policies.

11.5.2. Telemedicine Solutions

Advanced technologies allow the development of novel solutions that can deliver high quality biomedical services for patients that are not able to access a healthcare facility. Telemedicine solutions expand the team of medical professionals that can provide healthcare services and create a connection between medical staff and patients, with an unprecedented flexibility. Remote consultations can save traveling time for patients located far from medical facilities, who can talk to doctors and other professionals to discuss possible conditions or next actions to be followed. High definition video conferencing tools that combine specialized electronic equipment, such as tablets and mobile devices connected to ultrasonic transducers, are replacing other more traditional modalities.

Physicians can use smart devices to support their job and provide patients assistance in real time but non expert users may encounter difficulties when using these resources so it is important for doctors to be trained to share clear instructions. Nurses can work together with other medical staff using telemedicine solutions for daily tasks support, such as drug administration and for follow up patients. Remote assistance may decrease the burden of face-to-face visits and ensure for patients in risk of hospitalization an adequate monitoring to avoid or delay hospitalization.

11.6. Regulatory and Ethical Considerations

Biomedical devices are designed to be used on or in living humans for therapeutic or diagnostic purposes and can include everything from scalpel blades to respirators to highly sophisticated devices such as implantable cardiac pacemakers and vascular grafts. The design and development of devices can have significant health consequences for both intended users and the public at large, and in the United States, the regulatory body oversees the design, testing, and marketing of these devices to assess their safety and efficacy and to protect public health. The regulatory body was originally created to regulate foods, pharmaceuticals, vaccines, and other products classified as biologics. Regulations regarding medical devices were added later, and over time, amendments, updates, and new laws have made the device regulations what they are today. Engineering students and practitioners whose projects involve biomedical device design are working within a legal framework that has the force of law.

However, design regulation is only one of many issues that affect biomedical device design. Device applications raise myriad ethical issues as well. Because biomedical devices are constructed for use on or in living humans, ethical issues in their design and use are especially important. Possible issues include the biomedical device's effect on the intended user's status and self-image, the moral standing of the user, questions

surrounding soundness of consent, and legal liability when a device fails or is misused. Exploring these ethical issues involves understanding ethical principles from philosophy and medicine and also may require historical and contemporary examples to help codify specific practical solutions.

11.6.1. FDA Regulations for Biomedical Devices

The FDA was signed into law as the 1938 Federal Food, Drug, and Cosmetic Act. There had been several other federal acts that addressed these kinds of topics but nothing as comprehensive as the FFDCA. In 1976, the Medical Device Amendments were added to the FFDCA. The 1976 Amendments created a new regulatory framework for medical devices to ensure their safety, effectiveness, and quality. Led by an early FDA Director, the FDA set up a comprehensive strategy to regulate many devices useful to surgeons, especially orthopedic implant products.

There are a few distinct, specific steps that a biomedical engineer must follow to get FDA clearance on a medical device. The first step after the design phase is to do a Pre-Submission meeting. This unofficial meeting is a way for device manufacturers and FDA personnel to get on the same page before the device manufacturer spends a lot of time and resources working on a premarket application. It is common for a Pre-Submission meeting to take up to several months to schedule and complete. However, this informal meeting is an invaluable resource in getting feedback on the design, data collection, preconceived regulatory path, and other aspects of the planned study. Following the Pre-Submission meeting, there are a variety of regulatory pathways that cover the clearance of medical devices with varying levels of complexity, the most common being the abbreviated pathway. After a company has FDA clearance, the company must then comply with GMPs and possibly CLIA as well. Once the device has been approved and released to the public, the company must also be aware of post-market surveillance as well.

11.6.2. Ethical Implications of Biomedical Engineering

The exploration of ethical implications of biomedical engineering collaborations is merely at its genesis. This lack of progress can be largely chalked up to the relative novelty of the field, with the potential for ethical issues seeming so grand that researchers have not known where to start in mapping the territory. Biomedical Engineering stands poised to greatly impact patient care, and that role is heralded as both a privilege and a responsibility. There are an abundance of specific areas already put forth which specialize within the more broad ethical implications for medicine and engineering, such as medical decision making, global health, and professional identity. Yet, for these

topics, work usually begins with an explicit taxonomy. Here, we have composed a definitional backbone upon which to hang any later work on a more specific aspect of what makes Biomedical Engineering collaborations unique from other cross-disciplinary endeavors. While the idea of engineers in the clinic or working with patients is not new, the domain-specific aspects of Biomedical Engineering are unique which renders it both rewarding and ethically precarious.

The fact that Biomedical Engineering collaborations differ from other departments working in healthcare may draw people into the domain, but it also makes it particularly susceptible to relevancy issues and collaboration fatigue. When people believe negative evaluations reflect a lack of success, attention tends to drift toward evaluation and away from establishing lasting professional identities that link to concrete personal outcomes. The ethical implications of a Biomedical Engineering identity specifically should be more longitudinally evaluated to clarify actual tensions and positive outcomes - to allow for reflection, insight, and, we would hope, resolution. It is one of the most challenging, and rewards us to consider the potential of others regarding our work, the training and academics responsible for that growth, and the lasting importance of the work over time.

11.7. Education and Training in Biomedical Engineering

Biomedical engineering has emerged as a powerful blending of discipline, an interface between the natural sciences, and the clinical sciences of medicine and surgery. Education in and research within the realm has advanced rapidly but retains a number of tentative characteristics. Educational programs are often new and are evolving in response to need. Research, much of it being funded through established engineering mechanisms and directed toward obvious biomedical applications, is nevertheless often poorly focused, lacking the developmental support of the traditional and well-established clinical science mechanisms. Emerging areas with great promise, cell and tissue engineering and prosthetic implantation in particular, exemplify the need for well-organized initiation of research support to establish a strong clinical-scientific environment. Biomedical engineering education typically has a pedigree derived from engineering or the basic sciences, with contact courses in quantitative and life sciences as adjuncts to the primary curriculum. Increased pedagogical pressure from the medical schools for integrated and comprehensive exposure of the medical student body to the prerequisites of medical disciplines will add to the interest and urgency of BME education in the undergraduate setting. While integrated organ systems dissection, neuroanatomy, site-of-service visits, and early exposure to clinical medicine have always painted the background picture, integration of the detailed preclinical requirements with the clinical disciplines is now being actively pursued. Engineer educators in the field have thus been drawn into discussions of curriculum content and organization, as well

as critical student state factors, for the med school years. The potential exists for an exciting era of synergistic integration of information and methodology flow between biomedical engineering and clinical medicine.

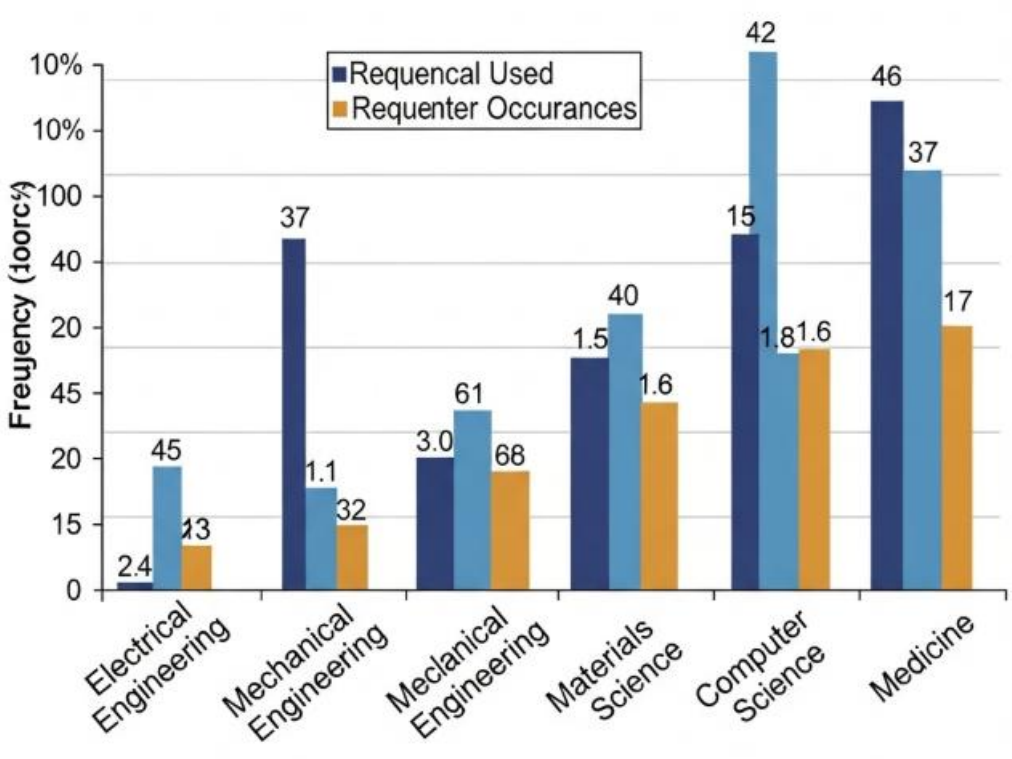

Fig 11.3: Biomedical Engineering and Clinical Collaboration

11.7.1. Curriculum Development

Biomedical Engineering (BME) programs in universities are extremely diverse in terms of both undergraduate and graduate training – the programs range from interdisciplinary, to primarily an engineering program, to primarily a biology program. Because the BME area is not a core discipline but rather an interface with many other fundamental core disciplines, the research and training environment at any one institution varies greatly from their others. At an interdisciplinary institution, BME students have access to a rich number of BME-related research efforts spanning multiple departments and core disciplines that go beyond the biomedical realm, e.g. transport phenomena from chemical engineering faculty, biomechanics studies from mechanical engineering faculty, modeling and control of physiological systems and robotics from electrical engineering faculty, artificial organs from biomedical engineering and chemical engineering faculty, etc. At an engineering-dominant institution, BME students interact

with engineering faculty while engaging in the specific application of engineering principles to biomedical problems. At a biology-dominant institution, BME students are mentored by BME faculty who have connections to multiple biology core disciplines.

At this time, there exist only 17 ABET-accredited undergraduate BME programs within either engineering or biomedical engineering. The ethos of engineering, together with ethics training during engineering programs, continues to attract the public's confidence in the ability of engineers to use the tools of engineering to address the pressing problems of the day. Efforts are underway in some of the major BME programs to become ABET-accredited. However, there exists a major concern by the BME faculty at these institutions that an ABET-defined curriculum will diminish the current ability of those graduates to operate at the BME interface and limit their employment opportunities to positions at engineering firms not associated with biomedical products. In procedural animation by physicians, graduates must be able to work in the environment where the high-pay, lower-risk, and lower-demand career opportunities are: medical devices and surgical procedure development.

11.7.2. Interdisciplinary Training Programs

Interdisciplinary training programs are an essential element in successfully bridging the gap between basic science, engineering, and medicine. In addition to educating students and faculty about the methodologies, philosophies, and approaches of different fields that enrich BME, these programs enable the trainees to carry out cross-disciplinary research. Interdisciplinary programs are being developed at universities around the world. These programs include formal dual-degree programs, graduate minors or certificates, and specialized PhD training programs. These programs usually have a similar goal in that they incorporate courses and research from multiple disciplines but often differ in implementation details including funding and duration.

11.8. Funding and Resource Allocation

Creating and implementing cross-disciplinary curricula costs money – teaching and program coordination takes time and resources, and creative, flexible financing is key to sustainability. In addition to standard funding sources assigned to undergraduate and graduate programs, potential support could come from the governments, as they currently emphasize the role of translational science in their agendas; private funding organizations, as they increasingly demand that funded discoveries return faster to the public, granting agency directive initiatives; and finally, biomedical industry, which has a vested interest in bridging the gap and shortening the timeline from basic to applied research applications.

Governmental and non-governmental agencies and financial institutions urge scientists to reach out to the general population, as they have a vested interest in ensuring that their grant funds generate as much social and commercial value as possible. Several agencies are also willing to support proposal development, prototyping, and the initial stages of collaboration with industry partners, through innovation bridging funds, sometimes even establishing specific funding lines. Initiatives provide tips to navigate the incentives inserted in the business funding system for academic research. Strategic grants may include support for collaborative curricula development, especially proposal sections describing the prospective graduated workforce employing translational science and a description of barriers to workforce training and emerging technologies partnerships. The Revenue from Diminishing Education Tax Credits could be used for partnerships between industry and academic institutions, to create advanced unique courses and programs.

11.8.1. Government Grants and Support

Biomedical engineering (BME) is, at its core, a basic and applied science. Discoveries made in the BME space typically require expert translation, which often falls within the purview of the biomedical and clinical researchers, whose work is supported by funding. By and large, however, the area of discovery and innovative application of tools, methods, devices, and other technologies that reside in the BME realm have been supported principally through governmental funds and less through private sector initiatives. It is only recently that venture capitalists and private investors have developed a level of comfort in funding and supporting university start-up companies to innovate, commercialize, and apply technologies that address problems identified by clinical collaborators in the health and biomedical fields. Furthermore, most state governments are keen to invest in these state university spin-out ventures, seeing the two-fold benefit of economic growth and further scientific development. These efforts have emerged, usually in concert with the universities and their venture acceleration programs, alongside a very focused international patent portfolio initiated and nailed down by the funding company and university.

Government funding agencies have taken the initiative in some fashion to develop much needed partnerships with private funding organizations in new areas of research and resource allocation in translational research. There is clearly a point of convergence for fruitful collaborative work in BME, and new funding initiatives and support will be needed at all levels to successfully advance translational research and development.

11.8.2. Private Sector Partnerships

To build the most useful and beneficial projects, corporate partners should assign proactive project leads whose interests naturally align with the research teams tackling the projects. Companies should ideally leverage expertise through interaction with center staff members who have experience in relevant areas, such as biomechanical engineering, proof of concept research, experimental and computational imaging, modeling, and design, and the clinical area. Exploring funded research projects of other academic research groups is helpful in identifying an area match. Projects that are too near commercial interests generally do not have enough rigorous effort to be useful to either side. Research and Clinical Collaboration Centers positioned in academic institutions are often able to take on a larger academic research effort specifically because they are attached to a larger, multi-faceted initiative. Regardless of the motivation for corporate involvement, a strategic and well thought-out plan can expedite development and de-risk clinical translation. Corporate partners are not only needed for funding and development input into pivotal clinical studies but also for distribution and product support post-market approval. For select devices and therapies, the clinical investment and market potential are so great that they will be at the center of fully private company funded research. Collaboration through initial research is certainly beneficial to the project. Devices in areas that are becoming more mature in research will tend to have an academic resources investor company partnership during their clinical development. These are barriers that should be anticipated when researching these areas. It is important that, when working with a large company, an academic device development group reaches out regularly to ensure that the company supports the academic work in a way that benefits their timeline.

11.9. Conclusion

At the end of this work, we would like to draw the attention of the readers to the fact that all the experimental biomedical towards the improvements of the healthcare systems put forward in the chapters of this book as well as throughout our research studies, designs, fabrications, and developments are only sustainable when they are implemented in the clinical settings. With this thought, we come up with the idea to present here some recommendations for the clinical interests that our book might motivate. Unlike biomedical researchers, readers might not have background knowledge of the challenges imposed by the complexity, diversity, and variability of the clinical scenarios. Along the way of translational metallurgy development, those readers might also be interested in several aspects of the research work that traditionally appeal to basic sciences and, as key players, their criteria might guide the expected results of intrusive, short, and expensive research studies.

Considering the readers' understandings about translatable results and also weigh in with their interdisciplinary opinions against researchers, authors would like to highlight the following issues. Each chapter of this work presents translatable methodologies mainly in fields from tissue engineering and regeneration to nanoscale applications, undergoing through immune response control and microbiome remediation. All these subjects are led by a top-down strategy involving the use of metals, alloys, and metal oxides as prototypes in plans for consecutive in vitro and in vivo testing rounds toward healthcare innovations. We hope that this work can inspire their ambitious interdisciplinary discussions. Moreover, we intend to give thanks by presenting it to the continued support and collaboration from all around the healthcare system, including so many doctors, researchers, and patients for all these years.

11.9.1. Future Trends

We are facing new and novel challenges from important vectors, ranging from an aging population to the ever-increasing explosion of the volume of rapidly generated life science data, including genetic, proteomic, and metabolomic reflections. Each of these elements is providing exciting new opportunities, and biomedical engineering research and practice has much to offer to answer these challenges. However, this will only happen if we engage the changed new experimental lines of important science-based questions from the clinical groups we now need to collaborate with. Similarly, meeting important clinical needs and engaging clinical and basic science partners in our innovator discovery-driven laboratory environments – external to both engineering and clinical partners' normal established comfort zones – will only happen if we can cultivate strong two-way collaborations with respect to clinical requirements and engineer-to-clinic solutions. This totally different paradigm, where practitioners have been required to explicitly engage in service-focused engineering and engineering-based clinical expertise to meet questions that are drawn from real-world needs, has evolved over the last 5 decades, but graduate program "How To" is still poorly defined.

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