Exploratory Examination of an Interdisciplinary Engineering Field: Tissue Engineering and Regenerative Medicine

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Introduction

This research paper examines faculty perceptions of a rapidly developing interdisciplinary engineering field to inform adaptive undergraduate curricular reform. Interdisciplinary engineering programs and courses, those that focus on solving problems that require skills and techniques of multiple disciplines [1], have gained traction in engineering education [2], [3]. Such programs have also been shown to promote 21st century skills (critical thinking, complex problem solving, self-efficacy, etc.) [4] and diversity in the engineering pipeline [5]. One field that both embodies the characteristics of interdisciplinary engineering and has motivated the development of undergraduate specific programming is tissue engineering and regenerative medicine (TERM). TERM, a subfield of biomedical engineering (BME), brings together researchers from a variety of traditional disciplines, including engineering and physical sciences, to perform research focused on the micro to macro-level fabrication and regeneration of tissues. While this field has continued to grow since the 1970’s [6], it faces challenges shared by other interdisciplinary fields when trying to develop and implement curriculum for interdisciplinary programs.

Rapid growth in interdisciplinary fields and subsequently interdisciplinary academic programs has created programs with ill-defined disciplinary skills for students graduating from those programs [7]. As a result, interdisciplinary engineering program graduates regularly pursue careers outside of traditional engineering jobs [8], often making career trajectories unclear after graduation [9]. In an effort to more effectively scope an interdisciplinary engineering field, many academic journals have created annual reviews to address trends in research. One example of such efforts is the annual Tissue Engineering and Regenerative Medicine International Society (TERMIS) Year in Review [6], [10]–[13]. Each year, TERMIS publishes a review of the groundbreaking advances in the field. Researchers in the field of TERM use these reviews to inform the direction of their research. However, it is unclear how or even if the new advances are integrated into TERM undergraduate curricula. As curriculum is the primary method for students to gain the knowledge necessary to enter into a field of study after graduation, research efforts wishing to improve student experience and success should focus on understanding the important aspects of the field through the lens of those who shape it.

The purpose of this study is to close the gap between interdisciplinary engineering practice and undergraduate curricula. In this paper, we develop a framework for studying interdisciplinary engineering programs in the context of the progression of engineering and situated learning theory. We then use this framework to explore TERM literature and characterize TERM professional practice. Findings from this study can be used to inform evidence-based curriculum development in rapidly evolving interdisciplinary engineering programs, particularly in TERM. The research was guided by two research questions:

1. How do faculty working in the field of TERM define or describe engineering generally and tissue engineering specifically?
2. How do those definitions inform their emphasis on specific skills and concepts important in TERM as well as the role of engineers in the field?
Research Framework

In this study, we first explore how an interdisciplinary engineering field is influenced by historical engineering definitions, drawing from literature using philosophy to inform engineering and technology [14], [15] and literature about the progression of engineering design in curriculum [16], [17]. We then examine the interdisciplinary community of practice through the lens of situated learning theory [18] to explore current interdisciplinary learning experiences. We use this theory of learning to reason that the important skills, concepts, and roles of engineers in a field are largely defined by the ‘community of practice’ [18] and that understanding the conceptions of the community members can better inform curricular and co-curricular efforts to improve the interdisciplinary engineering student experience.

Progression of the Engineering Discipline

While interdisciplinary engineering fields and programs have developed iteratively by working with several other disciplines to solve complex societal problems [19], a common link between these interdisciplinary engineering fields and programs is the context of what engineering is to the people who practice it. Historically, engineering is a broad discipline and has a history of fluctuating norms, disciplinary definitions, and values systems, and as such, consensus on how to describe the philosophy of engineering has yet to be reached [14], [15].

While not all individuals who have worked to describe engineering agree on the common aspects of engineering, the term has evolved to regularly incorporate concepts like transformation of the natural world, use of scientific principles for some practical end, and the incorporation of design principles [14], [15] across broad groups in engineering. These descriptions indicate that there is not a defined body of knowledge that engineering is based on, but rather, engineering is focused on the use of established knowledge for practical purposes, one common purpose being the design of solutions to problems [14]. Furthermore, the literature exploring philosophy and engineering commonly discusses the ethical implications of these designs and their influence on humankind [15]. While discussions about the relationship between philosophy and engineering is constantly evolving, the focus on application of science for some practical means continues to be prevalent in discussions [20]. Because the focus of engineering is not on a specific knowledge base, but rather a utilization of scientific principles to meet changing societal needs [21], engineering disciplines continue to evolve and therefore must be consistently analyzed to better inform curricular design.

The design process is also commonly discussed in engineering literature [14], [15], and has also gained traction in engineering curricula in recent years. Engineering design is now a key part of engineering curricula regardless of disciplinary emphasis [16], [17], [22] and is likely an area of discussion in many interdisciplinary engineering fields and programs. Design processes vary slightly across disciplines and even across universities or industries, but most processes share characteristic activities such as identifying a need, defining and analyzing a problem, making decisions, detailing, and presenting and communicating a product or solution [23].
**Situated Learning as a Lens for Interdisciplinary Engineering Field Development**

In practice, interdisciplinary engineering program development aligns with descriptions of learning by Lave (1991), both in the student experience and in the creation of knowledge by current members of the ‘community of practice’ [18]. In their paper, Lave (1991) described learning as “… a process of becoming a member of a sustained community of practice” arguing that “Developing an identity as a member of a community and becoming knowledgeably skillful are part of the same process… (pg. 65)”.

A previous study consistent with this theory of learning in an interdisciplinary engineering setting showed that participation in activities relevant to a discipline may increase students’ understanding of the disciplinary skills and concepts to the same degree as traditional engineering educational strategies [24].

In addition to meeting those educational needs, situated learning theory supports the notion that authentic and incremental participation in a given field may also help students identify themselves as part of the community of practice [18] after graduation. To develop an identity as a member of the community, it is important for students to know what the field deems important regarding skills, experiences, knowledge, and values. This has been particularly difficult for students in interdisciplinary engineering programs and fields because the broad scope of work performed has made it challenging to create interdisciplinary engineering curricula that effectively develop competencies and experiences to prepare all students for careers in a way that is satisfactory to them [9]. As such, effective engagement of students and strategic development of curricula in a rapidly evolving interdisciplinary engineering field may require a better understanding of how current members describe and comprehend their community [18] as it evolves.

**TERM Conceptual Framework**

We used our research framework to perform a literature review of TERM and develop a TERM-specific conceptual framework (Figure 1). Literature discussing design experiences as well as situated learning specific to TERM students is discussed below. This resultant conceptual framework was used to inform our analysis and data interpretation.

**Engineering Context in TERM.** Based on our interpretation of discussions in established engineering literature, we focus on three topics relevant to TERM: engineering design, human (ethical) focus, and science for problem solving. Currently, TERM undergraduates are commonly trained in biomedical or bioengineering programs, taking both foundational engineering and bioscience courses. Engineering design is a core concept taught in engineering programs. Additionally, students are often exposed to design concepts during co-curricular lab experiences [25]. Furthermore, the strong biological focus of TERM research efforts indicates that human and ethical focus could be prevalent in discussion on TERM, prompting investigation of this topic in our study. Finally, Newstetter’s (2005) study of BME labs indicated that engineers may emphasize maintaining focus on solving complex problems using biological concepts and strategies in addition to using the concepts and skills of a traditional engineering field [24].

**Situated Learning in TERM.** Learning environments in BME labs have been extensively studied to identify features (i.e. skills gained, concepts learned, and how) of positive learning experiences for students and create strategies to improve those lab experiences [24]–[28].
Various learning theories have been used to study these lab environments (e.g. distributed cognition [26], cognitive apprenticeships [25], situated learning [24], and agentive learning [28]). One of the studies specifically focused on a TERM research laboratory identified two skills which are relevant to the situated student learning environment [28]: the observed need for members to persevere in the face of failure and a focus on model systems as research tools [28].

Tissue engineers frequently work with complex biological systems (e.g. cells, tissues) and instruments when performing research. These complexities create significant risk of failure or difficulty when performing TERM research. These aspects of research are prone to unpredictable difficulties such as: unexpected death or contamination of cultured cells, malfunctions of instruments or experimental protocols, and unclear outputs of instruments. In turn, these research complications can have serious effects on the model systems [28] commonly used in TERM research. Model systems, as described by experienced BME researchers, are used as parallels to in vivo systems to perform systematic experimentation [28]. Due to their complexity, both cognitively and technologically, model systems are typically developed over the history of a research group, with multiple individuals contributing to the knowledge of the model system.

**Research Design**

Based on our research framework, we reasoned that the important skills, concepts, and roles of engineers in a field are largely defined by the TERM ‘community of practice’ in our study. We utilize qualitative methods as aligned with those typically used in engineering education research [29] to discuss those concepts with our participants and gain a deeper understanding of the important aspects of TERM.

**Participants**

In TERM, faculty are dually responsible for 1) interacting with members of the field and 2) training students on TERM practices so they may become members through apprenticeship. In our study, we focused on ways faculty described student curricular and co-curricular lab experiences as ways for them to move toward full participation in the TERM professional community. TERM faculty play a pivotal role in apprenticing students as they are entering the field. Not only do they educate students directly, but also frequently interact with other members of the community like clinicians, basic science researchers, and industry engineers, creating meaning together and actively shaping the TERM field.

With approval from the institutional review board (IRB), we conducted semi-structured interviews with 17 TERM faculty. We first employed purposeful sampling of faculty involved in TERM research at a large, R1 university in the Midwest to recruit our initial 8 participants [30]. As those interviews were performed, we employed snowball sampling, asking participants to identify TERM researchers outside the university who they feel would have insightful perspectives [30]. TERM faculty were selected because we identified them as primary stakeholders working in the field for the following reasons. Currently, TERM research is largely located in academic research institutions. Additionally, TERM faculty are the educators responsible for implementing curriculum and providing training to engineering students entering the field. We worked to recruit researchers of all academic and technical training backgrounds to increase the diversity in our sample population in order to improve the credibility of our study.
Participants were also diverse with respect to gender, ethnicity, experience, and institution type. For example, we interviewed 7 assistant, 4 associate, and 6 full professors (2 of which were chairs) from all regions of the United States except the Northeast. Faculty interviewed worked at R1, R2, and Specialty Institutions. During the interviews, we did not explicitly ask participants to express their identified gender or ethnicity, and as such, we do not report them here.

Figure 1. TERM conceptual framework of the integration of previous literature to inform the research questions asked in this study.

Data Collection

Semi-structured interviews are useful for exploratory research because the structure of the prepared questions reminds researchers of the topics to discuss while still allowing significant room to adjust the trajectory of the interview as the conversation necessitates [32]. Participants were asked to choose between a face-to-face interview (based on participant location), a phone call interview, or a video conference interview through a conferencing software, BlueJeans. Except for one, interviews were recorded, and field notes were taken by the researcher(s) present at the interview. One participant preferred their answers be recorded through field notes only and, therefore, no direct audio was collected. Interviews probing participants’ backgrounds and perceptions of TERM lasted approximately 30-45 minutes. Interviews were then transcribed using an external transcription service, checked for accuracy, and stored electronically on a secure server with the corresponding field notes.

Thematic Analysis as an Exploratory Research Approach

Using thematic analysis [33] as an approach to make meaning [34] of the qualitative data collected, the first two authors analyzed the data of this study using our conceptual framework which synthesized historical engineering definitions and situated learning theory literature in TERM. Similarly, roles held by members and important skills or concepts for new members to
master are defined by the same community of practice. As developing members of the TERM community of practice ourselves, the two researchers who performed the analytic work of this study found thematic analysis a valuable tool to develop a rich description of the values TERM community members placed on our areas of interest. Our knowledge of the general terminology used in the field allowed us to see emergent themes in the data that may have been missed if we were not already familiar with some of the practices in the field. The third author reviewed our interpretations of the data throughout the data analysis process to ensure that results can be understood by individuals not central to TERM.

Data Analysis

Using our conceptual framework as an analytical lens, the interviews were analyzed using a first and second cycle coding approach as described previously [35]–[37]. In first cycle analysis, the first two authors inductively coded participant responses using a hybrid of descriptive and in vivo codes [38]. We found descriptive, in vivo codes helpful in ascertaining common areas of discussion in the interviews. To aid in the consistency of our analysis process [33], we separated data in stanzas [37] which we defined as an interviewee’s talk uninterrupted by an interviewer’s question or commentary. Each stanza of our data could be coded with multiple codes in the first cycle of analysis. To establish a codebook, we coded three transcripts together, compiling and describing codes using Excel. We then each coded two additional transcripts independently using the codebook and calculated interrater reliability (IRR) using intra class correlation as an indicator of the reliability of our coding process [39]. After establishing a high intraclass correlation (0.94), the researchers divided the total dataset by interview. One researcher coded 9 interviews and the other 8 interviews. This included revisiting the data which had been used previously to establish IRR. In second cycle analysis, these codes were then analyzed further using strategies of meaning making such as counting, noting patterns and themes, clustering, and making metaphors [40].

Results

Overall, the participants of this study described both engineering and tissue engineering in ways which were consistent among participants and with previous studies of similar goals [41]. Faculty described three key categories when defining engineering including: design, the idea that engineering is purpose driven, and that engineering applies various scientific principles. Additionally, many participants described tissue engineering as interdisciplinary, which we link to the results of our discussions with participants about skills and concepts in TERM. Concepts discussed covered a broad range of topic areas that could be broadly generalized into two categories: concepts associated with content knowledge and concepts associated with product design or development knowledge. Similarly, numerous skills were identified and could be categorized as being developed through coursework or experientially. Interestingly, some skills mentioned also pertained to what we would consider personal attributes, such as creativity and practicality. When discussing the role of tissue engineers in biomedical research, participants described tissue engineers as being capable of bridging fundamental understanding and translational application research as well as a number of other distinguishing characteristics (collaborative nature, quantitative skills, and model development).
Descriptions of Engineering and Tissue Engineering

During the interviews, participants were asked to define both engineering generally and tissue engineering specifically. When asked to define engineering in a general sense, there were three consistent categories mentioned by participants (47% of participants identified all three, 65% identified at least two): design, the idea that engineering is purpose driven, and that engineering applies various scientific principles. Participants’ descriptions of engineering were highly aligned with how engineering has been defined historically [14], [15] as well as aligned with similar work interviewing engineering faculty about their descriptions of engineering [41]. As an example, participant 2 described all three categories in their definition of engineering and went on to explain that specific engineering disciplines apply different fundamental sciences.

Participant 2 “In general, to me engineering is applied science. Any fundamental scientific principle that you then seek to apply for some purpose, to build something, design something, fabricate something, that's engineering. The different disciplines of engineering, of course, are related to the different fundamental science that underpins those disciplines.”

Descriptions of tissue engineering followed a similar pattern with approximately half of the participants describing tissue engineering in nearly identical ways as they defined engineering in general; however, they often stated that tissue engineering solved a more specific type of problem. We investigated possible links between specific features of definitions and formal engineering education in our participants’ backgrounds but did not find any clear pattern. Participants with and without formal engineering training described tissue engineering in largely the same way as they described engineering. The following quotes exemplify the observed relationship between engineering and tissue engineering definitions.

Participant 17 “Engineering is the use of math, science, and physics to solve problems.”
“Tissue engineering is the use of math, science, and physics to develop tissue constructs. Oftentimes you're trying to design them to solve a problem, which is the loss of tissue due to injury or disease. That definition has expanded to the use of engineering principles to design tissue mimics, for testing or in our case for developmental biology testing or eliminate the use of incorrect animal models.” (underline indicates topic of definition)

Participant 4 “Tissue engineering is same definition [the use of physical and mathematical principles to design solutions to problems that can benefit mankind], but the problems that we generically spoke about in the engineering definition, here are the specific problems are regenerating and reconstructing tissue that's lost due to some type of insult, be it disease or trauma or aging, or generic conditions.” ([ ]) indicates general engineering definition

We further probed participants to evaluate what problems tissue engineers feel they solve. A commonly identified motivation for their research was to restore, repair, replace, or construct tissue(s). These motivations align with the human focus historically present in engineering disciplines [14], [15].

Participant 14 “I think it's combining what we know about biology and using kind of engineering principles to be able to construct something that would restore or repair something that's damaged. Or a tissue that's damaged.”
Tissue Engineering is Interdisciplinary. We also found that TERM faculty consistently described their field as multi- or interdisciplinary. Over half the participants described incorporating multiple sets of disciplinary knowledge to solve the problems tissue engineers address. Some identified disciplinary knowledge included basic sciences, physical sciences, traditional engineering, pharmacology, translational medicine, commercialization, and regulatory affairs. This theme was consistent through our interviews, with approximately half of participants describing the field in the same manner as Participant 12:

Participant 12 “I think it's sort of melting pot or integration of cell biology, biomedical engineering, some chemical engineering, material science, and some advanced math because you kind of need everything to make a good model for tissue engineering for any specific problem.”

In addition, four participants said that tissue engineer’s multiple disciplinary knowledge bases set them apart from other researchers in biomedical research. While participants felt that TERM incorporated multiple disciplines, the disciplines discussed were not consistent across participants. They varied by the number of disciplines mentioned and by the disciplines themselves. Unsurprisingly, this led to a wide variety of skills and concepts discussed by participants when asked about what was important in the field.

Participants Discuss Concepts and Skills

In discussions about what participants thought students should understand at the conclusion of their degree programs, the identified important concepts could be separated in two main themes: content knowledge and product design or development knowledge. Within content knowledge, participants discussed content knowledge that could be gained through coursework as well as content knowledge based on the specific problem they wished to address. Discussions on the second theme, product design or development knowledge, largely focused on understanding the clinical and translational context, market analysis, and the experimental context of their work on a problem (see Table 2 for more details).

Table 2. Descriptions of concepts starting at the thematic-level and moving to the code-level. Code descriptions indicate areas of discussion which were assigned to each code.

<table>
<thead>
<tr>
<th>Content Knowledge</th>
<th>Course-Related Content Knowledge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biology</td>
<td>cell behaviors, transport, metabolism and respiration, cell signaling - may be covered in cell or developmental biology courses</td>
</tr>
<tr>
<td>Chemistry</td>
<td>organic chemistry, diffusion, reaction, mass balance, chemistry related to biomaterials</td>
</tr>
<tr>
<td>Material Science</td>
<td>biomaterial properties like degradation, drug release, and formulation</td>
</tr>
<tr>
<td>Immunology</td>
<td>immunology as it relates to host-tissue (graft) interactions</td>
</tr>
<tr>
<td>Engineering</td>
<td>quality control, design, systems thinking - additional engineering fields (e.g. Chemical Engineering)</td>
</tr>
<tr>
<td>Physiology</td>
<td>concepts typically taught in a physiology course</td>
</tr>
<tr>
<td>Mathematics</td>
<td>modeling, quantifying functional properties of cells, statistical knowledge</td>
</tr>
<tr>
<td>Mechanics</td>
<td>mechanobiology, mechanotransduction, biomechanics</td>
</tr>
</tbody>
</table>
**Problem-Specific Content Knowledge**
A deep understanding of the specific content knowledge required to solve the problem addressed - could include biology of the focal tissue or system, cell interactions (with other cells or environment), multi-scale understanding of the biology of the problem

**Product Design or Development Knowledge**

*Clinical and Translational Context*
The healthcare problem addressed or having the application in mind when designing a product

*Market Analysis*
Commercialization: the commercialization process, including customer discovery
Regulations: the regulatory process required to bring a product either to the clinic or other market

*Experimental Context*
Success criteria of experiments, output measures, field norms for methods and research questions, how to appeal to funding agencies (grant writing), the pros and cons associated with animal models

Skills similarly varied and were separated into three themes: skills which could be learned through traditional coursework, skills which could be developed experientially, and a third theme which more broadly covered personal attributes that our participants thought made successful tissue engineers (see Table 3 for more details). Participants mentioned these personal attributes while identifying their perceived important skills, which indicated to us that they were intentionally included in this part of the conversation.

Participant 8 “...Lastly, I think tissue engineers need to be comfortable with failure. Just like in all research, there's a lot of failure, but I think in tissue engineering, there's the opportunity for enormous failure because there's so many variables going on that we can't always control. To be comfortable with failure and also be willing to keep trying different things...”

Table 3. Descriptions of skills starting at the thematic-level and moving to the code-level. Code descriptions indicate areas of discussion which were assigned to each code.

**Coursework Developed Skills**

*Engineering Skills:* design, rigorous methods, prototyping
*Quantitative Skills:* mathematics, modeling, statistics, bioinformatics, high throughput analysis

**Experientially Developed Skills**

*Field Specific Technical Skills:* cell and/or tissue culture, material synthesis, microscopy, imaging, device design, benchwork, mechanical testing, molecular biology, histology, adapting existing products, animal handling
*Communication Skills:* communication with different "languages" or "backgrounds", writing (grants), presentation skills
*Collaboration Skills:* interdisciplinary teamwork, knowing who to talk to, clinician interaction
*Research Fundamental Skills:* reading and comprehending literature, designing experiments, formulating hypotheses
**Personal Attributes**

Creativity, resilience, realism, practicality, caution, observational skills (attention to detail, focus), patience, willingness to “not know”

Finally, we examined the role of tissue engineers in biomedical research. In the interviews, participants often discussed what they thought distinguished them as tissue engineers in four ways. Some participants described themselves as a bridge between research focused on fundamental understanding and research focused on translational applications. Participants who discussed this distinguishing characteristic often attributed it to having a background or level of expertise in both basic sciences and engineering disciplines.

Participant 5 “…I think a good tissue engineer is not purely an engineer and not purely a basic scientist. It’s someone who straddles both fields or straddles multiple fields. Whether there’s a camp of people that are developmental in training but see value in engineering approaches to either answering developmental questions or trying to harness developmental programs for tissue repair applications. I think that’s a great example of people who care and are invested in biology but are also thinking about modulating or controlling those biologies for something translational. In my mind, people who can do that, who see value in both sides and can speak the speak of both sides, those are what I would consider true tissue engineers.”

In addition to describing “good” tissue engineers as those who can bridge basic sciences and translational efforts, participants described tissue engineers as important because they can collaborate with many different fields, apply quantitative skills to biological problems, and use their knowledge from multiple disciplines to develop better models for studying TERM problems.

**Discussion**

As a new field of study emerges, researchers in the field work together to create meaning and develop a community of practice around their research interests [42]. While these fields can help push research forward, the interdisciplinary nature of some fields creates difficulties when developing curricular content for students wishing to pursue these interdisciplinary fields of study.

Previously, quantitative work has examined general characteristics of undergraduate interdisciplinary programs regarding curriculum and content focus [7]. Other efforts to improve interdisciplinary curriculum in engineering have focused on content changes at an individual course level [43]–[45]. Our small-scale, qualitative study adds to work in interdisciplinary curriculum development by providing an in-depth analysis of one particular interdisciplinary engineering field to give a detailed description of what may be important in the curriculum for the success of students pursuing the field. Findings from this study emphasize the prevalence of the various historical definitions across engineering disciplines [14], [15]. Determining that TERM faculty also share this historic definition of engineering might be helpful in aligning the engineering content taught in TERM curriculum with the engineering content of more established engineering fields. One prevalent example of historically engineering related content in our study was an emphasis on design [22], which has been a growing aspect of engineering
curricula since the 1990’s, largely due to a push by accreditation bodies like ABET in the United States [16], [17]. Design considerations appeared throughout the definitions of engineering, concepts, and skills described by participants in this study.

While perceptions of engineering remained consistent throughout the interviews, participants’ emphasis on other disciplinary skills and concepts were much more varied. This is likely due to the involvement of members from multiple backgrounds in the community of practice, resulting in many participants describing the use of a variety of disciplinary knowledge within TERM research. Although the inconsistencies in the multi- or interdisciplinary focus of the faculty aligns with the motivation of this paper, this information alone does little to inform interdisciplinary engineering programs on how to improve curriculum or prepare students for careers after graduation [9].

Findings regarding the skills and concepts important for TERM varied greatly and may be due, in part, to faculty’s perceptions of TERM incorporating multiple disciplines. Conceptual understanding discussed by participants included ‘content’ and ‘product design or development’ knowledge. Within ‘content’ knowledge, participants placed an explicit focus on the need for problem-specific content knowledge. These findings also align with participants’ focus on engineering being purpose driven, as well as the context of engineering’s previous emphasis on solving human problems with its clinical and market analysis focus [14], [15]. Participants placed value on understanding which could be gained both in the classroom and as a practicing TERM member through experiential, co-curricular lab involvement.

Participants similarly described skills in ways that could be separated into themes of experiential and course-related skillsets; however, within skills, participants also addressed attributes of good tissue engineers, including personality traits like resilience, realism, and practicality that may be more difficult to teach as a part of a formal curriculum. One specific personality trait identified by the participants, comfort with failure, also appears in previously established BME education research [24] where perseverance in the face of failure is an identified theme for individuals in cell culturing labs. Skills and concepts which participants felt should be incorporated into curriculum were many, and due to our sampling and analysis strategy, likely not exhaustive; however, the list of skills and concepts generated in this study (see Table 2 & 3) can serve as a starting point for universities wishing to address the educational needs of students pursuing TERM. Beyond that, participants’ descriptions of the skills and concepts prevalent in TERM highlight a clear need for experiential learning in TERM. We argue that allowing students to participate in authentic research settings that are informed by the perspectives of members in the professional community of practice [18], [42], either by incorporating it in the curriculum or facilitating co-curricular experiences, may increase their participation beyond what traditional classroom settings might facilitate. This may also support students’ satisfaction with their interdisciplinary educational experience [9]. This argument is supported by the frequent emphasis participants placed on understanding problem-specific content knowledge and by the identification of personal attributes, neither of which is often taught or fostered in standardized curricula. In addition, the high number of skills and concepts indicated may make including them all in formalized curriculum difficult. Utilizing co-curricular experiences or mimicking the types of educational encounters students have in those experiences may help to build a sense of belonging in students who wish to engage in a community that places so much emphasis on problem-specific knowledge and experience-developed skills or attributes.
Additionally, TERM faculty placed emphasis on four areas which they felt set them, as tissue engineers, apart from other members of the biomedical research community. Overall, when discussing these four distinguishing characteristics: bridging fundamental understanding and application focused research, having collaborative abilities, using quantitative skills, and developing relevant models, participants often emphasized that these abilities were due to their broad background in multiple disciplines. These descriptions point towards an interdisciplinary skillset as a strength when performing as a professional in TERM. Additionally, the identification of developing relevant models as a distinguishing characteristics aligns well with previous BME education research that values the use of model systems as a research tool [28].

In this study, we used our research framework to scope our literature search and develop a conceptual framework specific to TERM. This strategy might be useful for education researchers interested in exploratory study of emerging interdisciplinary engineering fields beyond TERM. While more work would be needed to test the generalizability of the research framework for developing a field specific conceptual framework, we suggest that considering relevant contexts in engineering could be broadly applicable to studying developing interdisciplinary engineering fields. Additionally, using situated learning theory we identified members of the community and reasoned that probing their perceptions on skills, concepts, engineering definitions, and roles of engineers would give insight on necessary curricular efforts in an interdisciplinary engineering field. Given the utility of situated learning theory in our study findings, we suggest that researchers consider this theory of learning when choosing study participants and interview discussion questions.

Conclusions

While the small-sample, qualitative nature of this study limits the conclusions we can draw across the entire TERM community, this study serves as a starting point for education researchers and practitioners who wish to improve the educational experiences of students interested in TERM. Future work from our group plans to assess the curriculum available for students interested in TERM at the University of Michigan. We plan to evaluate the alignment of coursework and co-curricular experiences offered there with the concepts and skills discussed by faculty in our exploratory study. Our future work could lead to more meaningful engagement with students in TERM through improvements upon co-curricular experiences and focused curriculum. Further research in this area aimed at informing curricular change more broadly may wish to address the themes found in our study to see if they are upheld in a broader examination of TERM members (e.g. industry engineers, graduate students, postdocs, research scientists) and individuals peripheral to the field (e.g. clinicians or members of other traditional disciplines). This expanded study could create a more transferable framework for evaluating coursework and co-curricular experiences beyond the University of Michigan.

Beyond the TERM field, education researchers interested in emerging interdisciplinary engineering fields may wish to adapt our questions and research framework to perform a related analysis on their emerging community of practice, discipline, or field of study. Fields of study which may benefit from a similar exploration include: engineering science, general engineering, industrial engineering, etc.
References


