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Improving student outcomes through transdisciplinary curriculum design in biomedical engineering

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ABSTRACT

CONTEXT

The boundaries between traditional engineering disciplines are breaking down. It is increasingly important for engineering students to be equipped with the ability to integrate complex concepts across disciplines to tackle real world problems. Biomedical engineering is a discipline that marries concepts from mechanical, electrical, and chemical engineering, as well as computer science to develop technologies that improve human health. Most existing biomedical engineering curricula, however, do not reflect this transdisciplinary integration. These concepts are typically introduced to students in separate subjects with minimal or no cross-curricular references.

PURPOSE OR GOAL

Prior to 2021, the undergraduate Bioengineering Systems Majojr at the University of Melbourne featured a traditional structure with engineering mechanics, electrical engineering, chemical engineering and programming concepts sequestered into separate subjects. This has unintentionally resulted in students over-compartmentalising these concepts: they are often unable to appreciate how the different pieces fit together synergistically to form a coherent whole. To tackle this issue, we launched a curriculum redesign project centred around the student-led collaborative design of a bionic limb. This redesign has allowed us to link four core subjects across the major, covering key concepts in programming and modelling, biomechanics, electronics, and the engineering design process.

APPROACH OR METHODOLOGY/METHODS

A design-based research methodology was applied to form a team consisting of academics, educational technology researchers, and technology designers. We followed a four-stage iterative model involving: (i) initial problem analysis and identification of design principles; (ii) the prototyping of curriculum design solutions; (iii) evaluation and iterative redesign; (iv) and the refinement and sharing of design principles. This led to the design of a prototype bionic limb and associated teaching and learning materials that we have launched in two of our core subjects to date. This paper describes our progress and reflections to date.

ACTUAL OR ANTICIPATED OUTCOMES

While this curriculum design project is still in progress, we envision that it will reduce the degree to which our students tend to compartmentalise taught concepts. We believe that this will improve our students' abilities to recognise and harness the connections – both obvious and not-so-obvious – between different discipline areas, equipping them to push the boundaries of science and technology as more confident, job-ready biomedical engineers.

CONCLUSIONS/RECOMMENDATIONS/SUMMARY

We illustrate the application of a design-based research approach in the creation of a transdisciplinary curriculum revolving around the collaborative student-led design of a bionic limb. Progress to date involves interventions in two subjects, with positive student feedback.

KEYWORDS

Transdisciplinary, curriculum design, biomedical engineering, biomechanics, circuits and systems, engineering design, computer programming

Introduction

The boundaries between traditional engineering disciplines have become increasingly blurred. Modern engineers must be capable of integrating concepts across various disciplines to solve real world problems. This cross-pollination of ideas is evident in biomedical engineering, an engineering discipline that combines concepts from mechanical, electrical, and chemical engineering, as well as computer science to tackle issues related to human health. However, most existing biomedical engineering curricula do not reflect this integration of ideas. Concepts are often introduced to students in separate subjects with minimal or no cross-curricular references. As a result, students tend to over-compartmentalise the knowledge that they have gained (Garnetta et al., 1990). Students find it difficult to recognise and harness connections between those compartments. One possible solution to this is to shift towards curriculum design practices characterised by transdisciplinarity (Ertas et al., 2003).

Here, it is worth differentiating between the related terms multidisciplinarity, interdisciplinarity, and transdisciplinarity. Choi and Pak (2006) have previously described multidisciplinarity as the derivation of knowledge from multiple disciplines while maintaining disciplinary boundaries. Interdisciplinarity, on the other hand, is characterised by the dissolution of those boundaries and the synthesis of links between disciplines to form a more coherent whole. Lastly, transdisciplinarity involves the integration of multiple disciplines in a way that transcends their traditional boundaries (Burnett, 2011; Khoo, Haapakoski, Hellstén, & Malone, 2019). The three terms can all be thought of as states involving multiple disciplines, but to different degrees along the same continuum.

The challenges associated with achieving transdisciplinary curriculum design have previously been reported. For example, Foley (2016) identified the following hurdles in the context of designing a new biotechnology program: the assembly of a committed and flexible team of academics, regular reflections and program reviews, organised management, and sufficient training and/or teaching experience. While challenging, a transdisciplinary approach to curriculum design can help build students' capabilities to properly integrate complex concepts across disciplinary boundaries. This is critical to real world problem solving and devising creative design solutions (Burnett, 2011). This need is particularly so in intersectional disciplines such as biomedical engineering. McKenney and Reeves (2020) argue that Educational Design Research (borrowing heavily from Design-Based Research (DBR) and often used synonymously) provides a pathway to navigate these complexities. Namely, DBR provides a structured approach to transdisciplinary curriculum design (Figure 1) that can be applied to both engineering and medical education research and practice. Designing authentic learning environments is foundational to DBR curriculum design (Herrington, Reeves, & Oliver, 2014; Kartoğlu, Siagian, & Reeves, 2020).

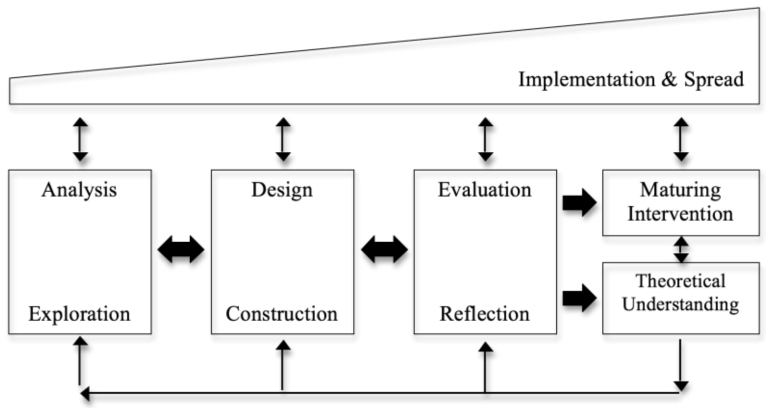

Figure 1: DBR curriculum design, adapted from McKenney and Reeves (2020)

This paper describes the initiation of a transdisciplinary curriculum design project centred around the design of a bionic limb. A DBR methodology was applied to develop an integrated collaborative project that authentically links four foundations of bioengineering across two years of a degree program: programming and systems modelling, human biomechanics, electronics, and engineering design.

Approach

A DBR methodology was applied to the specific challenge of transdisciplinary curriculum design. The DBR methodology has been defined as one that involves "continuous cycles of design, enactment, analysis, and redesign" (The Design-Based Research Collective, 2003). Each cycle consists of four basic steps or phases: identifying problems or challenges, designing potential solutions, evaluating those solutions, and reflecting on their implementation (Scott, Wenderoth, and Doherty, 2020). Kopcha, Schmidt and McKenney (2015) argue that each phase of DBR produces a story that is valuable to share and reflect upon. Here we describe the identification and design steps of the two DBR cycles that have occurred to date.

DBR Iteration 1

Identification

The importance of incorporating transdisciplinarity in the teaching of biomedical engineering was first identified at the subject-level. Two of the authors were involved in teaching a subject Biomechanical Physics and Computation (BMEN20001). This was an undergraduate-level subject that introduced students to both basic programming as well as fundamental physics concepts from engineering mechanics. Annual feedback via subject evaluation surveys indicated that students found making connections between the two distinct components of the subject challenging. Reflecting on this feedback, we identified three factors that affected the effective transfer of skills and knowledge of programming and mechanics: (i) varying levels of prior exposure to mechanical physics and programming, (ii) a preference in students for the rote-learning of steps or formulae, and (iii) assessment design that was misaligned with transforming student capabilities in using computer programs to perform complex biomechanical analyses (Biggs, 1999).

Design

To address the factors outlined above, the subject curriculum was modified as follows:

(i) Detailed programming tutorial sheets were developed to allow students to practise skills aligned with each of the assessment tasks in the subject. This addressed the varied capabilities in programming amongst our students. We also ring-fenced the mechanical physics content in the lectures and tutorials that were deemed essential and ensured that they were in good balance with the programming content. Specifically, we established a 60/40% weighting in lecture, tutorial and assessment content that reflected the percentage division in mechanics and programming-related intended learning outcomes.

(ii) Assessment weightings and rubrics were altered to increase the integration of the mechanics and programming components and to encourage independent, critical thinking. The mid-semester test and final exam were redesigned to reflect a 60/40% weighting of assessments on mechanics and programming capabilities, respectively. This was essential in signalling to students that mastery of both components was necessary to succeed in the subject. Assessment rubrics for programming tasks were revised from being overly prescriptive to encouraging self-regulated application of programming techniques that were most appropriate for the tasks at hand.

(iii) A final assignment was redesigned around the simulation and animation of a bicep curl (Figure 2). This assignment required students to integrate their understanding of the mechanics governing bicep curl motion and the programming concepts that they learned in the subject. Following constructive alignment practices, tutorials and lecture content were modified to incorporate the basic mechanics and programming concepts to achieve the goals of this assignment. Students were then expected to explore, expand, and integrate these concepts as part of their assignment brief, with scaffolding content where necessary.

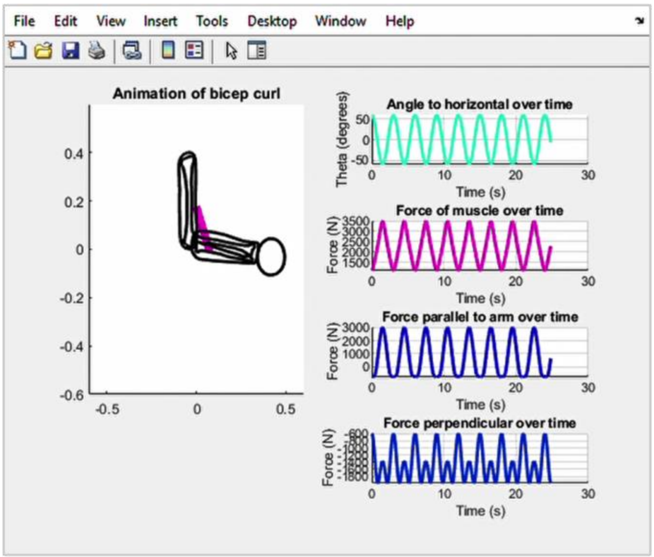

Figure 2: Assignment centred around the simulation and animation of a bicep curl.

Evaluation & Reflection

The progressive implementation of the modifications above resulted in a marked improvement in the student experience, as measured by university-level subject experience surveys. Survey responses to the prompt on whether the subject was well-taught increased from 3.15 in 2017 to 3.94 in 2019 (5-point Likert scale from 1: Strongly disagree to 5: Strongly agree). Student comments received as part of the same surveys indicated a general appreciation for transdisciplinary-aligned modifications; selected statements are included below:

- *“The lectures demonstrated the connection between physics, computation and biomechanics well.”*
- *“The physics side was interesting and practical and I found it extremely fun to solve problems then code them up and see them in practice.”*
- *“The subject is interesting in the fact that as a student, we are [typically] only taught hard theory, but with this subject we can see that theory applied and how programming is used for physical applications.”*
- *“The assignments were interesting and engaging applications of the content.”*

Negative comments received reflected inertia in the shift towards more open-ended problem-based learning:

- *“Lecture content rather than just helping us when we were stuck on problems.”*
- *“The mid-semester [test] can be more specific on what are the requirements to study and how to prepare [for] it, especially the multiple [choice] questions”*

A course structure overhaul occurring towards the end of this first DBR Iteration provided us with the opportunity to take our learnings in transdisciplinary design from the subject-level to the degree-level, described in the next section.

DBR Iteration 2

Identification

The pre-2021 undergraduate Bioengineering Systems Major at the University of Melbourne had a traditional structure characterised by the sequestration of concepts into distinct subjects, with minimal or no cross-curricular connections. Much like our subject-level observations in BMEN20001, this led to our students facing challenges in appreciating how different concepts might be combined synergistically to form a coherent whole across the course curriculum. In late 2020, a major course structure overhaul was initiated by the department, providing us with the opportunity to explore curriculum redesign at a larger scale. Expanding our learnings from BMEN20001, we identified the design of authentic transdisciplinary learning environments at the degree-level as the main goal in this second DBR iteration (Herrington, Reeves, & Oliver, 2014; Kartoğlu, Siagian, & Reeves, 2020).

Accompanying this shift in scope from subject-level to degree-level transdisciplinarity, we expanded our design team to include educational technology researchers, technology designers, and other academics involved in the teaching of the following core subjects within the overhauled Bioengineering Systems major (Lam et al., 2021; Rajagopal and Lam, 2021):

- **Applied Computation in Bioengineering (BMEN20003)**: a second-year undergraduate-level subject covering programming and systems modelling concepts
- **Mechanics for Bioengineering (BMEN30010)**: a third-year undergraduate-level subject covering human biomechanics concepts
- **Circuits and Systems (BMEN30006)**: a third-year undergraduate-level subject covering electronics and control systems concepts
- **Biosystems Design (BMEN30008)**: a third-year undergraduate-level integrative capstone-style subject covering engineering design principles

We note that as a result of the course structure overhaul, BMEN20001, the subject of focus in DBR Iteration 1, was split into two new subjects (BMEN20003 and BMEN30010 above). While seemingly contrary to the spirit of trandisciplinarity, the rationale behind this division was to allow for a deeper exploration of programming and biomechanics concepts. In navigating the shift to the new course structure, we ensured that the strong links between programming and mechanics continued by carefully coordinating the sequence of subject content and assessments across the two subjects.

Design

Focused discussions with the design team led to the identification of curriculum design principles informing the design of a collaborative student project integrated across the four subjects above, over two years of the degree. Expanding on the integration of mechanics and programming in BMEN20001 via the computer simulation of a bicep curl, we centred this collaborative student project around the design and construction of a physical bionic limb. Focus areas aligning with each of the four subjects were identified and mapped onto specific sub-systems to be considered in the design of the bionic limb. These, along with accompanying rationale, are summarised in Table 1.

We next considered subject progression order and its implications for staging student exposure to these sub-systems. This was primarily an issue for the non-capstone subjects BMEN20003, BMEN30006, and BMEN30008. In this context, the underlying course sequence meant that our students would encounter programming skills first (in BMEN20003). At this point however, students would not typically have completed BMEN30010 or BMEN30006 and would therefore be unfamiliar with mechanics or electronics concepts. We concluded that the best way forward would be to provide students with a complete functional bionic limb, designing it to allow each subject to focus on a specific sub-system while ignoring the others. This design strategy would allow students to investigate the key features of specific sub-systems, without losing view of how those sub-systems interact and contribute to form a greater functional whole. Upon enrolling into the capstone-style subject BMEN30008, students would finally get the opportunity to integrate everything they had previously learned in the construction of their own bionic limbs, or similarly complex projects featuring integrated sub-systems.

Table 1: Alignment of focus areas and relevant sub-systems in bionic limb design.

Subject	Focus Area	Bionic Limb Sub-system	Rationale
BMEN30010	Material design and fabrication, mechanical physics	Overall physical structure of the bionic limb	Mechanics concepts are necessary to understand the forces at play within the bionic limb when it is in motion. This is necessary to identify geometric and material design parameters. The shape and material chosen in the fabrication of the bionic limb must ensure structural integrity during operation.
BMEN30006	Actuation and control of arm motion	Electronics and circuitry	Motors and accompanying electronics and circuitry are necessary to control the motion of the bionic limb. Designing these elements requires an understanding of circuit and control systems analysis.
BMEN20003	User-bionic limb interface, programming and simulation	Conversion and transmission of user-supplied inputs into motion outputs	Instructions to control the arm may be supplied by users via hardware (physical levers, buttons) or software (computer-based inputs). In either case, programming skills are necessary to modulate and transmit these signals to actuator elements and generate desired motion patterns. Programming skills are also necessary to generate models that allow for the prediction of system behaviour and feasibility studies prior to implementation.
BMEN30008	Overarching engineering design and analysis principles	Feasibility studies, safety and risk analysis, assembly	By exploring the previous sub-systems of the bionic limb in isolation, students will gain an appreciation for the necessity of drawing on concepts across disciplines to construct a complete, functional engineering system. This capstone-style subject provides them with the opportunity to independently assemble those sub-systems into a cohesive whole. In the process, students are exposed to key general engineering design principles such as feasibility studies, hazard identification, and risk analysis.

With these considerations in mind, we engaged our technology designers in the actual design and construction of a functional prototype of the bionic limb (Figure 3). There were two intended outcomes of this process. Firstly, it would provide insight into the challenges likely to be faced by students during the design process and therefore identify any areas requiring scaffolding of information. Secondly, it would help inform the design of accompanying, constructively aligned learning activities, as well as the modification of existing ones.

Due to constraints imposed by the university's academic calendar, we have focused on developing and deploying teaching and learning activities for BMEN20003 and BMEN30010 so far, with those for BMEN30006 and BMEN30008 to be addressed in the coming semesters. For the programming focused subject BMEN20003, the bicep curl assignment previously developed in BMEN20001 was adapted for delivery. Because students would not yet be exposed to mechanics concepts at this point, the final mathematical expressions governing the forces at play were provided to students accompanied by explanatory statements foreshadowing the relevant mechanics concepts to be covered in BMEN30010. In the spirit of transdisciplinarity, but not directly related to the bionic limb design project, applications of programming in fields other than biomechanics were explored and discussed. These included concepts drawn from electromagnetism, probability and statistics, and systems biology, fields that our students would likely encounter in future subjects. Guest lectures by researchers in these fields were also organised to expose students to the multi-faceted nature of biomedical engineering.

For the mechanics focused subject BMEN30010, teaching and learning activities were modified to assume prior knowledge of programming, encouraging students to recall what they had previously learned in BMEN20003. In addition to this, a series of authentic scaffolded tasks constructed around the material design of the bionic limb (force and moment analysis, stress and strain analysis, materials testing, CAD design) was developed. Two project-based group assignments were established that required students to synthesise concepts of engineering design, mechanics, and computational analysis principles to develop a functional and robust bionic limb.

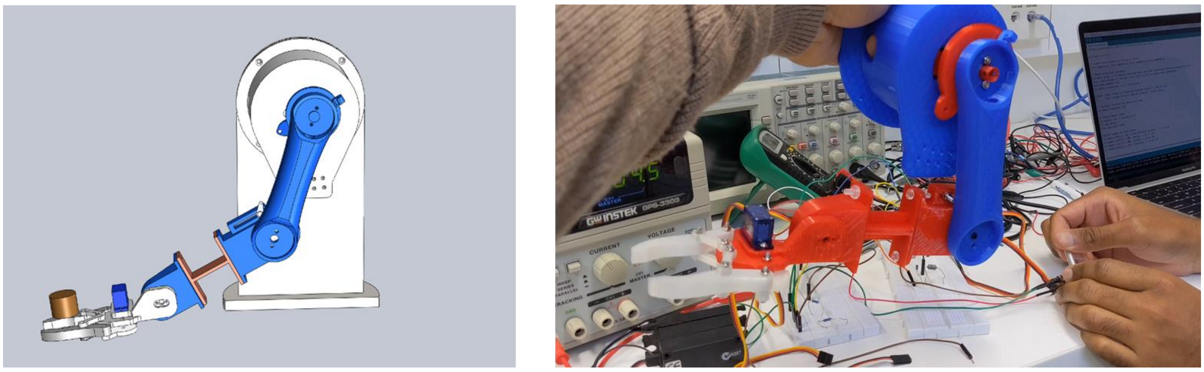

Figure 3: (Left) CAD drawing of bionic limb. (Right) Functioning bionic limb prototype.

Outcomes & Discussion

Preliminary feedback on the interventions introduced as part of the bionic limb project thus far have indicated that students are starting to make connections between the subjects that make up the major.

Within BMEN20003, the bionic limb was featured as an individual assignment adapted from the pre-existing bicep curl assignment designed in BMEN20001. This focused on teaching the core programming concepts of loops and conditional statements by requiring students to program an animation of the bionic limb moving in-sync with traces of the reaction forces at its elbow joint. In deploying this assignment, students were informed that this was a direct virtual simulation of a system that they would be experimenting on and designing in their future subjects: BMEN300010, BMEN30006, and BMEN30008. Subject experience survey feedback indicated that students were motivated and excited by this foreshadowing of future content, and appreciated the efforts made to forge connections with other subjects within the major sequence. Reflecting on this feedback, we might imagine expanding the project to include other bioengineering and biomedical engineering subjects, beyond just the current four.

Within BMEN300010, the two group-based, project-based assignments were focused on: (i) designing a component of the bionic limb to withstand large forces, and (ii) determining the forces during the motion of the bionic limb. Students engaged with the lecture content and tutorial sheets deeply to address the questions within the assignments. Students appreciated the connections being made between the two subjects. We observed students successfully transferring programming skills they gained in BMEN20003 within the two assignments. Within the two group-based project assessments we observed students taking ownership of specific tasks based on their strengths and working collectively to synthesise concepts to achieve the final goal.

Together, these preliminary observations suggest that degree-spanning curriculum design and coordination of assessment activities ensures depth of understanding of individual concepts and enables the provision of real-world learning experiences to students that require synthesis of different concepts, teamwork, and creative thinking. We are currently focusing our efforts on developing similar teaching and learning activities for both BMEN30006 and BMEN30008 that will allow students to explore sub-systems of the bionic limb relevant to those subjects in authentic ways. To increase the degree of interconnectedness between the four subjects, it has also been proposed that going forward, a common learner-centric ecology of resources (Luckin, 2008) be introduced to support student collaboration across the subjects. Current plans for this revolve around the student-driven curation of ePortfolios to reflect on their progress and learning as they complete the sequence of four core subjects. This might be supported by technologies and platforms such as PebblePad, GitLab, Microsoft Teams, and Adobe Spark.

Evaluation-wise, there are plans in place to conduct more focused student surveys in future DBR iterations, as opposed to relying on just the regular operational subject experience surveys conducted by the university. In addition to this, feedback from student focus groups will also be incorporated in the evaluation process moving forward.

Conclusion

Reeves and Lin (2020) argue that there is a dearth of examples of implementing DBR for complex real-world curriculum design that go beyond the simple “solutionism” prevalent in educational technology literature (McKenney & Reeves, 2020). The bionic limb project illustrates the application of design-based research to transdisciplinary curriculum design within the context of biomedical engineering. While the project is still in progress, preliminary outcomes indicate that our efforts at incorporating transdisciplinarity in curriculum design are making a positive impact on student learning. We also believe that the specific learnings of this project might be applicable to other courses wanting to reduce the degree to which students tend to compartmentalise key concepts.

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