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A project-based learning approach for university students in biomedical engineering

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***Abstract*—This paper explores the implementation of Project-Based Learning (PBL) in a ”Fundamentals of Biodesign” course for undergraduate biomedical engineering students, emphasizing its effectiveness in promoting practical application of knowledge, skill development, and innovation. Students work in groups on specific clinical cases, utilizing tools like Ishikawa diagrams and empathy maps to define problems and progress iteratively through stages, ultimately achieving a functional prototype for real medical needs. Results indicate 100% achievement of course objectives, fostering creativity, critical thinking, and knowledge integration, preparing students for their future careers. The conclusion suggests extending PBL methodology to other courses to train biomedical engineers capable of addressing public health challenges through innovative solutions.**

***Index Terms*—Course Structure, project-based learning, PBL, Active Learning, Biomedical Engineering, fibromyalgia, stroke, lymphedema and anemia**

I. Introduction

The field of engineering education has undergone significant changes in recent decades, moving from traditional passive teaching methods towards a more engaging and interactive approach: active learning. This emerging paradigm empowers students to become the protagonists of their learning, allowing them to interact with content reflectively and critically. The evidence supporting the benefits of active learning in engineering is compelling. Studies have shown that this approach motivates students to actively participate in the learning process [1]. This shift is also evident in other disciplines, such as mathematics and psychology, where it's recognized as crucial for optimal learning. Additionally, active learning can be further strengthened by active mentoring not only through in-class practices but also through mentoring outside the classroom [2].

The incorporation of active learning principles, such as problem-based learning, has been shown to positively impact the academic performance and critical thinking skills of students in various fields, including medicine [3]. On the other hand, project-based learning (PBL) has been highlighted as a methodology that enables students to actively construct knowledge by designing and implementing ideas in concrete projects. This methodology leads to a deeper understanding of course content and fosters the development of cross-cutting skills like creativity, communication, and teamwork [4]. In the context of PBL, the VDI 2221 methodological approach offers a framework for developing engineering projects. Through a series of well-defined steps, students can address real-world problems, analyze requirements, and propose viable solutions. This framework has been used in various projects to facilitate the understanding of the problem, requirements, and solution design [5].

The integration of technology in the classroom presents both challenges and opportunities. Various educational contexts explore the use of technology, such as virtual reality and gamified applications, as tools to facilitate engaging active learning experiences. These approaches align with the constructivist vision of learning, emphasizing the active role of students in constructing their knowledge [6], [7]. In higher education, the implementation of methodologies like flipped classrooms, where traditional learning is inverted, has shown increased student engagement and improved learning outcomes [8].

II. About the course “Fundamentals of Biodesign”

This course introduces biomedical engineering students to project execution and product creation, focusing on designing and producing devices to address specific medical needs. Participants tackle real challenges within the medical field, proposing innovative solutions in teams and presenting low- or medium-fidelity functional prototypes. The course follows a structured design process, from identifying needs to rapid prototyping, while emphasizing effective communication and teamwork.

The course methodology is based on Project-Based Learning (PBL), an educational approach that engages students in real-world projects to acquire knowledge and skills, while developing critical thinking, problem-solving, and collaboration. PBL's effectiveness has been demonstrated in specific course topics like technical drawing [9], 3D design and printing [10], electronic design [11], microcontroller programming [12], and even creating apps using APP Inventor [13].

To enable students to carry out a complex project, they have access to a masterclass (1 hour weekly) for theoretical concepts and three advisors during laboratory hours (4 hours weekly) for feedback and follow-up on project formulation, design, and development over 16 weeks. Additionally, they receive an extra hour of individual consultations with each advisor. The three advisors have diverse backgrounds: one specializes in electronics and microcontroller programming, another in 3D design and printing with knowledge of mechanics, and the last one is a healthcare professional with clinical experience.

A. About the case studies

During the 2022-II semester of the Fundamentals of Biodesign course, 118 students were divided into 6 groups according to their schedules. Each group, consisting of approximately 20 students, focused on a specific clinical case. There were a total of five distinct clinical cases, one of which was repeated in two groups. These clinical cases were selected based on the professional experience of the healthcare advisors involved in the course.

1) Fibromyalgia:

Addressing fibromyalgia is crucial due to its impact on the quality of life of patients, its underdiagnosis, the benefit of early diagnosis in patient satisfaction and reduced use of health services, its economic burden, and its association with mental health disorders [14], [15], [16].

The clinical case involves a 49-year-old woman diagnosed with fibromyalgia since 1999 and chronic pain in her hands, seeking help for chronic pain in her left hand and recent pain in her right hand upon active movement. She also experiences fatigue, bruxism, headaches, cervical and lumbar pain, and pain in her extremities. The treatment included pain explanation, normalization of muscle tone, mobilizations, myofascial inhibition, and electrotherapy. After 6 months of treatment, there was a favorable improvement in musculoskeletal and headache symptoms. The results of kinesiophobia and pain acceptance questionnaires were positive, with an improvement in the adaptation of the lumbar spine. Over time, there was a decrease in pain in various areas, better adaptation of the spine, and continued postural reeducation and electrotherapy treatment.

2) Cerebrovascular accident(STROKE):

It is crucial to address stroke due to its significant impact on health and the economy. It is one of the leading causes of disability and death worldwide, requiring urgent treatment to limit brain damage and improve patient outcomes [17]. Stroke represents a high economic burden due to the costs associated with treatment and lost productivity [18]. Additionally, stroke survivors face limitations in their quality of life due to various disabilities [19]. Effectively addressing stroke can improve both public health and the quality of life of those affected [20].

The 31-year-old user suffered a hemorrhagic stroke in the right hemisphere, with a history of previously undetected arteriovenous malformation. After a decompressive craniectomy and endovascular embolization, they experienced seizures and sequelae of left hemiplegia. They were admitted to the Occupational Therapy Service with adapted manual dominance, spasticity in the left upper limb, and difficulty in active motor movements. After 9 months of treatment, there was improvement in spasticity and functionality of the left shoulder, elbow, wrist, and hand. The importance of occupational therapy in post-hemorrhagic stroke rehabilitation was emphasized, with a focus on improving functionality and independence.

3) Lymphedema:

Addressing lymphedema is essential due to its progressive nature and adverse effects. This condition can result in increased swelling and risk of infection if not adequately treated [21]. Furthermore, lymphedema compromises immune function, increasing vulnerability to infections. It also limits mobility and causes pain, affecting quality of life. Psychological implications, such as anxiety and depression, are common due to physical limitations and the visible appearance of the disease [22]. Additionally, treating lymphedema involves direct and indirect economic costs, representing a significant financial burden [23].

A 38-year-old woman with invasive lobular carcinoma in the left breast in 2012 developed grade 1 lymphedema as a sequel to breast cancer. The patient had decreased function of the left shoulder, pain, and limited mobility, leading to the detection of increased volume in the left hemithorax. The treatment included manual lymphatic drainage, specific exercises, and education on preventive care for lymphedema. Various therapeutic maneuvers, such as neurodynamics and neural tension modification, were performed to improve sensitivity and mobility. The assessment of lymphedema was based on the increased volume of the limb and other subjective symptoms such as heaviness and sensory disturbances.

4) Anemia (occurred in 2 time groups):

Addressing anemia is of utmost importance due to its broad impact on health, affecting approximately 40% of children and 30% of women of reproductive age worldwide [24]. This leads to poor growth, cognitive deficits, and motor disorders [25]. This requires a coordinated effort involving government sectors, NGOs, UN agencies, and the private sector to implement evidence-based interventions informed by systematic reviews and rigorous research [26].

A 9-year-old girl with a history of persistent anemia despite a favorable environment and treatment adherence is referred to a higher-level hospital. Hematologic studies are requested that reveal a reduced mean corpuscular volume (MCV), suggesting another pathology. After performing hemoglobin electrophoresis in Lima, the diagnosis of sickle cell anemia is confirmed. The need to bring the diagnosis closer to vulnerable areas, reduce referral times, improve medical training in the diagnosis of hematologic diseases, and alert first-level health centers about other causes of non-iron deficiency anemia is suggested.

5) Diabetes mellitus:

Addressing diabetes mellitus is crucial due to its significant global impact on health. This disease, one of the main public health priorities, affects millions and carries risks of mortality and severe complications [27] [28]. It is essential to implement preventive measures at the population level and ensure access to essential treatments. Research provides valuable insights into prevention and management, including the relationship between diabetes and affective disorders [29].

This clinical case involves an 88-year-old male with type 2 diabetes mellitus, insulin-dependent, chronic kidney failure, heart failure, blindness in one eye, and vision loss in the other due to diabetic retinopathy, and psoriasis. The patient initially consulted for a lesion on the first metatarsal of the left foot that progressed to affect the left lateral aspect of the foot and necrosis of the third toe. After the amputation of the third toe and an infection by Pseudomonas, the patient experienced a favorable evolution, managing to take small steps in his house three months after the start of the recovery.

III. Materials and methods

The course is divided into four main modules, focusing on strengthening a capacity linked to the development of solutions with elements of technological innovation. These modules follow a performance qualification process for each student in the course based on weekly presentations to the course advisors, who provide feedback on a previously defined deliverable. The rubric takes into consideration aspects such as the organization of the presentation, attendance/punctuality, degree of compliance with the deliverable, reliability of the consulted sources, etc. The advisors provide feedback that is received by the students and must be resolved for the deliverable of the following week.

A. Identify the need or problem

In this module, each team is presented with a case or health issue, which becomes the framework for the generation of ideas and technical advice. Students are provided with tools for information searching, indicating how reliable each source is as a scientific reference. Based on the information found, the economic context is delimited in terms of cost/patient or hospital burden representing a disease at the national or global level, and the social context is outlined, stating with evidence how a health issue manifests, if it affects one social stratum or age group more than another, finding perspectives from public health that help to limit the scope of engineering design by focusing on the own capacities of the career. Teams use Ishikawa diagrams, Traveler Map, and Empathy Map as essential tools to define more specifically the problem of the clinical cases. The integration of these diagrams provides students with a comprehensive understanding of the problem, covering its fundamental causes to the user's experience. This structured and multidisciplinary approach not only allows them to accurately identify the nature of the clinical case but also to address it from various perspectives. Subsequently, the elaboration of the scientific/commercial context is addressed, where the most recent solutions used to address the particular problem found are mapped. This approach avoids redundancy in the proposal of solutions by leveraging lessons learned from previous approaches. For this, the student learns how to search for patents of invention and/or utility models in databases such as EspaceNet, Patentscope, or Google Patents. They also understand how to identify a commercially introduced and clinically validated product, searching for evidence that enhances its usefulness and effectiveness to provide the indicated benefit. Once both contexts have been built, an analysis of the collected information is carried out to find the gap that will allow the formulation of an adequate and fair proposal to a problem that can be solved through engineering, defining the population and the scope of the project according to the cost and availability of materials. In this part, the guidance of the thematic advisors is crucial, allowing the establishment of the team's activities to remain aligned with the specific problem.

B. Create solution concepts

With the particular problem defined and the commercial and scientific context developed, the work teams move on to devising strategies and solution concepts. They do this by initially establishing the initial design requirements, which are divided into functional and non-functional. Functional requirements answer the question "What should the design do?" while non-functional ones focus on "What characteristics and properties should the design have?" To meet the established requirements in the functional requirements list, a set of strategies (general approaches to solving a problem) is generated to solve a problem. These are basic approaches to solving a problem at a macro level. Once a strategy is chosen, the next step involves creating concepts for its implementation. If the strategy is the "what," the concept is the "how." The materialization of the solution concepts is done by applying the initial stages of the VDI 2221 design methodology "Systematic Approach for the Design of Technical Systems and Products". Developed by the German Engineers' Association (VDI), this methodology provides a structured framework for the systematic generation and evaluation of solutions in the product design process. Through a sequence of activities, it facilitates the identification of key information and the detection of potential errors, thus providing a robust and organized approach to the development of innovative solutions [30].

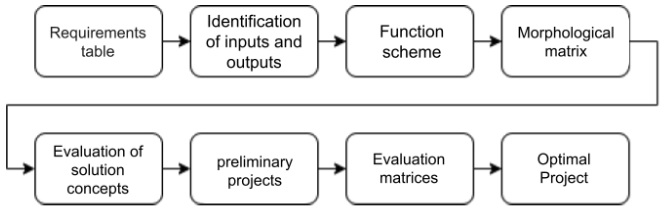

Fig. 1. Design Methodology Applied in Biodesign Fundamentals Based on the VDI 2221 Method

In this way, the inventiveness of the students is guided, ensuring an adequate distribution of engineering resources through evaluation matrices, resulting in efficient and cost-effective designs. For example, students are advised to select components and materials that are readily available to facilitate the implementation of their projects without inconvenience. This guidance is reflected in the criteria they establish in their solution concept evaluation matrices, highlighting the importance of the availability and accessibility of materials. When the morphological matrix is developed, students are provided with substantial guidance on the sensors and components they can use for measurement, processing, and control functions. They are provided with information to work with development boards from companies such as Arduino, Expressif Systems, or single-board computers (SBC) such as Raspberry Pi. The criterion for selecting any of them will depend on the complexity of the proposed solution concept.

C. Implementing the solution

Once the design stage is completed, the activities of manufacturing and digital manufacturing begin. This process is divided into multiple iterations presented by deliverables, which must show significant progress in the integration of the hardware-software elements of the proposed solution. To facilitate the implementation of the different projects, we have a Prototyping Laboratory, which is equipped with different equipment for printing by Fused Deposition Modeling (FDM), a laser cutting machine, and a CNC router for the prototyping of electronic boards.

The 3D modeled parts can be printed with PLA (polylactic acid) or ABS (acrylonitrile butadiene styrene) filament, depending on the requirements of the mechanical design. The housings or enclosures can be made from acrylic or medium-density fiberboard (MDF) for rapid obtainment. The electronic circuits are mostly presented on a breadboard (protoboard), but they can be transferred to a PCB (printed circuit board) depending on the speed of each team's progress. For the development of visualization interfaces or applications, the use of MIT App Inventor is often recommended, the free and easily accessible platform developed by MIT. During Iteration 1, the functionality of each of the modules defined for each project is evaluated separately, through the writing of simple codes, which will later be used for error debugging. Iteration II involves the integration of PCBs with their respective protective housings and their linkage to the interfaces where

Fig. 2. FDM Printing Area of the Prototyping Laboratory

measurements or captured signals will be displayed. The final iteration is presented during Milestone #2, which refers to the final low-fidelity prototype integrated, where the proposal should be seen in its optimal performance.

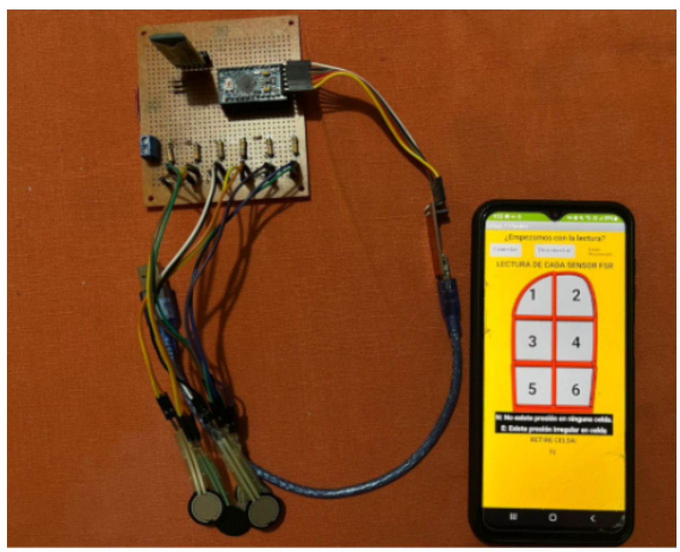

Fig. 3. FootCheck Project (Team 17) for the Diabetic Foot Clinical Case

D. Communicate the results

The final stage of the course focuses on the presentation of the results obtained during the project execution. In Stage 3, students participate in a 10-minute pitch-style presentation, where they are encouraged to promote their project as if it were a product to potential investors (professors). The pitch-style presentation simulates a business situation where students must convince the professors of the feasibility and potential of their project, learning to highlight the most attractive and valuable aspects of their proposal. Additionally, they are asked to prepare a final report in the style of a scientific article using the IEEE template, to provide students with experience in writing this type of document.

Fig. 4. Group Timetable Stage 3 Presentation on the Lymphedema Clinical Case

Fig. 5. Stage 3 Presentations by Timetable Groups on the Clinical Cases of Anemia, Diabetes Mellitus, and Fibromyalgia

To conclude the course, a poster fair is held to exhibit all the projects developed. In this fair, teams are evaluated by invited judges. Projects with the greatest potential are invited to complete an Invention Detail Sheet, to obtain an analysis of the potential patentability from the university's Intellectual Property Office (IPO).

Fig. 6. Biodesign Fundamentals Poster Session: 2022-II

IV. Results

Following the 16-week process, 100% of the 20 teams consisting of second-year students achieved the main objective of the course, which was to develop a functional low-fidelity prototype that integrated hardware and software components as a technological solution to a real medical issue. The creativity and originality of the proposals varied among the different teams. Some projects stood out for their high degree of innovation, while others consisted of the adaptation or incremental improvement of existing technologies. For example, Team 3 designed a novel robot-assisted upper limb rehabilitation system for post-stroke patients using virtual reality and haptic feedback. Team 5, on the other hand, developed a simplified glucose meter aimed at improving monitoring adherence in low-income diabetic patients. All projects underwent evaluation by the university's Intellectual Property Office after the course. This evaluation assessed the potential for patentability and provided students with feedback on intellectual property protection opportunities. As a result, three projects (15% of the total) with sufficient innovation and technical feasibility were identified for recommending the submission of a utility model application. Overall, the implementation of project-based learning methodology fueled creativity, critical thinking, and knowledge integration among students, allowing them to achieve tangible results addressing real medical needs, with varying levels of innovation depending on each team's capabilities. The course represented a significant experience in practical application and preparation for their future performance as biomedical engineers. Multiple projects achieved success thanks to the capabilities provided by the Biodesign Fundamentals course. The project "Kimberly's Project Title" presented its prototype progress at the "Poster Competition Name", an international event that promotes the use of TinyML globally. Likewise, the "Lymphedema Project Title" project obtained funding for its application and registration for a PCT patent, and other projects, such as the ”Footwear for, etc etc” project developed for monitoring plantar pressure to prevent diabetic foot progression, developed by Team No. 17, applied for a local utility model patent.

The results of this study support the effectiveness of project-based learning as a pedagogical strategy in biomedical engineering, in line with previous research reporting the benefits of this approach in various engineering branches [1] [4] [9]. The guided execution of design projects aimed at solving real medical needs promoted the practical application of knowledge and the development of key competencies identified in the literature, such as critical thinking, teamwork, and communication [4].

The integration of tools such as the systematic method VDI 2221 provided a structured framework that facilitates students' progress through the design process, from conceptualization to implementation of solutions. As previously reported, this systematic approach promotes the orderly analysis of requirements and effective evaluation of design alternatives [5].

On the other hand, the integration of technologies such as digital manufacturing, the use of electronic development boards, and the creation of mobile applications aligns with the growing trend of incorporating these tools into engineering education to promote active learning [10]. While they come with challenges, when well-implemented, they can significantly enrich the learning experience.

V. Conclusion

- The implementation of a project-based learning methodology in the ”Biodesign Fundamentals” course promoted the practical application of knowledge and the development of relevant skills in biomedical engineering students.
- Addressing real medical needs through a structured process of ideation and development of technological solutions allowed students to strengthen essential competencies such as critical thinking, collaborative work, communication of ideas, and user-centered design.
- The positive outcomes of the course in terms of student engagement and motivation, as well as the potential for innovation in the prototypes developed, demonstrate that this project-based pedagogical approach is suitable for training future professionals capable of creating technological solutions that address specific public health issues.
- Given the results obtained, it is recommended to extend the implementation of this methodology to other subjects in the biomedical engineering curriculum. Active learning through interdisciplinary projects can catalyze the development of comprehensive professional profiles in students.

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