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PAPER

Challenge-Based Learning in Biomedical Engineering: Developing Skills for the Future

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ABSTRACT

One of the primary objectives of higher education (HE) is to produce specialized human resources with the necessary competencies for the challenges encountered in our professional lives and our complex environment. One form of experiential education for biomedical engineering students is to expose them to real situations so that, based on acquired knowledge, they develop high-level disciplinary competencies that prepare them for a future job with greater expectations. This report analyzes the use of teaching strategies such as challenge-based learning (CBL) for the development of technical skills through the design and manufacture of a walking aid device, the implementation of effective methods for the development of medical devices, and the identification of sustainability in engineering. A tournament skills event evaluated the results by highlighting specific solution proposal points. This study is an illustrative case that provides significant evidence of the effectiveness of CBL and can serve as a model for pedagogically sensitive evaluation of the engineering classroom by integrating blended learning schemes using gamification techniques.

KEYWORDS

educational innovation, higher education (HE), challenge-based learning (CBL), biomechanics, sustainability, Tec21

1 INTRODUCTION

Since 2014, the Tecnológico de Monterrey has gradually implemented the Tec21 educational model, which involves a novel, flexible vision with comprehensive training and a challenge-based learning (CBL) approach [1] [2]. From the biomedical engineering perspective, the practical application of students' learning in generating specific solutions that consider patients' needs is vital during the formative stage. This application of knowledge empowers them to develop soft skills such as collaborative work and disciplinary competencies such as problem diagnosis, formulation of solution strategies, and, precisely, the development of medical devices. The social responsibility that a biomedical engineering student develops can be observed from

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two perspectives; the first is the intrinsic need to acquire engineering knowledge to provide technically adequate solutions to users [3]. The second is having the necessary expertise in the biological and medical fields to support technological proposals from a health viability perspective. However, the lack of or little interaction with patients sometimes limits the dimension of social learning. Specifically, in the biomechanics analysis and design course of this program, topics of engineering analysis and development are addressed to provide solutions to specific issues, such as the analysis of the kinematics of the human body and its injuries at a structural level, the design and manufacture of sports and orthopedic solutions [4]. In addition, a mechanical design methodology is also followed, where numerical simulation corroborates analytical calculations to evaluate a device. The evaluation rubric regarding the final proposal's functioning is only in the engineering orientation, without considering the social orientation that could imply factors that impact the patient's daily life. It is important to note that developing this skill in a biomedical engineer is essential for his professional performance. For this reason, the present work describes an innovative evaluation proposal based on gamification. This method can significantly enhance the social orientation of the CBL proposals for a course on developing orthopedic devices by providing a framework that motivates cooperation and the sustainable solution of biomedical engineering problems.

The thematic content of the training unit on *Analysis and Design in Biomechanics* was designed for implementation in 2015; its launch was in 2019, together with the launch of the Tec21 model. This content includes five areas of knowledge developed throughout the course: statistics, anxiety, continuous solid mechanics, design of mechanisms and structures, and engineering materials for constructing prostheses and orthoses. However, given the context of the training unit, the contents mentioned above are developed within the context of medical sciences. Figure 1 shows the evolution of research topics around human biomechanics, integrating the generation of knowledge from 2015 to date, which represents a guide on the trend of new paradigms and problems to be solved worldwide.

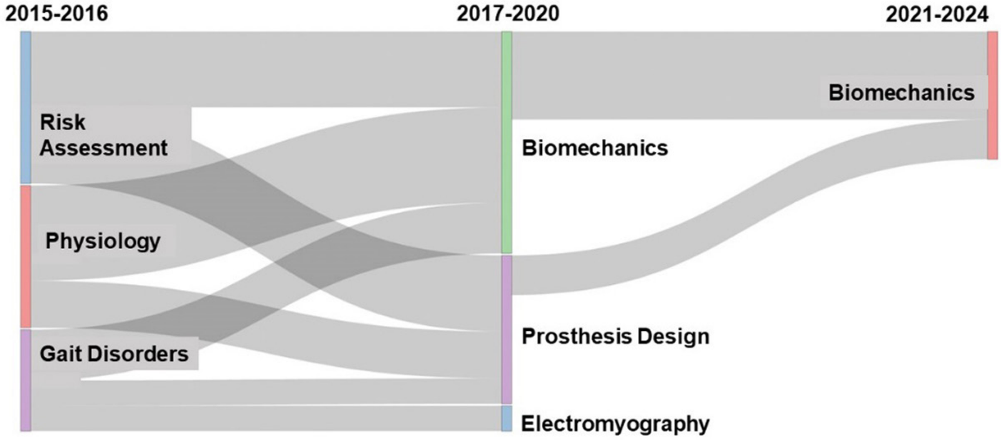

Fig. 1. Evolution of the topic in biomechanics research

The analysis uses a database extracted from SCOPUS, focusing on the search between 2015 and 2024, placing a turning point between 2017 and 2020. It is observed that the trend of interest is oriented towards biomechanics and the design of prosthetic devices.

Biomechanics studies the mechanical interactions between bones, muscles, ligaments, and joints within the musculoskeletal system during movement, highlighting the importance of understanding the forces that act on the body to promote quality of life and prevent injuries [5]. The search for research topics associated with human biomechanics in the last ten years has shown a specific interest in developing ortho-prosthetic devices with a focus on the mechanical design of the proposed solutions. Figure 2 shows a growing interest in the analysis of joint characteristics and functions, analysis of ranges of motion, weight balance, kinematics, and design of ortho-prosthetic devices for amputees. In this sense, the biomedical engineering program offered at the Tecnológico de Monterrey is aligned with these interests. It demonstrates adaptability and relevance by integrating the following contents into its biomechanics analysis and design course:

a) Statics. Statics is applied to biomechanics by analyzing the stability and mobility of the human body's joints, which is crucial to understanding movement and vulnerability to injury in different types of joints [6] [7]. Static principles, such as force systems and balance, can be applied in biomechanics to analyze the forces acting on the human body during movement and exercise, aiding in injury prevention and performance optimization [8].
b) Dynamics. Dynamics in biomechanics describes how forces on the musculoskeletal system influence human movement, such as in the analysis and description of human gait. The dynamics principles in biomechanics include analyzing kinematic and kinetic data, using motion analysis systems, and inferring joint moments and forces from measured accelerations [9] [10].
c) Continuum mechanics. The principles of continuum mechanics in biomechanics involve analyzing the mechanical behavior of materials as a continuous manifold, considering concepts such as deformation, motion, stress, and energy balance [11]. Stress is crucial in affecting biomechanical structures by influencing deformation, mechanical behavior, and overall performance of materials and structures [12] [13]. The relationship between stresses and strains, displacements and forces, and the dynamic behavior of materials are fundamental aspects of understanding how stress influences the mechanical properties of solids and structures in biomechanics [14].
d) Design of mechanisms and structures. Design principles play a crucial role in the construction of prostheses and orthoses, and advances in technologies such as computer-aided design (CAD), computer-aided manufacturing (CAM), and additive manufacturing are revolutionizing the process [15] [16]. These technologies allow for accurate modeling, efficient production, and cost-effectiveness while improving patient comfort, overall durability, and the effectiveness of the prosthesis or orthosis [17].
e) Engineering materials for the construction of prostheses and orthoses. Engineering materials are crucial in constructing prostheses and orthoses to improve performance and durability [18]. These materials require specific properties for successful application. Commonly used materials are polymers, metals, alloys, and composites [19]; they must possess mechanical strength, durability, and antibacterial properties [20] [21].

Current regulations: Until now, all biomechanics academic programs within biomedical engineering courses at the undergraduate level are mainly theoretical or based on examining a prototype already on the market or some bibliographical research project. The novelty of the approach presented here is using a challenge-solving tournament based on the didactic strategy of CBL [22] [23] [24]. A more contemporary approach, challenging students to higher cognitive levels not only to do bibliographical research and planning but also to create a prototype that solves a real need that is required at this time, that had its roots in a social need, and to test and evaluate it before an expert jury. Among educational strategies, CBL is an emerging approach that integrates concepts and skills from multiple disciplines to address real-world problems and search for an answer using several sciences and the application of sustainable principles [25] [26] [27] [28]. Therefore, CBL, focusing on biomechanics, can be a promising way to integrate disciplinary, soft, and sustainable skills into higher education (HE) [29] [30] [22]. Engaging students in real-world challenges enhances their ability to address complex problems, develop innovative solutions, and apply theoretical knowledge to practical scenarios through challenges [31].

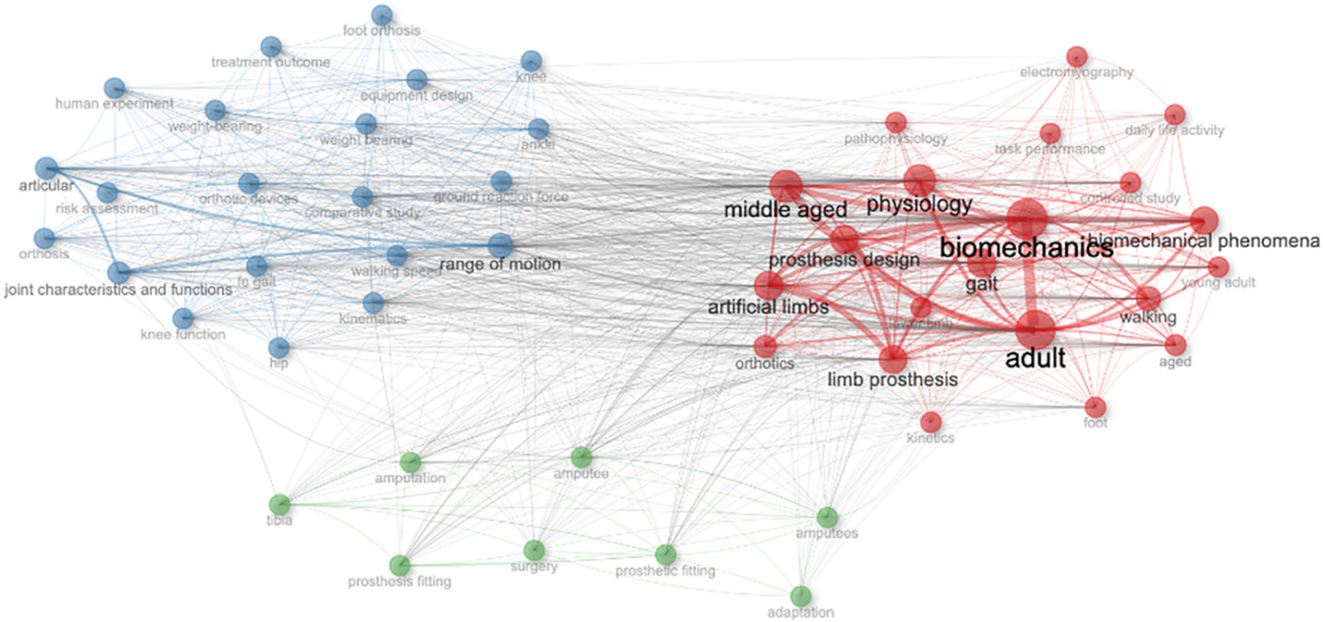

Fig. 2. Thematic cluster oriented to research and development interests in human biomechanics

2 METHODS

In the biomechanics analysis and design course, the student is expected to adequately develop the sub-competencies of collaboration, diagnose problems in the health area, formulate solution strategies, and design biomedical devices. The challenge sought to be resolved in the training unit involves the design of a transtibial orthosis to address amputation due to diabetic necrosis. Diabetic necrosis is a severe complication that affects patients with poorly controlled diabetes mellitus. This condition can lead to partial or total amputation of lower limbs due to lack of adequate blood flow and the subsequent appearance of wounds and ulcers that do not heal properly. As biomedical engineering students, they were challenged to design a transtibial orthosis that helps improve the quality of life and mobility of patients who have undergone amputation due to diabetic necrosis. Specifically, the challenge seeks to meet the **SDGs: 3**–Good Health and well-being, **10**–Reduction of Inequalities, and **12**–Responsible Production and Consumption. The training unit has the particularity of having a training partner entity that accompanies establishing, providing feedback, and evaluating the challenge. In this particular case, a company markets and manufactures ortho-prosthetic devices. Figure 3 shows the tree map of the words associated with recent research interests in biomechanics. This tool confirms that the challenge proposal developed during the course is relevant to our students' training.

The design objectives had to meet six crucial points to develop the abovementioned sub-competencies: *functionality, comfort, personalized fit, ease of use, durability, and cost-effectiveness*. These last two points were part of the sustainability approach integrated through the sub-competencies of formulating solution strategies and designing medical devices. The solution to the challenge should seek a long-term economic and environmental sustainability orientation by reducing non-degradable plastic materials.

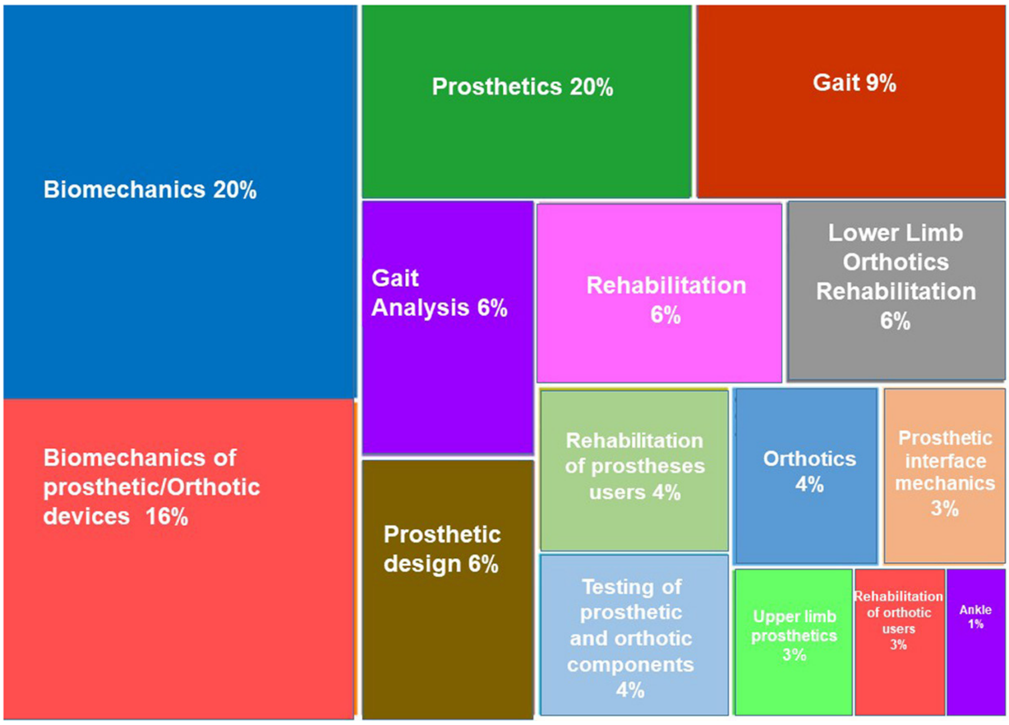

Fig. 3. Tree map of the words associated with research on biomechanics

The tree map of the words associated with research on biomechanics, shows 67% interest in orthoses, which highlights their biomechanical development, design, and use for rehabilitation of lower limbs.

For a better understanding of the CBL development methodology, Figure 4 describes the linear progress of the teaching experience that results in the design of the orthopedic prototype.

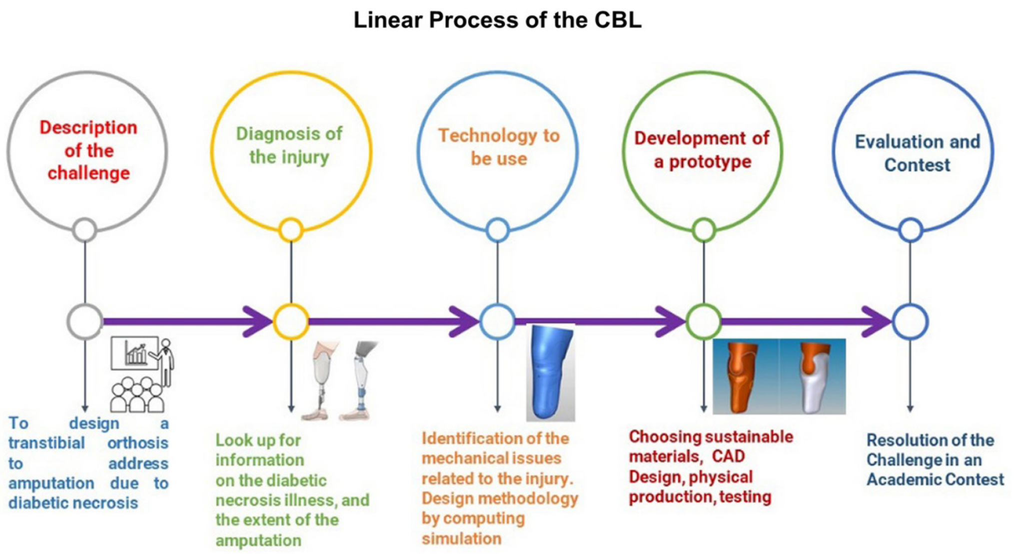

Fig. 4. Linear flow of the challenge-based learning experience

Note: Each stage is determined by an objective clearly described in the image.

3 RESULTS

For the development of the CBL teaching technique, the students followed the flow shown in Figure 4. Stages were distinguished by carrying out several steps.

Identification of injury mechanisms: The purpose of this step is for the student to identify the injury mechanisms and, based on the acquired knowledge, to develop a protocol for carrying out a quantitative diagnosis of the injury from a biomechanical point of view. The student also carries out a literature review oriented to existing joint injuries and the relationship of mechanical issues related to the injury's generation. After delivering this evidence, the student can understand the symptoms and limitations that can generate a joint injury. As well as identify the existing diagnostic methodologies. Consequently, the student also identified the technologies that could be used to perform a more precise quantitative measurement of the injury. The requested evidence was a 10-minute presentation about the problematic points, objectives, theoretical framework, and conclusions. This presentation was presented to the teaching staff of the training unit. Two works were selected randomly to generate a collaborative discussion and thus generate group knowledge. The evidence is used to partially evaluate the sub-competence of diagnosing problems in the health area and collaboration.

Evaluation of treatment and innovation proposal: The requested evidence is intended to evaluate and provide feedback at an early stage on the treatment proposal with an innovative approach outside the classroom before its final evaluation. The students use computational techniques for the design, assembly, mechanical simulation of stresses, and dynamic simulation of human walking to integrate a proposal presented to the external training partner entity.

The final evidence consisted of three deliverables:

1. File of the CAD software's parts, assemblies, and simulations of mechanical stresses to be validated by the teachers.
2. Develop a written report describing the design methodology used in each part of the orthosis proposal. This element includes the results of the computational simulations and their analysis. The highlights include static analysis, fatigue, fall, buckling, speed analysis, force, and joint acceleration during human walking with and without the device.
3. A one-minute video showing the design of the proposed solution and the results of mechanical studies. The purpose of delivering a short video was to show the proposals to the training partner entity and obtain specific feedback regarding the mechanical and design qualities.

Development of a prototype of a transtibial orthosis: The evidence requested in this stage is intended to evaluate the implementation of the knowledge acquired during the learning phase, focusing on the innovative and sustainable aspect, not only in the manufacturing processes but also in the materials selection processes. It should not be overlooked that professors and specialists in the subject previously provided feedback on the solutions proposed to the challenge to generate an improvement for the end user. The evidence deliverable consisted of the full-scale physical prototype of a transtibial orthosis. This deliverable evaluated the sub-competence of medical device design using a specific rubric.

Once the evidence described above was considered sufficient context about the challenge and having received feedback from the professors and the training partner entity (stakeholder), the students developed the design of a transtibial orthopedic device. However, the generation of this solution required a stage of implementation of the new knowledge and skills acquired to prototype and subsequently test the proposed solution. During this stage of evidence evaluation, the students recognized the mastery of the know-how on the different prototyping processes obtained in the learning phase, having developed novel skills and generating a feeling of satisfaction by obtaining positive results around their application. Figure 5 is a representative sample. Figure 5A shows the CAD design of a transtibial orthosis generated by the Biomechanical Analysis and Design course students. Figure 5B shows the prototype manufactured from the computational design, integrating traditional and additive manufacturing concepts to form their proposal.

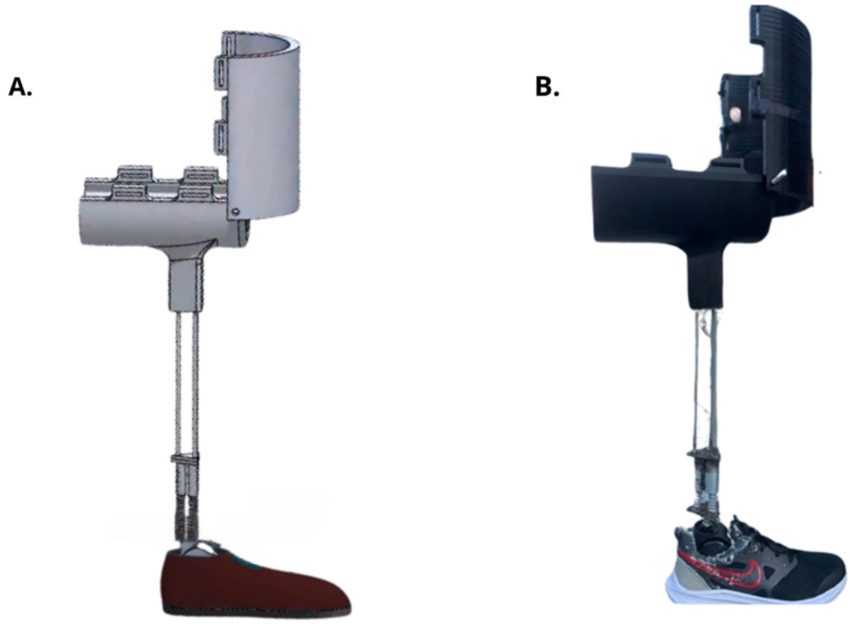

Fig. 5. A) CAD design; **B)** A prototype built by the same team of students and presented during the event

The points evaluated for this delivery are based not only on the evaluation of the prototype manufacturing process but also on its efficiency under normal conditions of use. The evaluation was carried out during a competitive event in which each team of students from all the groups in which teaching was given in the training unit of Analysis and Design in Biomechanics participated. Each team member played a particular role in demonstrating their knowledge about their device. These roles were: presenter of an elevator pitch, user of the orthotic device, and repair and support technician for the device. The evaluation committee comprised the course teachers, two invited expert teachers, and two representatives of the training partner company, who evaluated the efficiency of the devices based on the following aspects of use described below.

Evaluation of a transtibial orthotic prototype: Through the realization of a competitive event, which not only sought to evaluate the vision described above but also to promote student experience and collaborative work, the following points of the deliverable were evaluated:

Ergonomics: Identify the maximum compressive and tension load (static) the prosthesis can withstand depending on its manufacturing material, according to the patient's activity with the prosthesis. The students applied the concepts in the stress deformation charts and safety factors. The functionality of the orthotic prototype was also evaluated; the efficiency of the performance in the ankle joint of the orthosis; the resistance of the solid component; the functionality and efficiency of the performance of the orthotic foot; and the appropriate choice of materials: the materials must satisfy the characteristic of sustainability (economic, ecological, social, and scientific). The students must not include recyclable materials since, by regulation, the WHO indicates it in the manual of suitable procedures and following the college of Biomedical Engineers. The aim of assessing in this way is not only to reward the development of technical skills but also to increase the student's awareness of the human aspect to benefit healthcare. The goal is to put the student in the position of the end user, who will consequently be an amputee patient whose healthcare needs require very particular considerations. This way, SDGs three—good health and well-being and 10—reduced inequalities are addressed. It is essential to mention that to measure the development of sustainable skills, university experts challenged the students to various scenarios where they could choose between applying or not applying the principles of sustainability. Likewise, a close relationship was established between the SDGs and the activities to be completed; expert professors in sustainability established specific exercises for the students. Materials and research sustainability were mainly achieved through reviewing papers and patents for improvement, analyzing the life cycle of materials, and the probability of recycling the materials used. Figure 6 shows a view of the competition and presentation of the orthotic prototype devices.

Fig. 6. Students presenting their orthotic prototype in a competition

The students present their orthotic prototype in a competition where internal and external evaluators grade various items. This is the last step in the flow of events in the CBL experience.

As a post-CBL experience activity, students completed a satisfaction questionnaire. The statistical analysis applied to the responses given by the students was similar to that we have used in previous reports [31]. According to Slovin's formula, this sample represents a response rate of 95% and a margin of error of 2%, which indicates that the conclusions obtained in this work apply to the entire student population with an error of 2% and a confidence level of 99%. The questions asked were the following:

1. What word comes to mind when you finish this biomechanics block?
2. How satisfied are you with the learning results you obtained with this competency-based modality, taking as a reference other blocks where this modality is not used?
3. How important is it to encourage competition through games in this block and thus prepare yourself for the work competition you will experience when you finish your degree?
4. Would you have preferred to solve the challenge of this block individually?
5. How many subjects similar to this one with the experience of challenges and games have you had in your degree?
6. How was your experience in this block, taking into account the learning driven by the resolution of the challenge?
7. In the subsequent IMD blocks, to increase your knowledge, do you consider it appropriate to apply this system based on challenges by competency?
8. How complicated was it for you to design, assemble, and present your orthosis prototype in the competition?
9. After this experience, where do you place your understanding of all the aspects of making a biomechanics device?
10. Did knowing that there would be a competition, which would be part of the challenge evaluation, influence your involvement in solving the challenge?
11. What disciplines did you have to consult to solve the challenge as opposed to other blocks?

A Likert scale of satisfaction was used where, in the graph, 100 means 100% agreement with the statement in the question. Figure 7 shows the results of the questionnaire. When the students were asked how important it was to learn from competitive games, 93% of the interviewees said it was essential. 85% of the respondents saw the biomechanical prototype's planning, development, and presentation as collaborative rather than individual work. This is interesting since they prefer to develop this collaborative work competence rather than do it individually.

About 51% of the interviewees approved of the competition format through games, which is interesting, perhaps due to their lack of knowledge of the properties of CBL when mixed with a competition. In contrast, 85% of the students considered using CBL would be fundamental for their academic future, and 83% considered using a competency as a learning tool using CBL was appropriate for their training.

On the other hand, interestingly, 61% of the students considered the challenge of using the knowledge and skills acquired up to their time of development to be complex. This qualifies the chosen challenge as challenging and of high complexity.

To determine if the teaching experience would have helped to understand the general functioning of biomechanics, 80% of the students considered this experience very useful in their training.

An interesting question was whether knowing in advance that the course would be using a CBL teaching technique with competency would have influenced the decision to take the class. 65% of the students answered affirmatively, indicating they wanted a challenging learning experience.

Finally, a comprehensive evaluation of the experience shows that it is very satisfactory that 83% of students considered the learning strategy very useful for their training.

When asked what other disciplines the students had to consult to solve the challenge, they said they mainly studied mechanics and medicine. However, equipment such as bending, milling, lathes, and welding were almost unanimously mentioned.

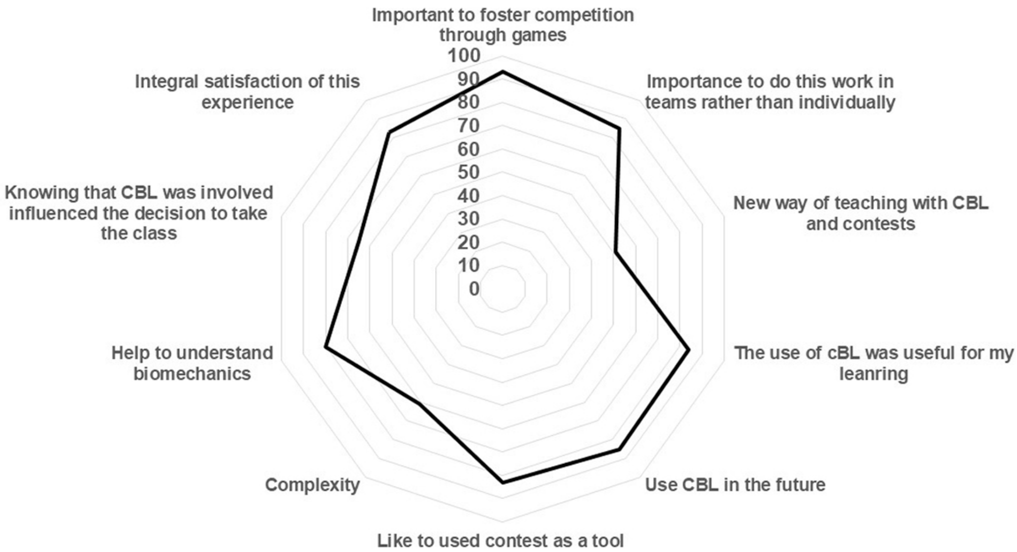

Fig. 7. Radar graph

Figure 7 is a radar graph summarizing the responses to the questionnaire applied to students after the CBL experience with competence in Biomechanics. The graph is on the Likert scale, with 100 being equivalent to 100% agreement with the statement in the questionnaire

Very interestingly, the 17% that were not satisfied with the CBL experience expressed that "I don't have to invest money in generating a prototype," "I didn't like that it took me so long to solve the challenge," and "not all team members showed the same level of interest in solving it."

Then, students were asked the first word that came to mind when looking back at CBL's experience with biomedical engineering competitions. Figure 8 shows the word cloud mentioned, with orthosis being the most mentioned. However, teamwork, the challenge, and mentions of difficulty, design, creativity, and feelings of stress and anxiety were all present.

Fig. 8. Word cloud in response to the question: What is the first word that comes to mind when you finish the biomechanics block?

4 DISCUSSION

Biomedical engineering is making steady progress, aided by cutting-edge technology. New mechatronic, electronic, physical, and sustainable mechanisms are the path that awaits biomedical engineering. Specialized human resources today require transversal (soft) and disciplinary (hard) skills. And more and more emerging skills, such as sustainable or digital skills, are often needed [32].

This report uses CBL as a skills development tool and an innovative competition game format that challenges students to generate ideas and design prototypes, considering lower extremity injuries. The concepts of physics and mechanics are analyzed to provide solid scientific backing for each proposal.

This format was challenging, innovative, and educational for the students regarding skills they would not have had otherwise. They faced the uncertainty of concepts they may not have had and had to seek them out with experts from other disciplines. They increased their vision of the current work environment by having internal judges (other professors) and external judges (from some companies).

Biomedical engineering increasingly uses other sciences to support itself in solving problems; therefore, better human resources are required. The faculty must also be prepared with new technologies and teaching techniques. It is not easy to have a faculty of up-to-date professors willing to participate in courses to improve teaching instruments and strategies.

The natural benefit of this CBL experience in Biomedical Engineering is addressing a real health problem, using a patient's data, clinical context, and socioeconomic context when making a solution proposal regarding mobility and health, and learning different manufacturing and prototyping techniques for the health sector. This knowledge is not in the syllabus and belongs to the formation training part of a HE student.

An important point to highlight is the fact that concepts such as stress and anxiety emerged in the word cloud. However, teamwork, challenge, and mentions of difficulty, design, creativity, and feelings of stress, difficulty, and anxiety were present. This is particularly significant given that these feelings are similar to those described when graduates have their first work experience. Later conversations with students who mentioned these concepts expressed their gratitude that these feelings had arisen during their academic training and for being prepared for the current work reality, which, as we can see, is changing and uncertain. Perhaps there should be specialists who can manage and channel these feelings more appropriately in the future.

Our proposal to use CBL with a competition increased the development of students' capabilities, challenged professors, and created an environment of competition and desire to win and learn more and better than ever before. This undoubtedly pushes professors and students to improve daily, generating a critical mass to discuss and plan new educational techniques and strategies for HE. In any case, our institution's biomedical engineering academic program has benefited from this approach, and it does not escape our attention that it can be adapted to other engineering programs.

5 ACKNOWLEDGMENTS

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