Integrating Biomedical Engineering Design into Engineering Curricula: Benefits and Challenges of the CDIO Approach

Andrés Díaz Lantada[1], Antonio Ros Felip[1], Javier Jiménez Fernández[2], Julio Muñoz García[1], Rafael Claramunt Alonso[1], Jaime Carpio Huertas[2]

[1]Mechanical Engineering Department – [2]Energy Engineering Department
Escuela Técnica Superior de Ingenieros Industriales (School of Industrial Engineering),
Universidad Politécnica de Madrid (ETSII – TU Madrid)
c/ José Gutiérrez Abascal 2, 28006 Madrid, Spain, Contact: adiaz@etsii.upm.es

ABSTRACT

Biomedical engineering is one of the more recent fields of engineering, aimed at the application of engineering principles, methods and design concepts to medicine and biology for healthcare purposes, mainly as a support for preventive, diagnostic or therapeutic tasks. Biomedical engineering professionals are expected to achieve, during their studies and professional practice, considerable knowledge of both health sciences and engineering. Studying biomedical engineering programmes, or combining pre-graduate studies in life sciences with graduate studies in engineering, or vice versa, are typical options for becoming qualified biomedical engineering professionals, although there are additional interesting alternatives, to be discussed. According to our experience, graduates and post-graduates from more traditional and multidisciplinary engineering programmes, especially industrial engineering, can play varied and very relevant roles in the biomedical industry and in extremely complex biomedical device development projects, even outperforming the graduates from programmes mainly focused in bioengineering. However, such impact of industrial engineers in the biomedical field can be importantly increased, by means of an adequate integration of biomedical engineering design concepts, methodologies and good practices into the traditional engineering curricula.

In this study we present the complete development of a novel subject on "Biomedical Engineering Design" for the Master's Degree in Industrial Engineering at ETSII – TU Madrid. The subject is based on the CDIO approach, as we consider it a very remarkable way of promoting student active learning and of integrating, with impact, novel concepts into ongoing curricula. During the subject, groups of students live through the complete development process of different biomedical devices aimed at providing answers to relevant social needs. Computer-aided engineering and rapid prototyping technologies are used as support tools for their designs and prototypes, so as to reach the implementation and operation phases with enough time for a re-design cycle. Main benefits, lessons learned and challenges, linked to this CDIO-based subject, are analyzed, taking into account the results from 2014-2015 academic course. Students from several specializations of our Industrial Engineering MSc (i.e. Mechanical Engineering, Energy, Manufacturing Technology, Materials Science, Chemical Engineering, Automation and Electronics…) have taken part in the subject, what has helped the groups to tackle very complex biodevices and implement them with success. To our knowledge it constitutes the first subject following a complete CDIO cycle in the field of Biomedical Engineering in our country.

KEYWORDS

CDIO as Context, Integrated Curriculum, Integrated Learning Experiences, Active Learning, Biomedical Engineering, Biomedical Engineering Design.
(Standards: 1, 3, 5, 7, 8).

INTRODUCTION

Biomedical engineering a quite recent engineering field, as the first Biomedical Engineering programmes appeared at US universities in the late 1950s, with Drexel University, the Johns Hopkins University, the University of Pennsylvania and the University of Rochester as pioneers. In the late 1960s and 1970s other relevant universities followed them, including: Boston University, Carnegie Mellon, Harvard and MIT, Ohio State University, the University of Illinois, among other interesting examples (Fagette, 1999). Biomedical Engineering is aimed at the application of engineering principles, methods and design concepts to medicine and biology for healthcare purposes, mainly as a support for preventive, diagnostic or therapeutic tasks. Biomedical Engineering professionals are expected to achieve, during their studies and professional practice, considerable knowledge of both health sciences and engineering. Studying Biomedical Engineering programmes or combining pre-graduate studies in life sciences with graduate studies in engineering, or vice versa, are typical options for becoming qualified biomedical engineering professionals, although there are additional interesting alternatives, to be discussed. According to our experience, graduates and post-graduates from more traditional and multidisciplinary engineering programmes, especially industrial engineering, can play varied and very relevant roles in the biomedical industry and in extremely complex biomedical device development projects, even outperforming the graduates from programmes mainly focused in bioengineering. However, such impact of industrial engineers in the biomedical field can be importantly increased, by means of an adequate integration of biomedical engineering design concepts, methodologies and good practices into the traditional engineering curricula.

In fact, according to the Biomedical Engineering Society, a biomedical engineer uses traditional engineering expertise to analyze and solve problems in Biology and Medicine, providing an overall enhancement of healthcare. Students choose the Biomedical Engineering field to be of service to people, to partake of the excitement of working with living systems and to apply advanced technology to the complex problems of medical care. The biomedical engineer works with other healthcare professionals including physicians, nurses, therapists and technician. Biomedical Engineers may be called upon in a wide range of capacities: to design instruments, devices and software, to bring together knowledge from many technical sources, to develop new procedures, or to conduct research needed to solve clinical problems (BMES). The aforementioned duties are directly connected to the traditional corpus of Industrial Engineering (in its broadest sense) and, being applied tasks in direct relation with real and complex problems (pathologies) and systems (human body), can potentially be taught and promoted by means of project-based learning CDIO-related approaches (Crawley, 2007), not necessarily within Biomedical Engineering programmes, but in other more traditional areas of Engineering.

In this study we present the complete development of a novel subject on “Biomedical Engineering Design”, in the framework of the “INGENIA” Initiative, for the Master’s Degree in Industrial Engineering at ETSII – TU Madrid. The subject is based on the CDIO approach, as we consider it a very remarkable way of promoting student active learning and of integrating, with impact, novel concepts into ongoing curricula. During the subject, groups of students live through the complete development process of different biomedical devices aimed at providing answers to relevant social needs. Computer-aided engineering and rapid prototyping technologies are used as support tools for their designs and prototypes, so as to reach the implementation and operation phases with enough time for a re-design cycle. Main benefits, lessons learned and challenges, linked to this CDIO-based subject, are analyzed, considering the results from 2014-2015 academic course.

THE “INGENIA” INITIATIVE:

INTEGRATED PROMOTION OF CDIO INITIATIVES AT ETSII – TU MADRID

The implementation of Bologna process has culminated at ETSII – TU Madrid with the beginning of the Master’s Degree in Industrial Engineering, in current academic year 2014-15. The program was successfully approved in 2014 by the Spanish Agency for Accreditation (ANECA), with the inclusion of a set of subjects based upon the CDIO methodology denominated generally “INGENIA”, an acronym from the Spanish verb “*ingeniar*” (to provide ingenious solutions), also related etymologically in Spanish with the word “*ingeniero*” (engineer). INGENIA students experience the complete development process of a complex product or system and there are different kinds of subjects (and projects), within the initiative, covering most of the engineering majors at ETSII – TU Madrid. Students choose among the different INGENIA subjects (and projects), depending on their personal interests.

The INGENIA subjects are compulsory for all students enrolled in the first year of the Master’s Degree program at ETSII – TU Madrid (a two-year program with 120 ECTS after a four-year Grade in Industrial Technologies with 240 ECTS). The subjects (with a similar CDIO orientation but offering different topics and projects) are 12 ECTS equivalent, which correspond to a student workload between 300 to 360 hours, distributed along two semesters with the following structure: 120 hours of supervised work plus between 180 to 240 hours of personal student work, organised usually in teamworks. Professor supervised part of the subjects is divided into 30 hours dedicated to adapt basic theoretical knowledge derived from other subjects to those directly related with the project, and a second set of 60 hours is devoted to practical work in the lab, with professor supervised sessions. Students also receive two seminars of 15 hours; one oriented to transversal outcomes, in particular, workshops on teamwork, communication skills and creativity techniques, and the other one about social responsibility issues such as environmental impact, social, political, security, health, etc. These lectures, practical sessions, seminars and workshops, are distributed along the 28 weeks of the two semesters of the first year, resulting in 5 hours per week of lectures or practical sessions in the regular schedule of students. Placing the INGENIA subjects in the first year of a 120 ECTS program is indeed interesting, as additional 12 ECTS are devoted to the final degree thesis normally during the second year. Therefore, at least 20% of the whole Master’s Degree is devoted to project-based learning aimed at the complete development of engineering products and systems. Program structure is detailed in Figure 1 and the integration of CDIO activities can be easily appreciated (INGENIA subjects in pale blue and Final Master’s Thesis in pale green).

Hours/week	THIRD SEMESTER	ECTS	Hours/week	FOURTH SEMESTER	ECTS
	Final Master's Thesis	6		Final Master's Thesis	6
6	Curricular configuration	9	6	Curricular configuration	9
2	3 specialization subjects (Automation & Electronical,	3	2	3 specialization subjects (Automation & Electronical,	3
2	Chemical, Electrical, Energetic, Materials,	3	2	Chemical, Electrical, Energetic, Materials,	3
2	Mechanical, Construction, Org.)	3	2	Mechanical, Construction, Org.)	3
2	1 subject on Industrial Installations	3	2	1 subject on Industrial Management	3
2	1 subject on Industrial Technologies	3	2	1 subject on Industrial Technologies	3

Hours/week	FIRST SEMESTER	ECTS	Hours/week	SECOND SEMESTER	ECTS
4	INGENIA (first part)	6	4	INGENIA (second part)	6
2	2 subjects on Industrial Management	3	2	2 subjects on Industrial Management	3
2		3	2		3
2	2 subjects on Industrial Installations	3	2	2 subjects on Industrial Installations	3
2		3	2		3
2	4 subjects on Industrial Technologies	3	2	4 subjects on Industrial Technologies	3
2		3	2		3
2		3	2		3
2		3	2		3

Figure 1. Program structure (Master’s Degree in Industrial Engineering).
120 ECTS program with at least 20% devotion to project-based learning activities.

In addition, the INGENIA subjects are helping us to complement our competence-based strategy, in accordance with CDIO Standards 1, 3, 7 & 8, by placing special emphasis on several professional skills difficult to obtain in more traditional teacher-centred activities, such as conventional master classes and expert talks. Expected outcomes include the promotion of: students' ability to apply knowledge of mathematics, science and engineering, students' ability to design experiments and interpret data, students' ability to design engineering systems and components to meet desired goals, students' ability to communicate effectively and to work in multidisciplinary teams, or students' ability to use modern resources, in accordance with the ABET professional skills our program tries to promote (Shuman, et al. 2005). Different subjects within the INGENIA framework cover diverse disciplines such as: automotive engineering, mechanical engineering, automation and electronics, construction, materials science, energy engineering and biomedical engineering. Next sections describe and analyze the implementation and first experience with our new subject on "Biomedical Engineering Design", as a relevant example of success within the INGENIA framework.

FIRST IMPLEMENTATION OF "BIOMEDICAL ENGINEERING DESIGN" WITHIN THE INGENIA INITIATIVE: MAIN RESULTS, LESSONS LEARNED AND CHALLENGES

The "Biomedical Engineering Design" subject at ETSII – TU Madrid was prepared during academic courses 2012-2013 and 2013-2014, supported by the "Bioingenia" TU Madrid Teaching Innovation Project, on the basis of 30 years of the research work and teaching activities in the field of Biomedical Engineering. Preparing the new subject was considered a strategic opportunity for the collaboration of three teaching units (Machines Engineering, Elasticity and Mechanics of Materials, and Fluid Mechanics) and a challenging and motivating experience, as always happens with multi-departmental subjects. The Teaching Innovation Project was focused on the integration of multi-disciplinary concepts from the different teaching units, adapted from previous more focused subjects on "Biomechanics", "Biofluids" and "Biodevices" from TU Madrid Master's Degree in Biomedical Engineering, so as to obtain a more complete 12-ECTS equivalent subject on "Biomedical Engineering Design". The topics covered in the subject are listed below and provide an excellent introduction to biomechanics, biomaterials, biofluids, biodevices, systematic medical product development, engineering design and medical industry:

- Content block 1: Introduction to biomedical product development.
- Content block 2: Design and simulation of medical devices.
- Content block 3: Biomechanics of joints and prostheses.
- Content block 4: Modeling and simulation of joints and prostheses.
- Content block 5: Fluid mechanics in the human body and related prostheses.
- Content block 6: Modeling and simulation of fluid-related medical problems.

The Teaching Innovation Project was also devoted to the development of case studies and of new laboratory facilities for the promotion of hands-on activities and for supporting the development of medical devices to be carried out by groups of students, in a PBL-approach, as main part of their assessment. Figure 2 includes some of the new case studies, work-benches, testing facilities and supporting resources developed. The subject counts with the support of the "Product Development Lab", the "Material Strength Lab" and the "Fluid Mechanics Lab", where several design and simulation software, testing facilities and rapid prototyping technologies by means of additive manufacturing and rapid form copying are available. Such facilities are very relevant for letting students live trough the complete development process of a new medical device, from the conceptual and design phases, to the implementation and operation stages, which are normally more difficult to achieve (Díaz Lantada, 2013).

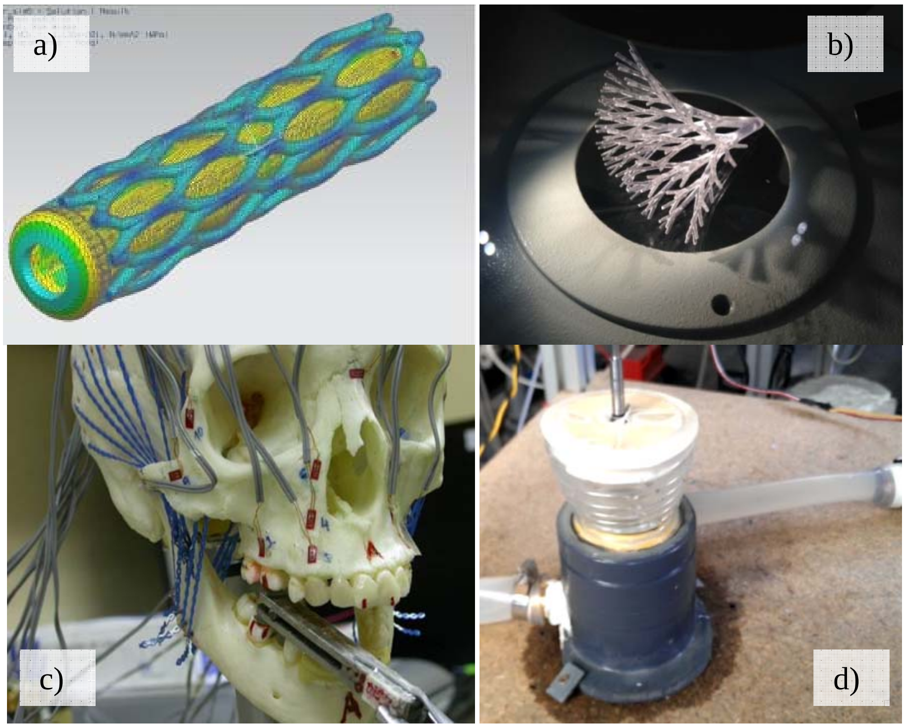

Figure 2. Examples of case studies and workbenches as infrastructure for the subject:
a) Expandable stent, b) vascular network, c) jaw testing system, d) extra-corporeal pump.

During academic course 2014-2015, 28 students from the first promotion of our Master's Degree in Industrial Engineering (among a total of 180 engineering graduates) have taken part in the "Bioengineering Design" subjects of the INGENIA Initiative. At the beginning of the subject, the different students were divided into 6 groups and each group proposed at least 5 different medical devices, which could potentially be developed within the subject. All the proposals were written down (as shown in Figure 3) and a voting session was carried out, with participation of students and teachers, so as to decide the final medical devices to be developed in parallel to the subject. In the end, the 6 devices (one per group) were selected:

- Intradermal pump for drug delivery.
- Extra-corporeal pump for assisted heart surgery.
- Eardrum protecting device with water detection system.
- Tissue engineering scaffold for tendon and ligament repair.
- Device for sleep apnea management.
- Instrumented artificial heart valve.

In the subject, the conceptual stage is supported by creativity-promotion tools such as TRIZ, morphological boxes and systematic procedures for promoting the generation, combination and selection of ideas. The design stage counts with industrial state-of-the-art modeling and simulation software of main engineering disciplines. The aforementioned labs help with the implementation and operation stages with resources including: 3D printers, rapid prototyping facilities, Arduino kits, libraries of sensors and actuators and conventional manufacturing and testing resources. Some results from students' designs, simulations, prototypes and trials are included in Figure 3, although the final results will be obtained along the second semester just before the 11th International CDIO Conference, where we hope to discuss them with colleagues from partner universities.

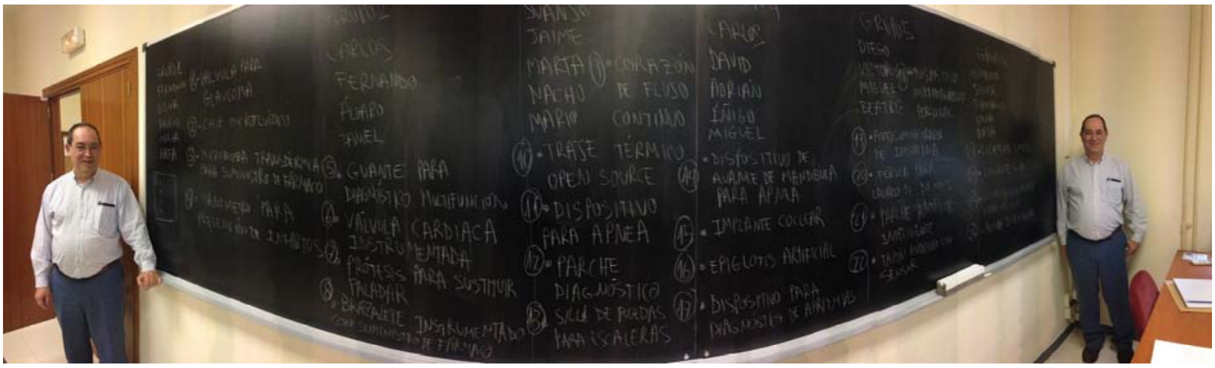

Figure 3. Picture with Prof. Julio Muñoz, showing the initially proposed list of biodevices.

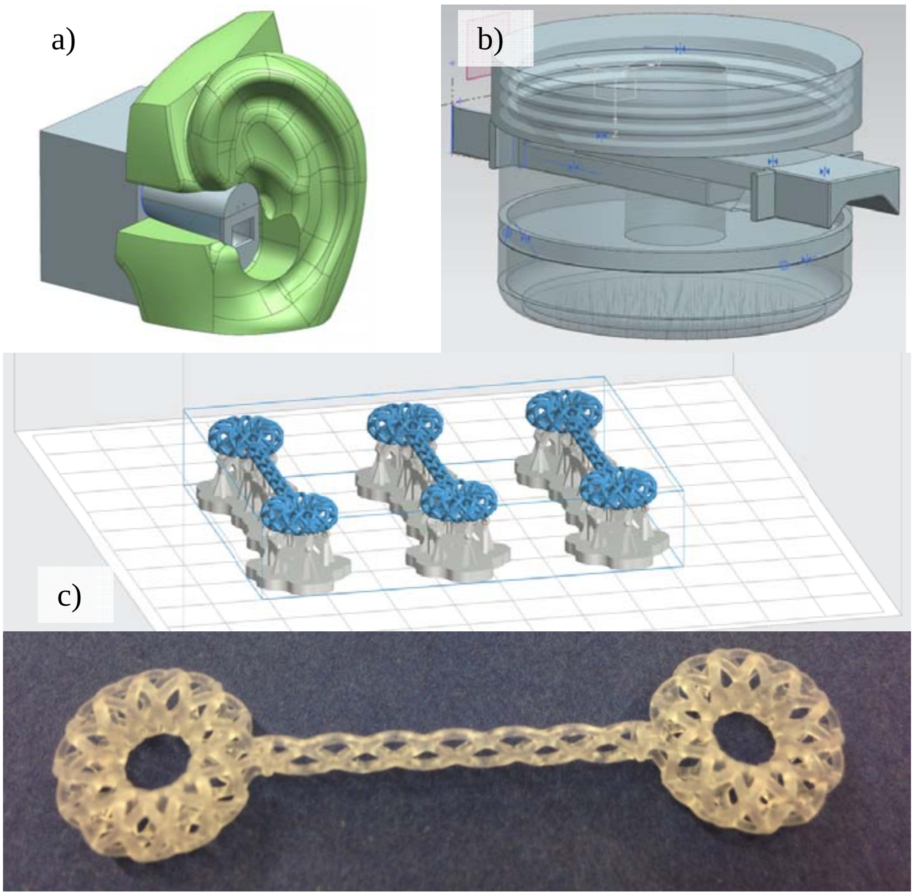

Figure 4. Some preliminary results from students' designs, simulations, prototypes and trials. a) Conceptual design of ear protecting device. b) Basic computer-aided design of intradermal pump for drug delivery. c) Rapid prototype of tissue engineering scaffold for ligament repair.

Among already detected positive results within the subject of "Bioengineering Design", it is very important to highlight the following aspects, which we believe are intrinsically connected with a well implemented CDIO framework within the Master's Degree in Industrial Engineering and with a successful PBL-based subject:

-- Students' success ratio and attendance to formal lessons is importantly improved.

-- The interaction between teachers and students has experienced a relevant increase.

-- Intra- and inter-departmental communication has been promoted.

As preliminary summary of results, Table 1 includes some figures related to student and teacher success, motivation and implication in the subject, which is compared with mean values of other department subjects. The positive effect of shifting towards CDIO related methodologies can be clearly appreciated. It is necessary to indicate that the benefits affect not only learning and acquisition of outcomes, but also student and teacher motivation and mutual relation in a very special way, which is starting to influence the overall ambience of learning, collaboration and respect present in our novel Master's Degree in Industrial Engineering. For the first time, students from our Department took part in the "Actúa UPM" Enterprise Creation Competition presenting results from their work within the subject. One group was selected as finalist for their instrumented heart valve design, which can be considered a relevant success and an additional way of validating the learning outcomes, as the mentioned competition is typically aimed at PhD students, post-doc researchers and faculty staff. All groups are currently (April 2015) constructing their prototypes for final testing, after having completed the whole design cycle, according to expectations.

Thanks to implementing the CDIO approach, students taking part in our subject lived, for the first time, through the complete development process of an engineering system and are now better prepared for their final master's theses, as students themselves have highlighted in several occasions during the subject. In addition, they received, again for the first time, training in relevant engineering resources and improved their comprehension and application of several professional skills, all of which adds to the learning outcomes of the subject. Some seminars organized for the promotion of learning outcomes and professional skills include:

- Introduction to computer-aided design and engineering (4 hours of tutorials / group).
- Introduction to the relevance of IP management and protection (4 hours).
- Introduction to sustainable engineering design (12 hours and an impact assessment tasks linked to the product being developed).
- Practicals on professional skills: communication, teamwork, creativity (12 hours).

These positive aspects clearly rely on an important increase of teacher dedication outside the classroom to the CDIO-based subject, but the general impression among the different teachers is that such additional dedication is compensated by the highly satisfactory results. In addition, the practical activities of the new subject are more expensive to implement, than more traditional practicals, as can be appreciated from the data in Table 1. However, the additional amount lays between 1000€ and 2000€ for a whole subject, allowing all the students to live through the complete development process of a complex biomedical device. Again, the general impression is that the results are worth the effort.

As additional reflection, the proposed two-semester structure for the INGENIA subject on "Bioengineering Design" is very appropriate, as the "conceive" and "design" phases are adequately carried out during the first semester and the "implement" and "operate" stages are tackled in the second semester. A whole academic year is ideal for maturing the development process of complex products and systems and is helping us to improve several prior experiences, limited to design and simulation activities, with the benefits from obtaining final prototypes and carrying out operational trials. It is also important to note that students from several specializations of our Industrial Engineering MSc (i.e. Mechanical Engineering, Energy, Manufacturing Technology, Materials Science, Chemical Engineering, Automation and Electronics…) have taken part in the subject, what has helped the groups to tackle very complex biodevices and implement them with success. **To our knowledge it constitutes the first subject following a complete CDIO cycle in the field of "Biomedical Engineering" in our country.**

Table 1. Some figures related to student and teacher motivation and implication in their subjects before and after the INGENIA Initiative. *According to data of the first semester.

Control aspect	In conventional subjects of our departments	In the CDIO subject on "Bioengineering Design"*
Success ratio (student completion rate)	65% – 75%	100%
Student attendance to scheduled lessons	45% – 65%	>90%
Typical number of answers to debate questions	1 – 3	6 – 8
Typical number of student questions / hour	2 – 5	4 – 7
Number of teachers inside the classroom at once	1	2 – 4
Frequency of meetings between the teachers of the same subject	2 / semester	4 / month
Frequency of meetings between the teachers of different departments	1 / semester	1 / month
Number of interactions with students outside the classroom / week	0 – 3	8 – 10
Resources needed for practical activities	0 – 100 € / student for practical sessions	75 – 100 € / student for practical sessions 750 – 1.000 € / group for prototyping tasks
Number of professional skills promoted and assessed	1 – 4	9
Hours devoted by the teachers outside the classroom / class hour	1 – 1.5	3 – 4
Students living a whole CDIO cycle	-	100%
Students aiming at enterprise creation based on their results	<5%	20% (with one group as finales of UPM Enterprise Creation Competition)

Regarding assessment, we are facing and managing the typical problems that arise when assessing teamwork activities. First of all, the proposed biodevices are complex enough to promote positive interdependence between members of the team, so that each of the members is needed for the overall success and that there is enough workload to let all students work hard and enjoy the experience, thanks to learning a lot. In addition, we are encouraging individual assessment, complementing the teamwork activities with individual deliveries and during the public presentations of their final results (which account for a 30% of the global qualification). The evaluation of professional skills counts with the help of ad hoc designed rubrics, as part of an integral framework for the promotion of engineering education beyond technical skills, consequence of recent educational innovation projects (Hernández Bayo, et al., 2014). Main results are to be presented at Cheng-Du after forthcoming analyses.

Considering future challenges, we would like to incorporate the developed products of 2014-2015 academic course as case studies, in a continuous improvement cycle, which hopefully will help us complete a large library of biodevices. Counting with a library of designs and prototypes of several biodevices will be positive, not only for teaching purposes, but also for research activities.

The detailed subject may be the first seed towards the creation of a biomechanical engineering research centre at ETSI Industriales – TU Madrid, based on the collaboration among the teaching units in charge of the subject. We are also confident that students have clearly perceived the relevance and potential of biomedical engineering and we are sure that several of them will enroll with us in research activities, linked to their master theses or even to their PhD theses, which may result in an excellent input for an eventual research centre and constitute an excellent way of linking teaching and research.

CONCLUSIONS

Present study has detailed the complete development of a novel subject on "Biomedical Engineering Design", in the framework of the "INGENIA" Initiative, for the Master's Degree in Industrial Engineering at ETSII – TU Madrid. The subject has been implemented with the CDIO approach in mind, as we consider it a very remarkable way of promoting student active learning and of integrating, with impact, novel concepts into ongoing curricula. During the subject, groups of students have lived through the complete development process of different complex biomedical devices aimed at providing answers to relevant social needs. Computer-aided engineering and rapid prototyping technologies have been used as support tools for their designs and prototypes, so as to reach the implementation and operation phases with enough time for a re-design cycle. Main benefits, lessons learned and challenges, linked to this CDIO-based subject, have been analyzed and discussed, considering the results from 2014-2015 academic course.

Finally, our attendance to the 2015 Cheng-Du 11th International CDIO Conference will help us to discuss our new subject with experts of CDIO framework. Their comments and proposals for improvement will help us to adjust our views and strategy, so as to obtain optimal results. We understand that the CDIO framework is a continuous improvement process and we are already expectant to experiment its results. We would like to acknowledge our students for their motivation, implication and proposals for improvement, which will be taken into account in forthcoming editions of the "INGENIA Initiative" and in its "Bioengineering Design" subject.

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CDIO Standards 2.0: http://www.cdio.org/implementing-cdio/standards/12-cdio-standards

BIOGRAPHICAL INFORMATION

Dr. Andrés Díaz Lantada is Professor in the Department of Mechanical Engineering at ETSII – TU Madrid. His research activities are aimed at the development of biodevices, based on special geometries and on the use of smart materials, with the support of computer-aided engineering resources and solid freeform manufacturing technologies. He incorporates research results to subjects on "Bioengineering Design", "Design and Manufacturing with Polymers" and "Computer-aided Mechanical Engineering". He has been guest editor for the International Journal of Engineering Education for the special issues on "Learning through play in Engineering Education", "Collaboration between Academia and Industry on Engineering Education", "Engineering Education: Beyond technical skills" and "Engineering Education for all". He has received the "TU Madrid Young Researcher Award" and the "TU Madrid Teaching Innovation Award" in 2014.

Dr. Antonio Ros Felip is Professor in the Department of Mechanical Engineering at ETSII – TU Madrid. His research activities are aimed at the modeling and performance assessment of natural and synthetic biomaterials and at the development of complex biomechanical models. He has been involved in teaching-learning tasks in the fields of Biomechanics and Biomedical Engineering for more than 20 years, being a pioneer in these topics at TU Madrid. He has received the "Golden Vector" Prize for teaching excellence.

Dr. Javier Jiménez Fernández is Full Professor of Fluid Mechanics in the Department of Energy Engineering at ETSII – TU Madrid. He leads the TU Madrid Research Group in "Fluid Mechanics Applied to Industrial Engineering". He has been involved in teaching-learning tasks in the fields of Biomedical Engineering, covering topics on biological fluids, for more than 20 years, being a pioneer in these areas in our University.

Dr. Julio Muñoz García is Professor in the Department of Mechanical Engineering at ETSII – TU Madrid. His research activities are linked to mechanical systems, vibration theory, tribological phenomena, biomechanics and biomedical product development. He has been involved in teaching-learning tasks in the fields of Biomechanics and Biomedical Engineering for more than 20 years, being a pioneer in these topics in our University.

Dr. Rafael Claramunt Alonso is Professor in the Department of Mechanical Engineering at ETSII – TU Madrid. His research activities are aimed at the characterization, modeling, application and performance assessment of natural and synthetic biomaterials and at the development of complex biomechanical models.

Dr. Jaime Carpio Huertas is Professor in the Department of Energy Engineering at ETSII – TU Madrid. His research tasks are linked to of modeling and numerical simulation tasks based on the use of partial differential equations, with applications to most areas of Fluid Mechanics, Environmental Engineering and Civil Engineering.

Corresponding author
Dr. Andrés Díaz Lantada
ETSI Industriales – TU Madrid
c/ José Gutiérrez Abascal 2,
28006 Madrid, Spain
+34913363120
adiaz@etsii.upm.es

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