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The Education, Scholarships, Apprenticeships and Youth Entrepreneurship

EUROPEAN NETWORK FOR 3D PRINTING OF BIOMIMETIC MECHATRONIC SYSTEMS

INTELLECTUAL OUTPUT O2 - EMERALD REPORT

Project Title	**European network for 3D printing of biomimetic mechatronic systems 21-COP-0019**
Output	**O2 - EMERALD e-toolkit for teaching purposes, basic knowledge about realizing biomimetic mechatronic systems**
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bizzcom

Content

1. Introduction, objectives and tasks of O2

The EMERALD project aimed to bridge the gap between theoretical knowledge and practical applicability in the biomimetic mechatronic systems, particularly used for people with amputated arms. This ambitious goal led to the conception of the EMERALD e-toolkit manual that has been developed collaboratively by the EMERALD consortium partners, the manual serving as a laboratory guide, transcending basic knowledge to provide practical insights into the design and realization of these advanced systems using 3D printing technologies.

A core objective of the e-toolkit manual was to facilitate a deep understanding of the entire process of creating bio-mechatronic systems, such as robotic arms, orthoses, and prostheses. This comprehensive guide covers crucial stages starting from the pre-validation of CAD models and use of CAE methods to the selection of materials, part production by 3D printing technologies and integration of sensors and transducers into the developed bio-mechatronic systems. The e-toolkit manual also addresses programming, assembly issues and the application of VR/AR technologies in relation to the developed systems.

The e-toolkit manual aims to immerse both professors and students in a hands-on learning experience, encouraging the application of theoretical knowledge in practical case studies. This approach is designed to stimulate the creation of personalized mechatronic designs, incorporating innovative ideas in shape and material selection, tailored to specific 3D printing technologies like FDM or DLP methods. The end goal was to ensure that the products meet the real-world requirements and needs of patients with amputated arms. In line with this, the EMERALD project also focused on fostering real-world applications by identifying potential diploma project thesis topics. This was supported by healthcare experts and industrial partners, ensuring that the solutions presented in the e-toolkit align with actual patient needs. The involvement of the industrial partner BIZZCOM was particularly significant, offering valuable insights and ensuring that the developed bio-mechatronic components meet the end-user demands in terms of material type and design considerations. The collaborative effort of educational institutions, medical experts, and industrial partners in the EMERALD project aimed to innovate beyond traditional teaching methods. The e-toolkit manual was a central tool in this endeavor, leading to partnerships with companies that provided access to advanced 3D printing tools and materials. This collaboration resulted in innovative solutions for bio-mechatronic systems for real patients, a key outcome showcased in the Multiplier Event organized by the Technical University Cluj-Napoca (TUCN).

Moreover, the e-toolkit manual was integrated into the e-learning virtual laboratory platform that has been realized in the frame of O3, making this valuable information accessible to a broad audience, from students and professors to business professionals in the end. This initiative ensured that the benefits of the EMERALD project resources reached a wide range of people globally.

In terms of responsibilities, the University of Agder (UiA) in Norway played one crucial role in supervising and monitoring O2. They developed the basic concepts of an initial variant of a sensorized robotic arm, a cornerstone of the EMERALD project. This development was showcased during the EMERALD summer school in Norway, where participants experienced firsthand the complete lifecycle of such a bio-mechatronic system – from CAD design to 3D printing, sensorization, programming, and testing for repeatability. PUT took the lead in CAD design, preparing case studies for both active and passive orthoses. TUCN contributed through Computer Aided Engineering (CAE) analyses of these models. UPB was tasked with material analysis and selection, a critical aspect of the EMERALD project. Their focus on testing new materials using the innovative FRESH (Freeform Reversible Embedding of Suspended Hydrogels) 3D Printing method added a cutting-edge dimension to the project. This collaboration extended to TUCN and PUT, who conducted joint tests with UPB, integrating these findings into the e-toolkit manual. PUT was also responsible for assembling and programming the bio-mechatronic systems, thus ensuring a comprehensive approach from CAD design to final testing. UiA, initially set to produce the assembling and testing module, was later assigned to provide feedback on the new case studies developed by PUT for specific patients. Last but not least Bizzcom company was entrusted with the development of AR applications, while PUT was responsible for the VR component of the e-toolkit manual. These applications aimed to provide practical insights into the design, realization and application of bio-mechatronic systems for people with special needs (patients with amputated arms) in the end. The e-toolkit manual that has been realized by the EMERALD consortium partners can be freely accessed and downloaded from the next following link: https://project-emerald.eu/?page_id=23.

2. EMERALD e-toolkit manual description

As it was mentioned before in the previous chapters, CAD is the first step to be considered when a bio-mechatronic system for people with amputated arms is considered to be realized using 3D printing technologies.

The primary objective of the CAD part of the e-toolkit manual realized by PUT partner was to provide the main knowledge and skills for designing modular mechanical hand prosthesis initially intended for children, but later adapted to the needs of adult patients. The focus was on enabling adults to perform continuous and physically demanding activities, such as cycling, with ease (see Figure 1). This entailed a transformation from a simple mechanical prosthesis to more complex biomechatronic prosthesis, equipped with sensorization to optimize functionality for adult use.

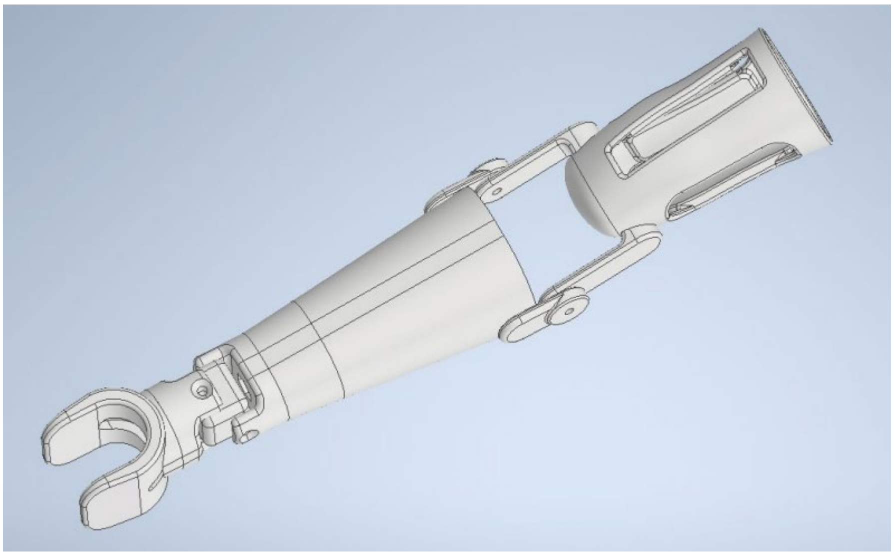

Figure 1. CAD model of a bicycle prosthesis

One of the most important features of this prosthesis is its generative CAD model. This model uniquely incorporates anthropometric data and various configuration inputs, facilitating the creation of components that are anatomically compatible with individual patients. The toolkit leverages the AutoMedPrint system from the Poznań University of Technology, demonstrating an innovative approach in the rapid design and production of custom orthopedic and prosthetic products.

The CAD part of the e-toolkit manual provides an in-depth look at each component of the prosthesis. The prosthetic socket, for instance, is custom-generated based on spatial scanning data of the patient's residual limb. The manual details the algorithms and techniques used for data processing and model generation, ensuring precise and personalized fit. The forearm and end effector sections of the prosthesis are also discussed in detail. The design of these components is focused on versatility and adaptability, ensuring they can be customized to meet the varied requirements of different patients.

An intriguing aspect of the CAD part of the e-toolkit manual is the evolution of the prosthesis from a mechanical model to a biomechatronic one. This transition involved the integration of a simple electronic system for activity monitoring, particularly for cycling. The manual discusses the design alterations necessary for embedding electronic components such as a microcontroller, force sensor, inertial sensor, and an SD card module into the prosthesis. This transformation highlights the e-toolkit emphasis on practical application, showcasing how mechanical designs can be enhanced with electronic systems for better functionality and user experience.

In essence, the CAD component of the EMERALD e-toolkit manual is not just a guide for designing a prosthetic device. It is a detailed exploration of the journey from a basic mechanical model to advanced bio-mechatronic prosthesis. By focusing on modular design, 3D printing, and sensor integration, the manual contributes significantly to the field of biomechatronics, offering valuable insights into the customization and optimization of prosthetic devices for people with amputated arms in the end (see Figure 2).

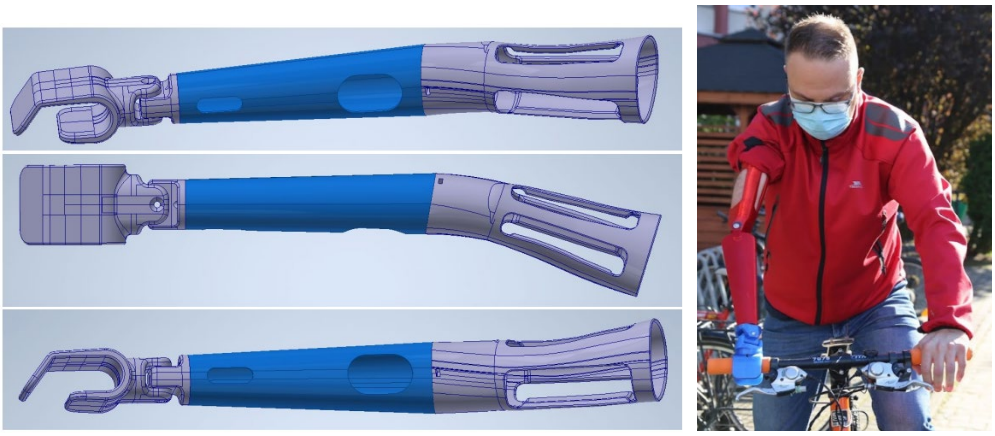

Figure 2. Customizing and optimizing of prosthetic devices for people with amputated arms

The **Computer-Aided Engineering (CAE) part** of the EMERALD e-toolkit manual, realized by TUCN is focusing on the strength analysis of an upper-limb prosthesis using finite element analysis (FEA) through a detailed simulation of a distal tensile test (see Figure 3). This has been achieved using the FEA module SolidWorks Simulation included in the SolidWorks CAD package. The test involves applying a gradually increasing traction load, from zero to 750 Newtons, to the prosthesis while it is firmly attached to a rigid support fitting the upper arm's inner surfaces.

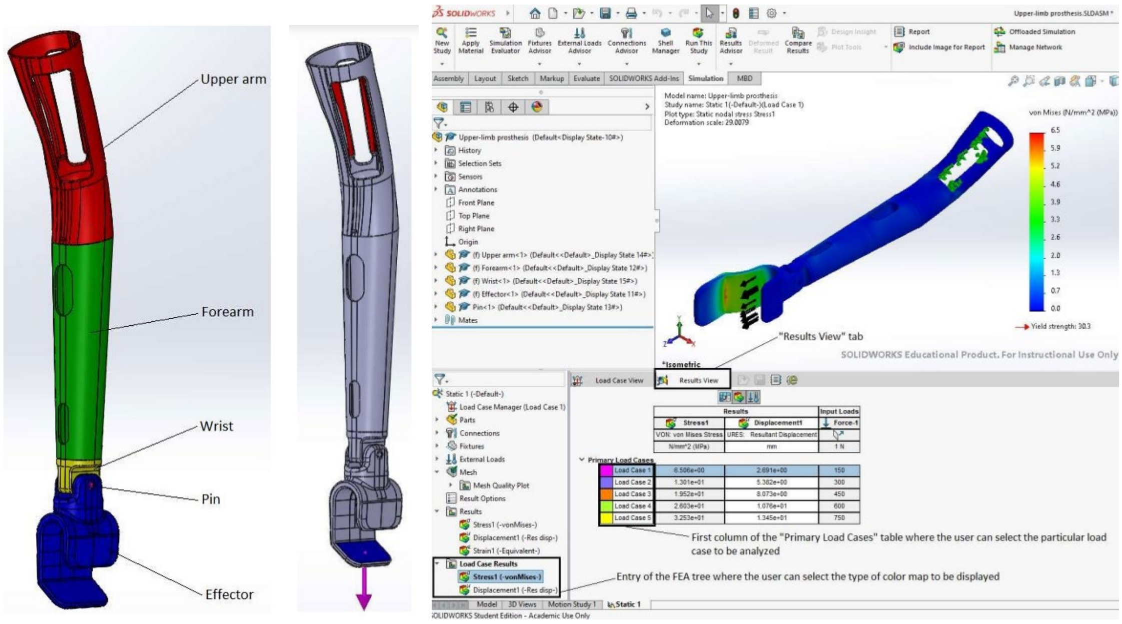

Figure 3. Strength analysis of an upper-limb prosthesis using finite element analysis

The prosthesis components were made of PETG, a material chosen for its isotropic linear elastic behavior. The CAE part of the e-toolkit manual details the physical and mechanical properties of PETG which are essential for the FEA model of the tensile test. These components are bonded together along their contact surfaces, a crucial aspect of the simulation setup.

The preparation of the FEA model involves several steps outlined in the manual, including opening the 3D model in SolidWorks, activating the SolidWorks Simulation module, and adjusting working parameters like unit systems and measurement units. The toolkit guides users through adding the Upper-limb prosthesis FEA folder to SolidWorks' material libraries, setting up the model for the tensile test, and defining material properties for the prosthesis components. To simulate the tensile test, the CAE part of the e-toolkit manual provides instructions on setting up full locking boundary conditions, applying the distal traction load, and generating the finite element mesh. The guide meticulously details each step, from defining load cases to adding sensors for tracking stress and deflection. The numerical results of the FEA are interpreted to analyze the mechanical response of the prosthesis under different load cases. The toolkit provides data on the maximum von Mises equivalent stress and maximum deflection corresponding to various traction forces, illustrating the linear relationship between stress and force, and deflection and force. This analysis helps determine the critical load at which the prosthesis material reaches its yield strength.

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Additionally, the manual suggests individual tasks for further exploration, like evaluating the prosthesis strength characteristics using different materials like PLA and developing alternative designs for the upper-limb prosthesis.

The 3D Printing part of the EMERALD e-toolkit manual, realized by the UPB partner offers an in-depth exploration into the basics of 3D printing for medical applications, specifically focusing on personalized orthosis, robotic arms, and 3D Fresh printing of organ phantoms for surgical applications.

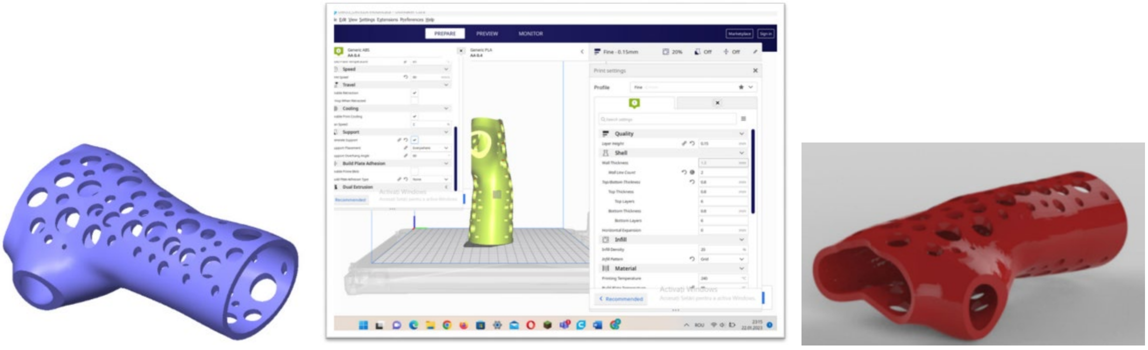

Figure 3. Realizing of hand wrist orthosis by 3D printing technologies

This comprehensive part of the 3D printing of e-toolkit manual begins by detailing the process of 3D modeling using software like SolidWorks, emphasizing the creation of detailed and accurate models necessary for effective 3D printing. It then delves into the conversion of these models into STL files, which are pivotal for the 3D printing process, highlighting the importance of selecting appropriate resolution settings to ensure the accuracy and quality of the print. The e-toolkit manual extensively covers the selection of suitable 3D printing software and hardware, including the use of Fused Deposition Modeling (FDM) and Stereolithography (SLA)/Digital Light Processing (DLP) printers. The e-toolkit manual provides practical guidance on software like Ultimaker Cura and FormLabs, demonstrating the processes of file preparation, machine setup, and the actual printing process. A significant part of the e-toolkit manual on 3D printing is dedicated to explaining the detailed instructions on material selection, with a focus on materials like ABS and PLA for producing personalized orthosis. The part of the e-toolkit manual on 3D printing goes deeper through the entire process from file preparation to the final printing, detailing settings like layer thickness, orientation, support structures, and printing parameters.

Additionally, the 3D printing part of the e-toolkit manual explores the advanced technique of 3D Fresh Printing, which involves the use of Freeform Reversible Embedding of Suspended Hydrogels. This method is particularly beneficial for creating realistic organ phantoms for surgical applications, offering an innovative approach to medical training and preoperative planning. The guide provides insights into the preparation of models for this method, material selection, and the particularities of the 3D printing process.

The Materials part of the EMERALD e-toolkit manual, realized by UPB partner serves as an important resource in the selection and application of materials for 3D printing in biomechatronic systems. Central to this part of the e-toolkit is the use of the Total Materia database (see Figure 4), which provides comprehensive data on over 450,000 metallic and non-metallic materials. This database is instrumental in determining the properties of materials used in the project, including alloys, polymers, ceramics, and composite materials.

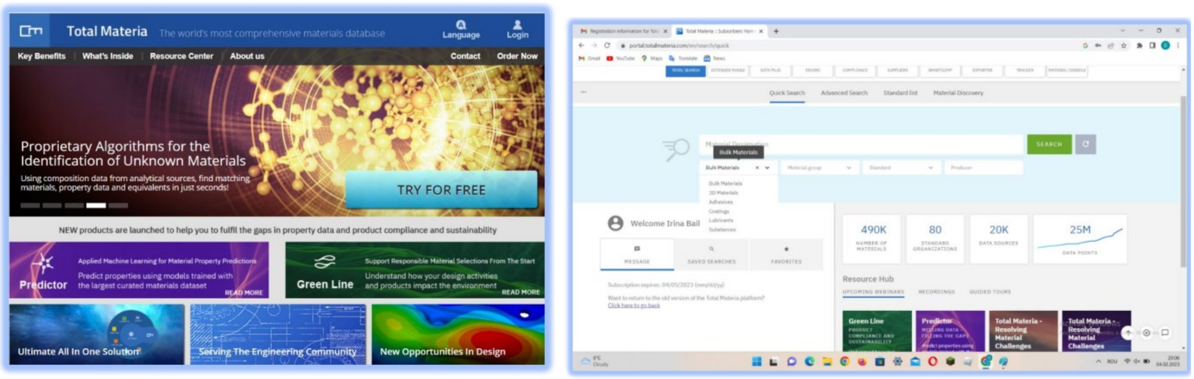

Figure 4. Total Materia database for proper material selection

The Materials part of the e-toolkit manual begins with an exploration of alloys, particularly focusing on Ti6Al4V, a titanium alloy known for its strength, lightweight, and biocompatibility, making it ideal for medical applications. The Materials part of the e-toolkit manual guides users through the process of identifying the chemical composition and mechanical properties of this alloy using advanced research techniques in the Total Materia database. The Materials part of the e-toolkit manual also goes deeper into the study of polymers, particularly PLA (Polylactic Acid), a widely used material in 3D printing due to its ease of use and biodegradability. The manual details the mechanical properties and manufacturing processes of PLA, emphasizing its suitability for various biomedical applications.

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Another significant aspect of the Materials part of the e-toolkit manual is the exploration of ceramics, with a specific focus on Hydroxyapatite (HAp). HAp is known for its application in bone grafts and dental implants due to its osteoconductive properties. The toolkit provides detailed information on the mechanical properties and manufacturers of HAp variants, offering insights into its usage in additive manufacturing processes like SLS (Selective Laser Sintering) and SLA (Stereolithography). Furthermore, the Materials part of the e-toolkit manual covers composite materials such as plywood, detailing their mechanical properties and potential applications. This section underscores the versatility and wide-ranging applications of composite materials in various engineering and medical fields.

Going further, the **Virtual Reality (VR) and Augmented Reality (AR)** part of the EMERALD e-toolkit manual, realized by BIZZCOM partner goes into the innovative use of VR and AR technologies in the development of biomimetic mechatronic systems (see Figure 5).

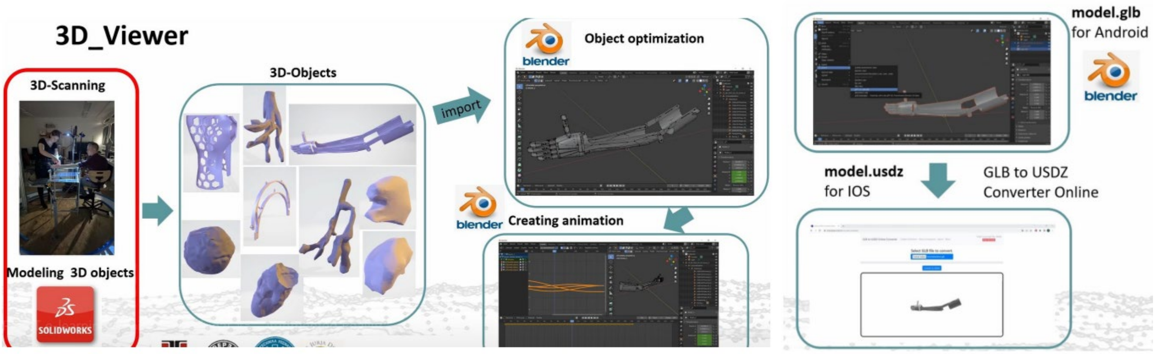

Figure 5. VR /AR applications realized in the frame of the e-toolkit manual

The VR /AR part of the e-toolkit manual begins with an introduction to AR applications, particularly focusing on the use of Blender software for creating and optimizing 3D models. These models are essential for AR visualizations, and the VR /AR part of the e-toolkit manual guides users through the process of 3D scanning or modeling objects, optimizing them for use in AR environments. A key part of the VR /AR part of the e-toolkit manual is dedicated to building AR applications using Unity and the Vuforia Engine. It provides step-by-step instructions for tasks like preparing the Unity project for AR work, importing 3D models, adding simple interactions, and compiling the application for use on devices like tablets. These processes are crucial for creating interactive AR visualizations, allowing users to engage with the models in a more immersive way.

In addition to AR, this part of the e-toolkit manual also covers the creation of VR applications, with an introduction to creating SteamVR compatible projects. This includes importing 3D models, creating scenes, programming product configurations, and developing animations. The manual outlines the process for creating executable applications, allowing users to experience and interact with the 3D models in a virtual space. A particularly innovative feature discussed is the creation of an AR configurator for prostheses. This tool allows users to visualize and interact with different prosthetic designs in AR, providing a practical and engaging way to explore various configurations. The VR/AR part of the EMERALD e-toolkit manual is a comprehensive guide to the application of VR and AR technologies in the field of biomimetic mechatronics since it combines theoretical knowledge with practical tutorials, enabling users to create and interact with 3D models in both virtual and augmented realities. This part of the e-toolkit manual is an invaluable resource for educators, students, and professionals interested in the intersection of digital technology and biomechatronic system development.

The last part of the EMERALD e-toolkit manual, realized by University of Agder (UiA) which has constituted the base of the e-toolkit manual realized by the other partners of the EMERALD consortium is a comprehensive guide that delves into the construction, programming, assembly, and testing of a 3D printable robotic arm, which can also function as a haptic device (see Figure 6).

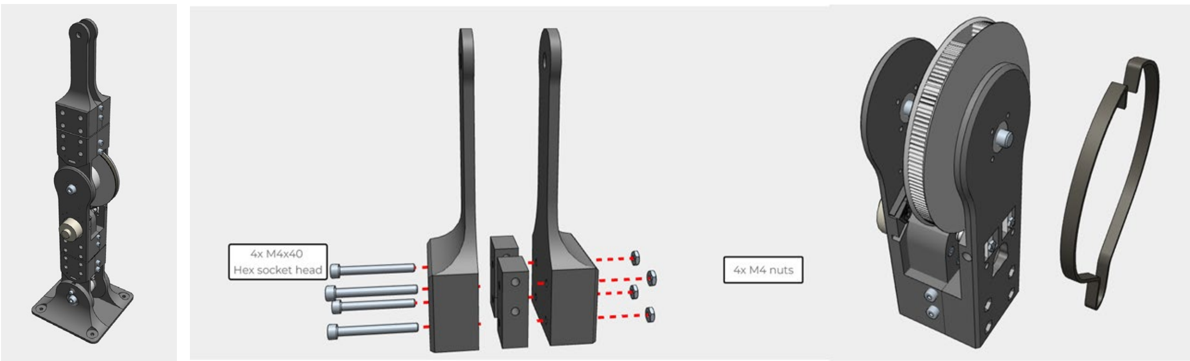

Figure 6. Haptic device realized by the University of Agder partner in the frame of O2

In this part of the e-toolkit manual, the convergence of 3D printing technology and robotics is explored, highlighting the advantages of this integration in creating programmable, versatile, and customizable robotic arms. It addresses the printing of various components such as joints, grippers, and end-effectors, underscoring the customization possibilities afforded by 3D printing in the realm of robotics.

The guide also goes deeper into the programming aspects of these robotic arms, with a particular focus on using the Arduino platform. It covers various control systems, including PID control and more advanced methods like machine learning and computer vision, showcasing the versatility and applicability of Arduino in robotic programming. Furthermore, this part of the e-toolkit manual discusses different 3D printing technologies, such as Fused Filament Fabrication (FFF), for constructing low-cost robotic arms. It reviews current designs of robotic arm grippers, providing insights into gripper fabrication processes. An interesting aspect of this part of the e-toolkit manual is its focus on the use of robotic arms as haptic devices, creating immersive experiences in applications ranging from teleoperation and virtual reality to medical training and simulation.

The section on the biomimetic 3D printable robotic gripper is particularly notable, where the design and construction of a simple, one-axis robotic arm are detailed. This section includes comprehensive information on the arm's construction, control methods, and software development for various control and sensor functions. The manufacturing and testing processes are also elaborated upon, providing a step-by-step guide on assembling the robotic arm using 3D printed components and electronic parts, as well as methodologies for ensuring its functionality as a haptic device. Overall, this part of the e-toolkit manual is a rich resource that provides in-depth knowledge and practical guidelines for anyone interested in the fields of robotic design, programming, and 3D printing. It demonstrates how available technologies and low-cost components can be utilized to create functional robotic arms, making it an invaluable educational tool for students and researchers in the global community.

3. Conclusions

The EMERALD project, with its e-toolkit manual represents a significant step in connecting theoretical knowledge and practical applicability in the field of biomimetic mechatronic systems. Aimed primarily to provide educational resources to anyone interested in supporting people with amputated arms, this project brought together EMERALD consortium partners to develop a manual that transcends basic academic knowledge, offering practical insights into the design and realization of advanced systems using 3D printing technologies in the end. The e-toolkit manual stands out as a comprehensive guide, meticulously covering every phase of creating biomechatronic systems like robotic arms, orthoses, and prostheses.

From the pre-validation of CAD models and the use of CAE methods to the careful selection of materials, part production by 3D printing technologies and the integration of sensors and transducers, the manual encapsulates the full spectrum of skills and knowledge needed for conceiving and realizing of bio-mechatronic systems. Additionally, it addresses crucial aspects such as programming, assembly, and the application of VR/AR technologies, thus ensuring a holistic understanding of the system development process. In conclusion, the EMERALD e-toolkit manual, that is freely accessible at https://project-emerald.eu/?page_id=23 is a testament to collaborative innovation and practical education in biomechatronics, exemplifying theoretical knowledge mixed with practical applications and industry collaborations, paving the way for future advancements in the field of biomechatronic systems for people with special needs (real patients with amputated arms) in the end.