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BRIGHT

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BOOSTING THE SCIENTIFIC EXCELLENCE AND INNOVATION CAPACITY OF 3D PRINTING METHODS IN PANDEMIC PERIOD

O5 - BRIGHT e-case study 5

Project Title	**Boosting the scientific excellence and innovation capacity of 3D printing methods in pandemic period** **2020-1-RO01-KA226-HE-095517**
Output	**O5 - BRIGHT e-case studies for project based learning method used in developing, testing and manufacturing of new medical products by 3D printing technologies in pandemic period** **BRIGHT e-case study 5 – modular hand prosthesis for bicycle**
Date of Delivery	**February 2023**
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Version	**FINAL VERSION**

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1 Introduction

This is a documentation regarding the e-case study #5 of the BRIGHT project, focused on 3D printable modular mechanical hand prosthesis for bicycle drive, based on own design that has been created by team of Poznan University of Technology in scope of another project (AutoMedPrint, automedprint.put.poznan.pl) with the main aim to be adjusted, realized and further on improved, tested and used in the BRIGHT project. In this e-case study, all main four stages of work are presented – design using intelligent CAD models, simulations in CAE, manufacturing using FDM 3D printing technology and testing with patients (both adult and juvenile).

2 BRIGHT e-case study #5 – main ideas

2.1 Main concepts of the product

The product is a 3D printable mechanical prosthesis, which was intended for use with personal transportation devices, such as bicycles or scooters. The prosthesis is a mechanical device, anatomically adjusted to a specific patient by a set of constraints and dimensions. It is intended for patients with transhumeral amputations or defects (above or at the elbow level), although patients with a short forearm stump could also possibly use it.

Figure 1. Bicycle hand prosthesis
Source: automedprint.put.poznan.pl

The prosthesis is printable of any material – PLA and PET-G are recommended as being known for proper behavior in contact with user's skin. PLA is suitable for children version, while more durable materials, such as PET-G, are recommended for adult users. ABS and other materials could also be used, provided that there is no direct skin contact (e.g. foam is used) or sterilization is performed before and also after use. 3D printing of the whole prosthesis in children version lasts approx. several hours, depending on the material and printer used. It could be realized simultaneously, as the prosthesis contains few larger parts and several smaller parts. Standard nuts and bolts are used for assembly, along with straps and EVA foam for lining of socket's insides.

The prosthesis design and solutions is a protected intellectual property of Poznan University of Technology. The prosthesis has been developed as part of the AutoMedPrint system and is subjected to a patent. It is not allowed to use the design for commercial purposes, the shared 3D model can be used solely for educational properties in the scope of the BRIGHT project, by authorized persons taking part in training performed with participation of instructors accepted by AutoMedPrint team.

2.2 Requirements and recipients

To realize a 3D printing and manufacture the prosthesis, the following is needed:

1) anthropometric data – 3D scan of a limb, or measurements done on living person (lengths, widths, heights etc.),
2) customizable, parametric model of the prosthesis,
3) FDM printer (of any type – the cheapest ones are also able to perform) with PLA or other material,
4) connecting parts (normalized nuts and bolts),
5) foam for internal lining of the socket part,
6) velcro straps for mounting,
7) basic tools for post processing (file, sandpaper, knife, driller etc.)

The prosthesis comes in several variants and modules, depending on the intended use and amputation level. In general it can be used by both children and adults. The preferred defect level is transhumeral amputation or transradial amputation with relatively short forearm stump. The prosthesis works purely as mechanical device and its main destination is as support while driving any kind of vehicle (bicycle, scooter, even car), also serving as counterweight to maintain proper balance and prevent various scoliosis.

2.3 Plan of work and task distribution

The prosthesis model was first designed and created independently, in the AutoMedPrint project realized at Poznan University of Technology. Then, it was manufactured and tested, also with real patients. On that basis, educational materials were developed (lectures, instructions for the students, movies etc.). In the BRIGHT project it was then used as an educational tool during the second summer school, realized in Pula, Croatia in 2022. Two groups selected the prosthesis for their work.

The scope of work with the case, keeping the order right, is presented in the scheme given in Figure 2:

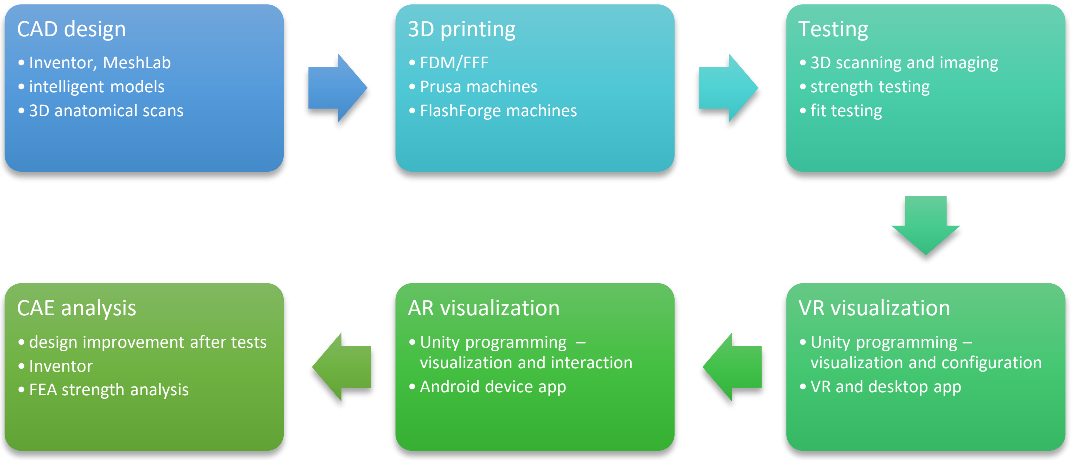


Figure 2. Scope of the work and stages defined in relation with realized case study 5

3 BRIGHT e-case study #5 – realized work

3.1 Design of the prosthesis

The complete model of a customizable prosthesis was made in Autodesk Inventor software. The parameters (dimensions) are entered through an Excel spreadsheet (which could be edited using MS Excel or Google Sheets, alternatively Open Office package). The prosthesis preparation is based on anatomical data. The prosthesis is usually made on the basis of healthy limb – unless there is significant disproportion in the size of the amputated limb remains. Work with the model requires entering dimensions into the spreadsheet, updating the model and checking for errors. Improving the model, both functionally and visually, is optional and can be done if special needs arise.

The prosthesis consists of basic parts (as visible in the Figure 3):

- socket (stump part) with elbow coupling,
- forearm part,
- wrist coupling (4 parts),
- end effector.

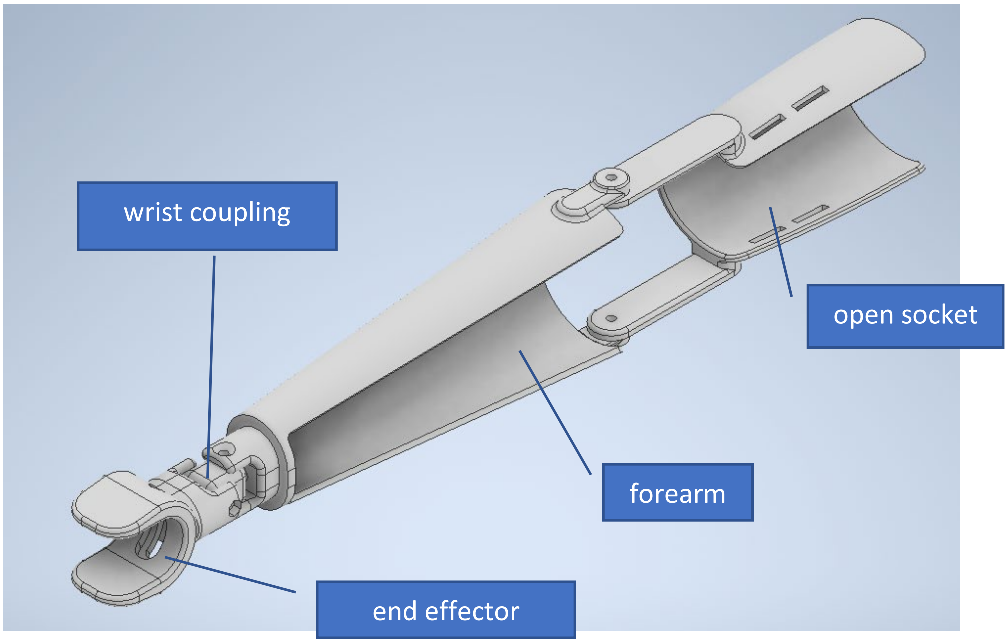
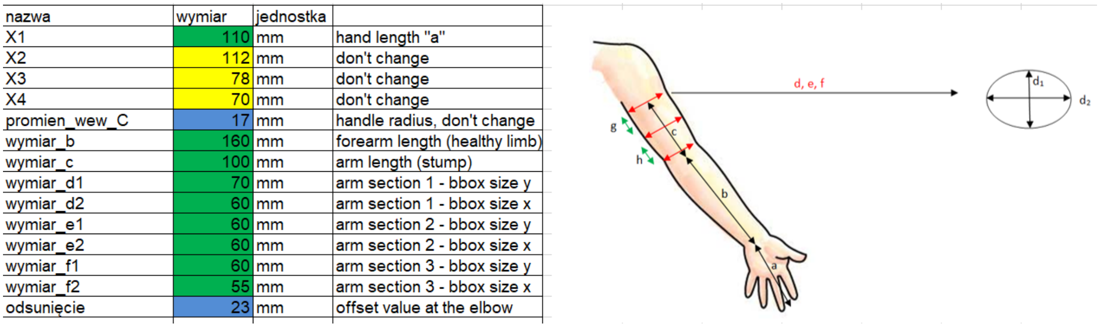


Figure 3. Bicycle hand prosthesis - parts

The basic, fundamental model used in BRIGHT teaching material is a part in the Inventor software, consisting of multiple bodies (quasi-assembly). The user does not directly interact with the parameters in Inventor – instead they need to work with the Excel spreadsheet (Figure 4). The spreadsheet is an interface for the model, it is ment for manual filling by the user and it contains instructions and illustrations to help the users do so.



nazwa	wymiar	jednostka	
X1	110	mm	hand length "a"
X2	112	mm	don't change
X3	78	mm	don't change
X4	70	mm	don't change
promien_wew_C	17	mm	handle radius, don't change
wymiar_b	160	mm	forearm length (healthy limb)
wymiar_c	100	mm	arm length (stump)
wymiar_d1	70	mm	arm section 1 - bbox size y
wymiar_d2	60	mm	arm section 1 - bbox size x
wymiar_e1	60	mm	arm section 2 - bbox size y
wymiar_e2	60	mm	arm section 2 - bbox size x
wymiar_f1	60	mm	arm section 3 - bbox size y
wymiar_f2	55	mm	arm section 3 - bbox size x
odsunięcie	23	mm	offset value at the elbow

Figure 4. Excel spreadsheet – bicycle prosthesis

After introducing a set of parameters, the model redesigns itself, results of which are presented in Figure 5.

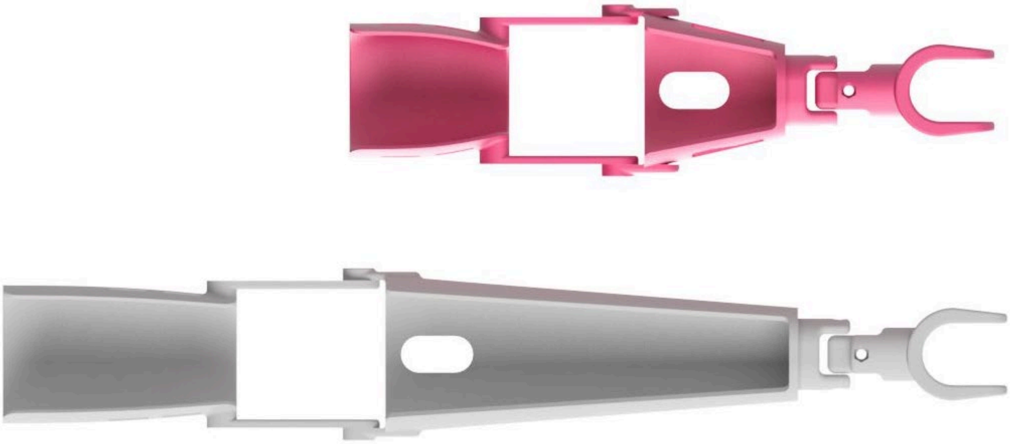


Figure 5. Update of model with different patient data

After updating, check for errors and possible improvements, the model must be saved to external file for further use. It is usually done in two ways:

- whole prosthesis is saved in STP file
- individual parts (solid bodies) are saved as STL files for 3D printing.

3.2 Manufacturing

The manufacturing of the prosthesis elements is realized using the FDM technology different machines and materials can be used. For the summer school, Prusa i3 MK2 machines were used, with the Prusa Slicer software used for programming (Figures 6 and 7).

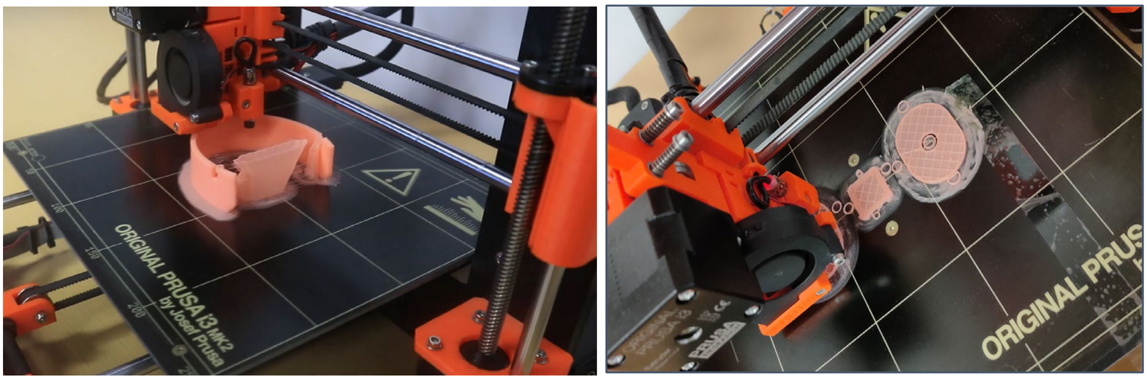


Figure 6. 3D Printing of prosthesis parts using Prusa FDM machine

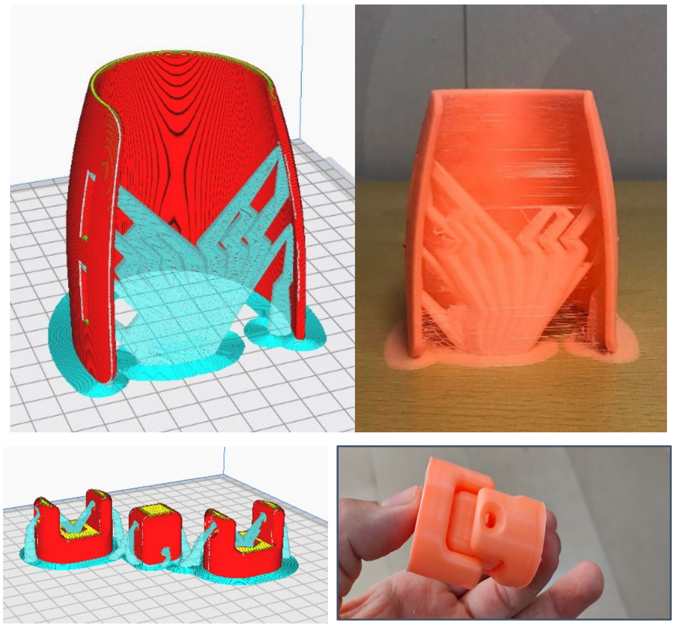


Figure 7. Process planning (left) and result (right)

Most of the printing for testing and use purposes is realized using FlashForge Creator Pro machines. Some part examples made of PLA material are shown in Figure 8. For the adult version of the prosthesis, other machines have to be used, with slightly larger build chamber.

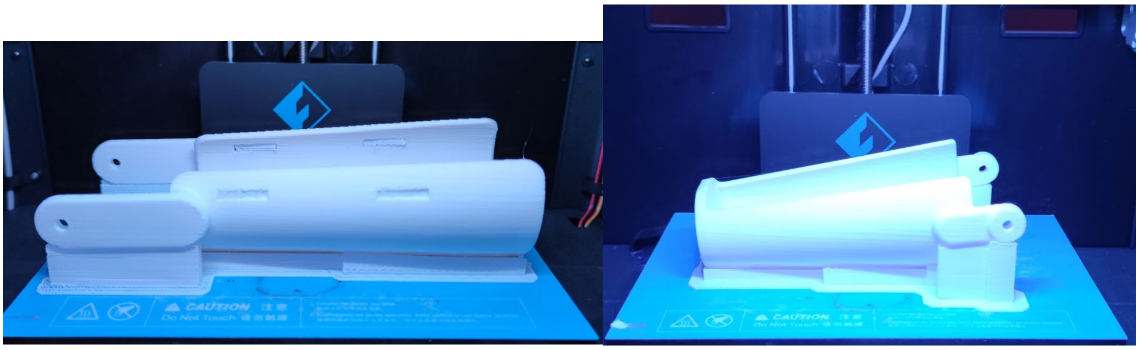


Figure 8. Parts of prosthesis (socket and forearm) made using FlashForge Creator Pro machines

For the manufacturing, more or less standard settings are used – with infill of 30%, layer thickness around 0,2 – 0,3 mm and maximum possible velocity for a given material. Temperature settings were used similar as in recommendations of the machine producer. Open socket printing time for children prosthesis is around 4-5 hours, while forearm takes 5-6 hours, depending on the size. Using 4 printers simultaneously, it is possible to 3D print a whole prosthesis in time of one day.

Post processing of printed parts requires the following actions:

- support removal (mechanically),
- manual grinding and polishing to get rid of sharp edges,
- lining the socket with foam.

Post processing takes around 30-60 minutes, depending on the size of the prosthesis, used material and machine. Then, assembly is realized, using standard nuts and bolts (size depending on the version – child or adult). Examples of assembled prostheses are shown in Figure 9. The assembly takes another 30-60 minutes to realize.

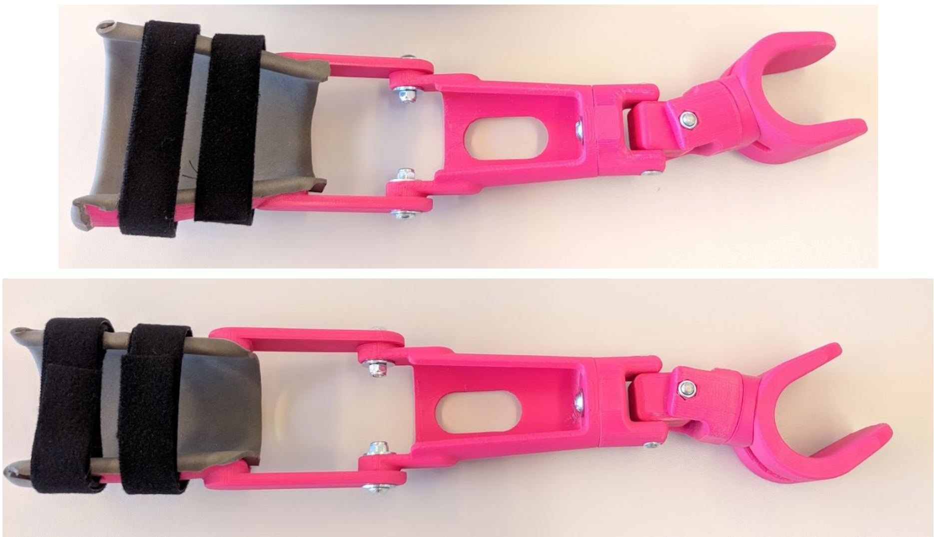


Figure 9. Prostheses made for different patients

3.3 Testing - fitting

Apart from standard methods of accuracy and strength testing (quality control via caliper measurements, as in case study #4, plus destructive testing), the bicycle prostheses realized in this case study are tested using the three-phase testing procedure:

1) virtual testing using mesh processing software – where mesh of patient stump is placed together with model of prosthesis, to check for possible collisions and fitting (Figure 10)

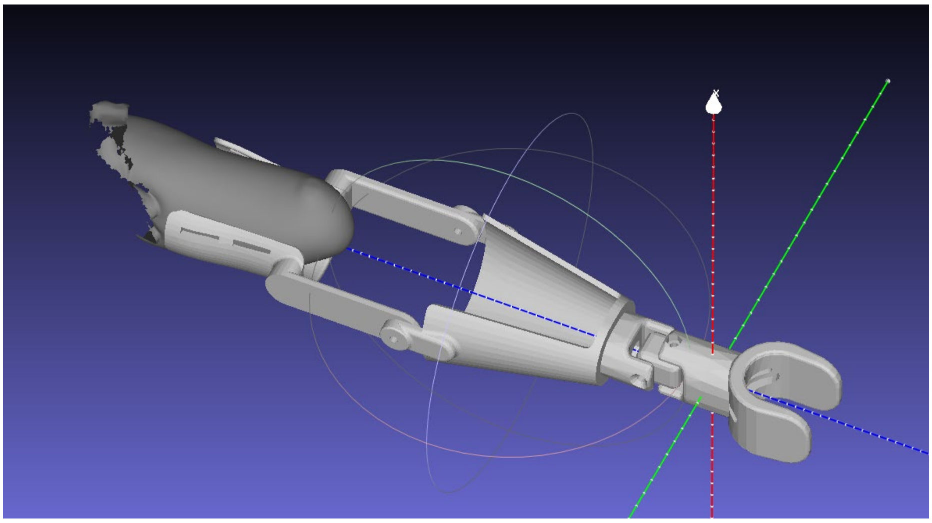


Figure 10. Fitting test realized in MeshLab software

2) virtual testing using VR software – where meshes of patient stump and healthy limb are placed together with model of prosthesis + possibly model of bicycle, to check for possible collisions and fitting in immersive environment, which enables introducing design changes if needed (Figure 11)

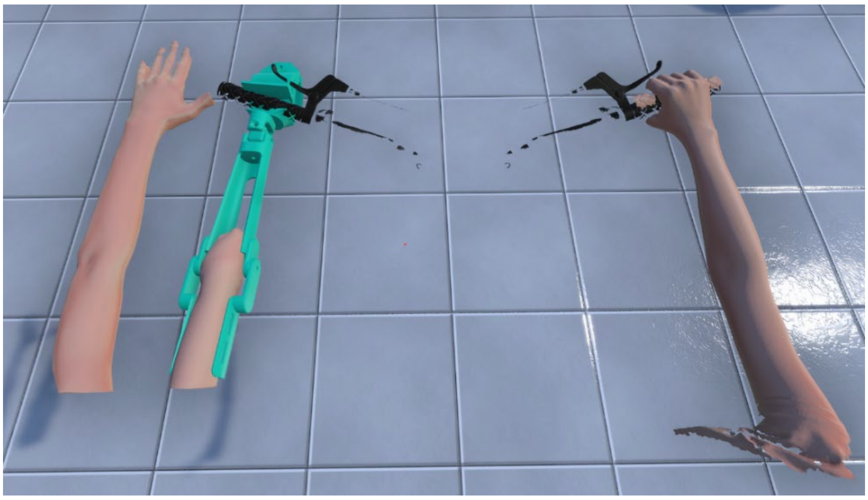


Figure 11. Fitting test realized in Virtual Reality environment

3) physical testing in laboratory conditions and in real-life conditions – where patients are given their prostheses and they just test it in real-life scenarios, giving feedback on possible uses and misuses of the prostheses (Figure 12 and 13)

Figure 12. Testing of prosthesis by children patient

Figure 13. Testing of prosthesis by adult patient

Aside from that, strength and accuracy testing are realized similarly as in the case study #4, using 3D scanner for measurement and universal testing machine for compression and bending tests (examples of these are described in papers by the author).

3.4 VR and AR solutions

The prosthesis is a complex modular device. Its design phase can be partially realized using virtual technologies, such as VR and AR. This has been encouraged during the summer school use case, where the students were tasked with creating a configurator of the prosthesis in immersive space. The results were promising (Figure 14).

Figure 14. Virtual Reality visualization developed by students at BRIGHT Summer School

After gathering the feedback from the patients and engineers, as well as taking into account developments achieved by the students in the summer school, VR and AR configurators were created for the prosthesis. Figure 15 shows the VR configurator, realized as a diploma project at Poznan University of Technology. Figure 16 shows the AR configurator, developed by the students during the course of Augmented Reality in Medicine, introduced at Poznan University of Technology after the summer school.

Figure 15. Virtual Reality configurator of the prosthesis

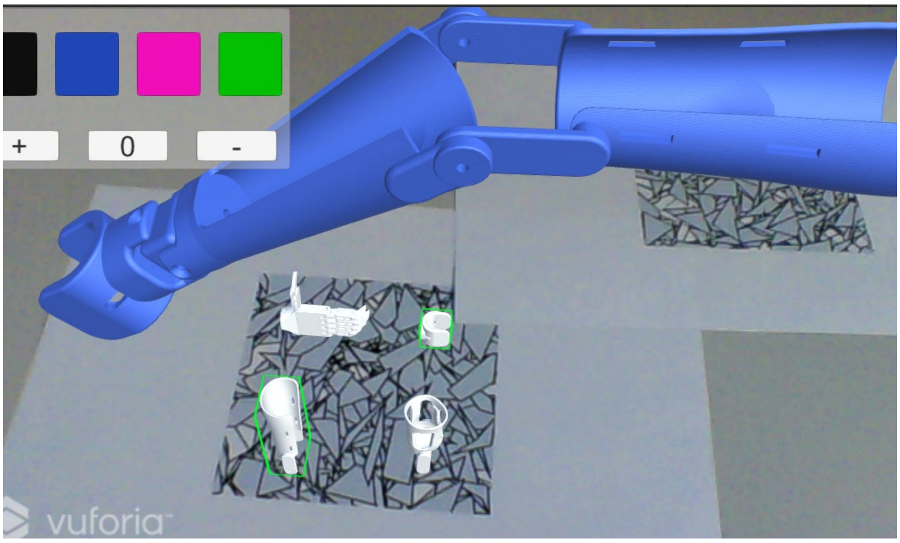


Figure 16. Augmented Reality configurator of the prosthesis

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3.5 Design improvement

Over the course of initial and further testing, a number of various purpose end effectors and modules were added to the prosthesis. It resulted with obtaining a set of possible different sockets, forearms and end effectors (Figure 17). As such, an assembly, "mother" model was created in Autodesk Inventor. This was realized in a diploma (Master's) thesis, realized at Poznan University of Technology. Its result was gaining a possibility of modular automation – easy switching between variants in CAD, representing user's choice in the configurator (Figure 18).

Figure 17. Modular construction of the prosthesis

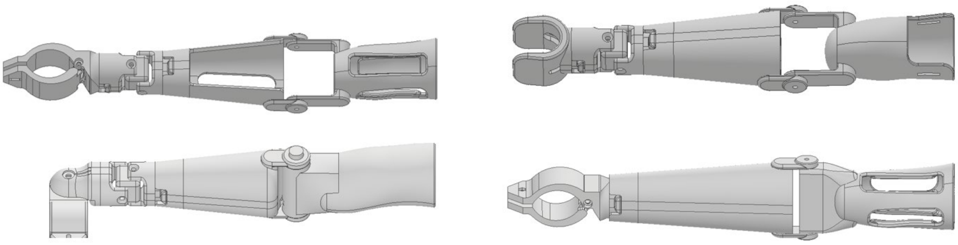

Figure 18. Modular automation – examples of possible different variants for one patient

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Also, work in summer school brought a number of suggested possible improvements of design by the students – these improvements are being considered (Figure 19). Prolonged testing with adult patients resulted in making certain improvements of the design, to get another version of the prosthesis (Figure 20), more rigid and allowing for more safe bicycle ride.

Figure 19. Design improvements suggested by students at the summer school

Figure 20. Design improvements suggested after extensive testing by adult patient

3.6 CAE simulations

The main objective of the finite element analysis has been to evaluate the strength characteristics of the improved design of bicycle prosthesis made for the adult patient (Fig. 21) by simulating a distal tensile test. The principle of the test is shown in Figure 22. As one may notice, the prosthesis is subjected to a distal traction load after being firmly attached to a rigid support that fits inner surfaces of the upper arm. The traction load gradually increases from 0 (zero) to 750 N.

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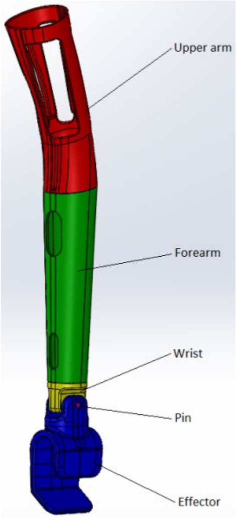


Figure 21. 3D model of the bicycle prosthesis

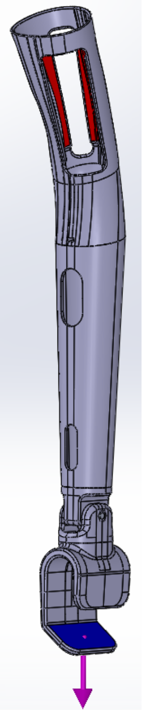


Figure 22. Principle of the distal tensile test simulated for evaluating the strength characteristics of the bicycle prosthesis (red surfaces – regions where the upper arm is firmly attached to a rigid support; blue surface – support of the traction load)

The following assumptions have been made when preparing the finite element model of the tensile test:

a) The prosthesis components are made of PETG exhibiting an isotropic linear elastic behaviour defined by the following parameters: elastic modulus E = 1660 MPa, Poisson's ratio v = 0.419, and yield strength Y = 30.3 MPa.
b) The prosthesis components are bonded together along their contact surfaces.

The finite element model of the tensile test has been elaborated and solved with SOLIDWORKS Simulation in the following sequence of steps:

a) Associating the PETG material to the prosthesis components
b) Specifying the contact interaction between the prosthesis components: bonded contact
c) Enforcing a full locking kinematic constraint on some inner surfaces of the upper arm (see also Figure 22)
d) Defining a downward vertical unit force applied to the effector (see also Figure 22)
Note: The actual values of this force have been specified later as load cases (step (f)).
e) Controlling the dimension of finite elements and generating the mesh
f) Specifying the actual values of the downward vertical force applied to the effector: 150 N (load case 1), 300 N (load case 2), 450 N (load case 3), 600 N (load case 4), and 750 N (load case 5).

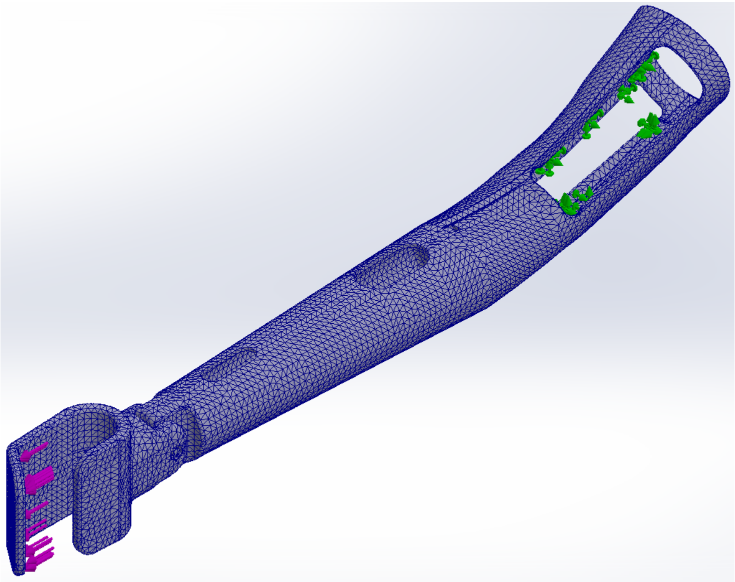
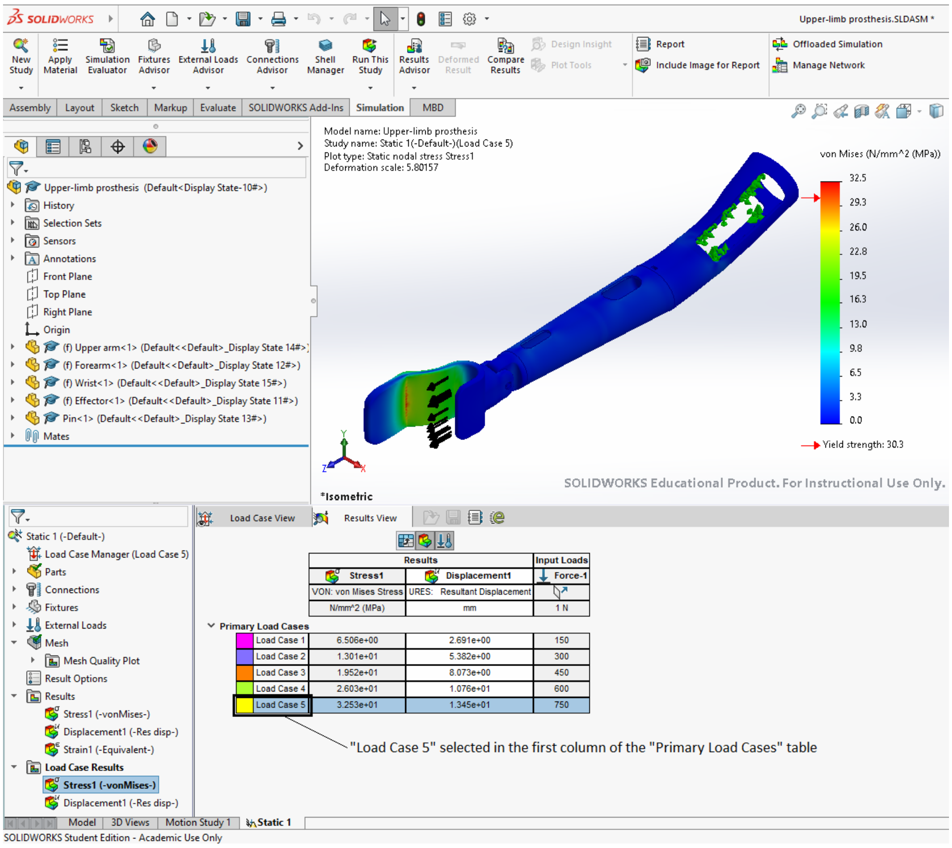


Figure 23. Finite element model of the tensile test simulated for evaluating the strength characteristics of the bicycle prosthesis

Figure 23 shows the most important result provided by SOLIDWORKS Simulation: distribution of the von Mises equivalent stress in the bicycle prosthesis for the fifth load case (traction force of 750 N). The maximum values of the von Mises equivalent stress $\sigma_{eq,max}$ associated to different load cases are displayed on the diagram in Figure 24 to show their dependence on the traction force F.



Model name: Upper-limb prosthesis
Study name: Static 1(-Default-)(Load Case 5)
Plot type: Static nodal stress Stress1
Deformation scale: 5.80157

	Results		Input Loads
	Stress1	Displacement1	Force-1
	VON: von Mises Stress	URES: Resultant Displacement	
	N/mm^2 (MPa)	mm	1 N
Primary Load Cases			
Load Case 1	6.506e+00	2.691e+00	150
Load Case 2	1.301e+01	5.382e+00	300
Load Case 3	1.952e+01	8.073e+00	450
Load Case 4	2.603e+01	1.076e+01	600
Load Case 5	3.253e+01	1.345e+01	750

"Load Case 5" selected in the first column of the "Primary Load Cases" table

Figure 24. Distribution of the von Mises equivalent stress in the bicycle prosthesis for the fifth load case – traction force of 750 N

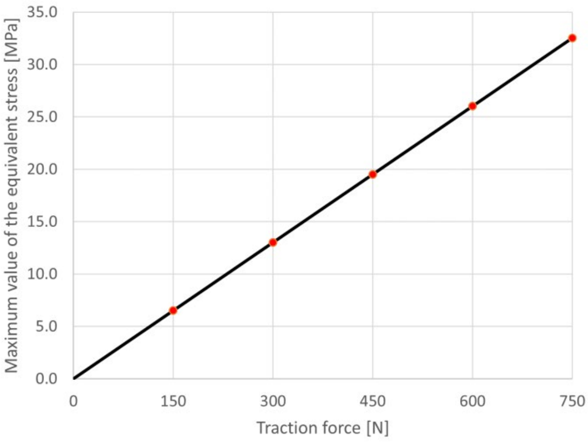


Figure 24. Maximum values of the von Mises equivalent stress associated to different traction forces: red dots – numerical results; black path – linear regression $\sigma_{eq,max} = 4.337 \cdot 10^{-2} \cdot F$

The following conclusions have been formulated after examining the diagram shown in Figure 25:

a) The mechanical response of the bicycle prosthesis is well approximated by means of the linear regression $\sigma_{eq,max} = 4.337 \cdot 10^{-2} \cdot F$ (see the black path displayed on the diagram in Figure 25).

b) This regression can be used to determine the traction force at which the maximum value of the equivalent stress equals the yield strength of the PETG material: 698.64 N.

3.7 Dissemination results

The prosthesis has been used during the BRIGHT summer school in 2022. Two groups realized work on the prosthesis, with very good results, as shown in previous chapters. One of the group won the first place among all the groups – this was the most successful case.

Apart from that, during BRIGHT project, the prosthesis was tested by a number of patients, both child and adult. Improvements to the design of the prosthesis were realized by some diploma theses – in time of BRIGHT project, two Master's theses were realized at Poznan University of Technology – PUT (Poland), one focused on obtaining a cosmetic prosthesis on the basis of the modular model (Figure 26), and the other one – realizing the modular intelligent automation concept, as shown in chapter 3.5. Aside from that, two other theses at BSc engineer's level were realized in 2023, focused on 3D printing processes of the customized sockets (Figure 27) and VR configuration of the prosthesis (mentioned in earlier chapter). So this case study, in scope of BRIGHT, was a part of four diploma theses in total.

Figure 26. Cosmetic prosthesis done in Master's thesis at PUT

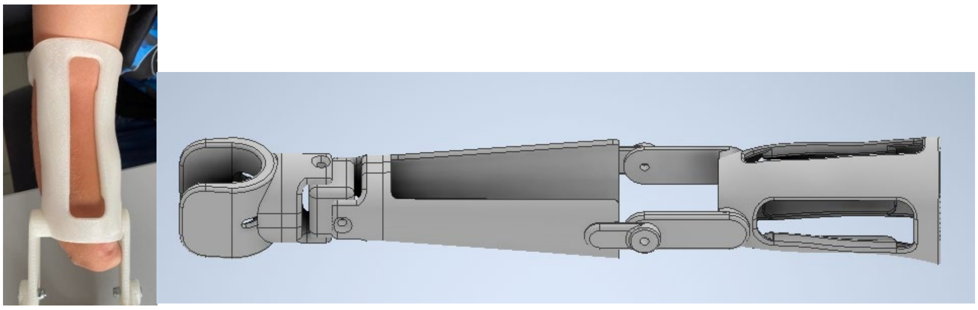


Figure 27. A complete bicycle prosthesis made in diploma thesis at PUT

The prostheses themselves have received a widespread acclaim in Poland (both from patients, doctors and media) and the AutoMedPrint system was named as Polish Product of the Future 2022. As of winter 2023, design of the prosthesis is nominated to the Polish contest for innovative inventions – Eureka! held by a large newspaper (Dziennik Gazeta Prawna). Aside from that, an extensive scientific paper was written at the end of the BRIGHT project (in scope of O5), describing innovations in the prosthesis design. This was a joint paper between PUT and TUCN and it has been submitted and accepted to Facta Universitatis: Series Mechanical Engineering journal (Q1 journal) in 2023 as it was presented in the Final dissemination report of the BRIGHT project. The concept of the prosthesis has represented also the basis of starting in another project – EMERALD (financed in EOG) (financed by Norwegian grants, project in which TUCN is the coordinator and PUT (Poland) and BIZZCOM partners in the BRIGHT project are also part in the consortium of the EMERALD project) for another case study, in which the prosthesis is being converted into a mechatronic device.

4 Conclusions

The presented case study pertains to an innovative prosthetic device that can be printed on most FDM printers. It was designed and prepared by representatives of Poznan University of Technology. The model was used in educational activities in BRIGHT project, first and foremost as a case study in the BRIGHT summer school realized in 2022. It is a versatile and flexible device, and a perfect example for students to work with design of simple, 3D printable, customizable prosthetic devices. For educational effect, all the stages were realized in product development, starting from design for specific patients, through CAE simulation, 3D printing (with experimental phase) and fitting, as well as VR and AR. Positive feedback was obtained from some patients and doctors. The case was also used to integrate partners from PUT and TUCN and it is going to be widespread scientifically, by means of research papers.