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

O5 - BRIGHT e-case study 4

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 4 – robotic mechanical hand prosthesis**
Date of Delivery	**February 2023**
Authors	**Filip Górski, Dan-Sorin Comsa, Răzvan Păcurar, Miloš Simonović, Remigiusz Łabudzki, Sven Maričić, Mate Babic, Branislav Rabara, Peter Koštál**
Version	**FINAL VERSION**

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1 Introduction

This is a documentation regarding the e-case study #4 of the BRIGHT project, focused on 3D printable mechanical hand prosthesis, based on open source projects available on the Internet (RoboHand, UnLimbited Arm and similar). 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 – both destructive and non-destructive.

2 BRIGHT e-case study #4 – main ideas

2.1 Main concepts of the product

The UnLimbited Arm prosthesis is an open source mechanical prosthesis, designed for 3D printing. Originally placed on Thingiverse portal, it has multiple versions and designs and is used by children with forearm amputations or birth defects, all over the world. The main working principle is transforming the elbow joint rotation into grasp by the prosthesis fingers, via elastic fibers, that are stretched from the arm to the prosthetic hand. When the forearm stump is straightened, the fingers are opened – when it is bent, the fingers close.

Figure 1. UnLimbited Arm Prosthesis
Source: thingiverse.com, teamunlimbited.org

The basic, open source version of the prosthesis is customized on the basis of several dimensions of a patient. It is originally designed for 3D printing of PLA material and then thermoforming (the printed parts are flat).

The proposed version in the case study is customizable and 3D printable, but no thermoforming is included (the parts are ready for use directly after 3D printing) and customization is more precise, requiring total of 12 dimensions, measured on patient's arm, forearm and hand. 3D printing takes approx. 2 days, if a single printer is used, or 5-6 hours if utilizing 4 printers (assuming fingers, palm, forearm and arm parts are printed on separate machines). PLA or ABS materials are recommended, with PET-G as a possible alternative. Hard TPU (or any partially flexible material) could be also used for the arm part, for better fit.

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The model is an intelligent model created in another project (AutoMedPrint), used in BRIGHT as a teaching and educational tool. It is based on open source projects; however, know-how of the intelligent model and methods of its creation are intellectual property of team of Poznan University of Technology.

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, bolts and pins),
5) elastic line (e.g. fishing line) for the movement transfer,
6) basic tools for post processing (file, sandpaper, knife, driller etc.)

The prosthesis comes in two variants – the long and the short one. The long version is based on UnLimbited Arm project, while the short one – on RoboHand project. The following persons may be recipients:

1) children with transradial amputation and functional forearm stump and elbow joint,
2) children or adults with finger amputation or defect, with functional palm and wrist joint
3) adults with transradial amputation – only in the case of larger FDM printers (large size of forearm component)

The basic requirement for the patient is capability to exert force with the stump using a functioning joint (wrist, in case of RoboHand or elbow, in case of RoboHand). Otherwise, the patient would be unable to use the prosthesis grasping capability.

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 first summer school (realized by TUCN remotely in 2021, one group supervised by STU representative). It has been also used as an AR model in building of the virtual platform in O3. The scope of work is presented in the scheme presented in Fig. 2:

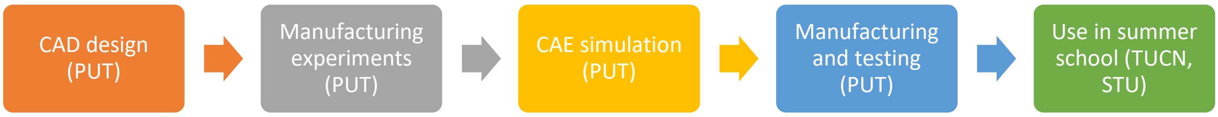

Figure 2. Scope of the work defined related to case study 4

3 BRIGHT e-case study #4 – 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 four main component types (Figure 3):

- arm – C-shaped, usually relatively short component mounted above the elbow,
- forearm – component of full anatomical length, mounted below the elbow, with space for the stump,
- hand (palm with wrist joint),
- fingers (consisting of two segments each).

In the case of the short version (RoboHand), arm part is non-existent and the forearm part assumes its role, being mounted below elbow of the patient. Patient's remains of the palm then fit in the cavity of the hand part of the prosthesis.

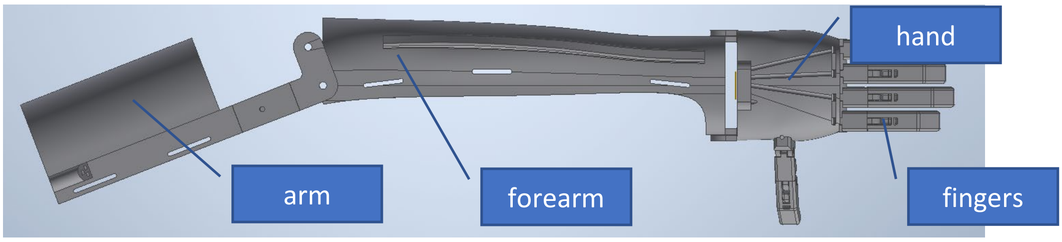

Figure 3. Robotic hand prosthesis - parts

The model is an assembly in the Inventor software. The user does not directly interact with the parameters in Inventor – instead they need to work with the Excel spreadsheet. The spreadsheet is divided into two parts – the RoboHand part (Figure 4) and the UnLimbited Arm part (Figure 5).

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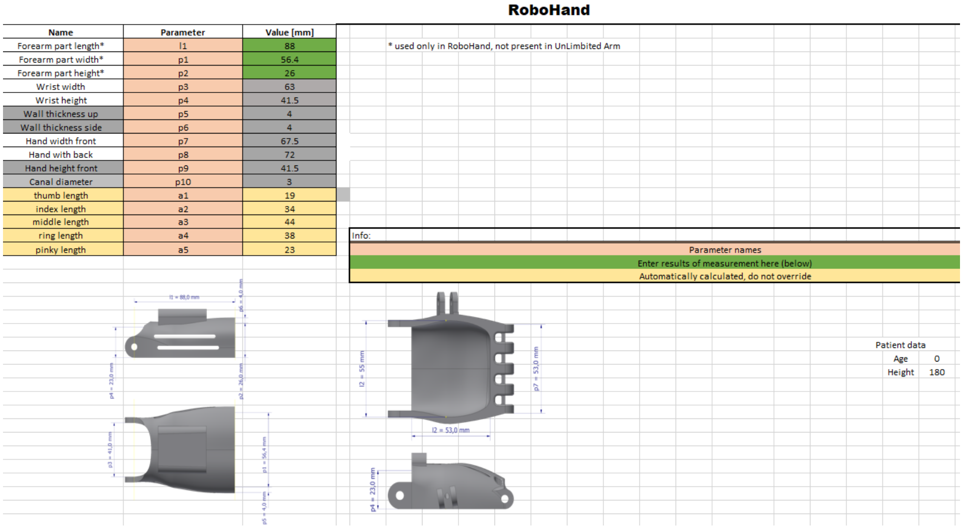


RoboHand

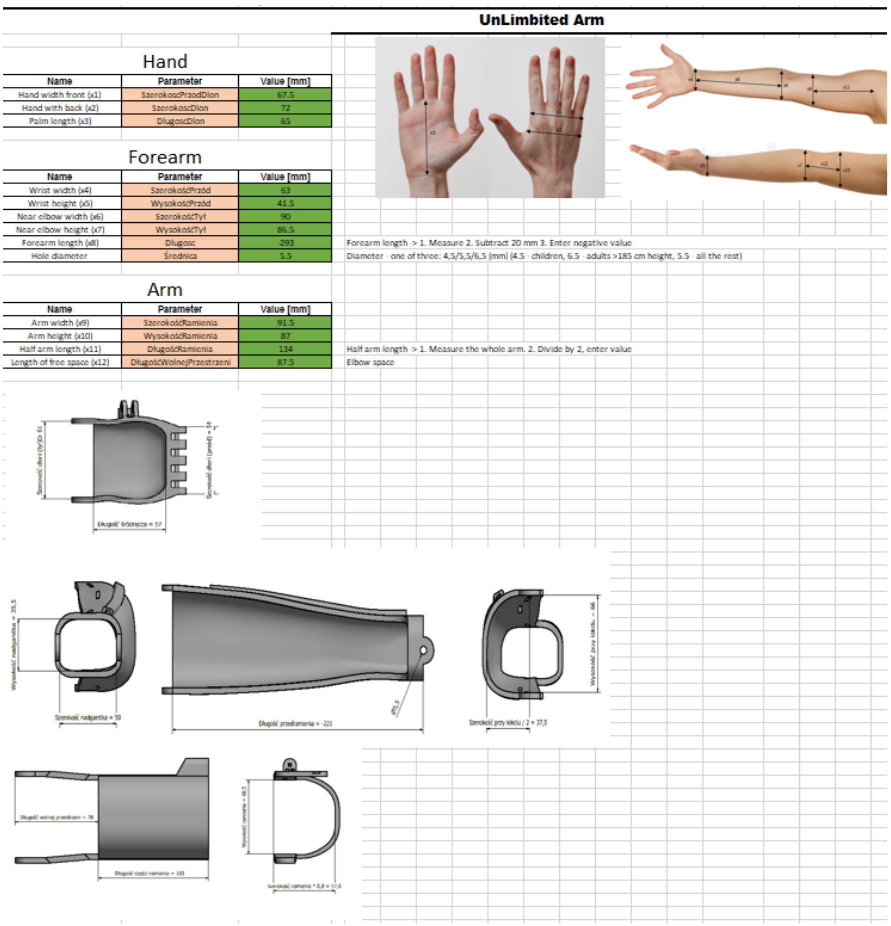
Name	Parameter	Value [mm]
Forearm part length*	l1	88
Forearm part width*	p1	56.4
Forearm part height*	p2	26
Wrist width	p3	63
Wrist height	p4	41.5
Wall thickness up	p5	4
Wall thickness side	p6	4
Hand width front	p7	67.5
Hand with back	p8	72
Hand height front	p9	41.5
Canal diameter	p10	3
thumb length	a1	19
index length	a2	34
middle length	a3	44
ring length	a4	38
pinky length	a5	23

* used only in RoboHand, not present in UnLimbited Arm

Info:
Parameter names
Enter results of measurement here (below)
Automatically calculated, do not override

Patient data	
Age	0
Height	180

Figure 4. Excel spreadsheet – RoboHand part



UnLimbited Arm

Hand

Name	Parameter	Value [mm]
Hand width front (x1)	SzerokoscPrzodDlon	67.5
Hand with back (x2)	SzerokoscDlon	72
Palm length (x3)	DlugoscDlon	65

Forearm

Name	Parameter	Value [mm]
Wrist width (x4)	SzerokośćPrzód	63
Wrist height (x5)	WysokośćPrzód	41.5
Near elbow width (x6)	SzerokośćTył	90
Near elbow height (x7)	WysokośćTył	86.5
Forearm length (x8)	Dlugosc	293
Hole diameter	Średnica	5.5

Forearm length -> 1. Measure 2. Subtract 20 mm 3. Enter negative value
Diameter - one of three: 4,5/5,5/6,5 [mm] (4.5 - children, 6.5 - adults >185 cm height, 5.5 - all the rest)

Arm

Name	Parameter	Value [mm]
Arm width (x9)	SzerokośćRamienia	91.5
Arm height (x10)	WysokośćRamienia	87
Half arm length (x11)	DługośćRamienia	134
Length of free space (x12)	DługośćWolnejPrzestrzeni	87.5

Half arm length -> 1. Measure the whole arm. 2. Divide by 2, enter value
Elbow space

Figure 5. Excel spreadsheet – UnLimbited Arm part

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. Some parameters in the top section are used only for the RoboHand model, which is a separate assembly file. Some parameters are universal and the bottom section pertains to the UnLimbited Arm version only.

After introducing a set of parameters, the model redesigns itself, as presented in Figure 6. Example of model in the shorter version is presented in Figure 7.

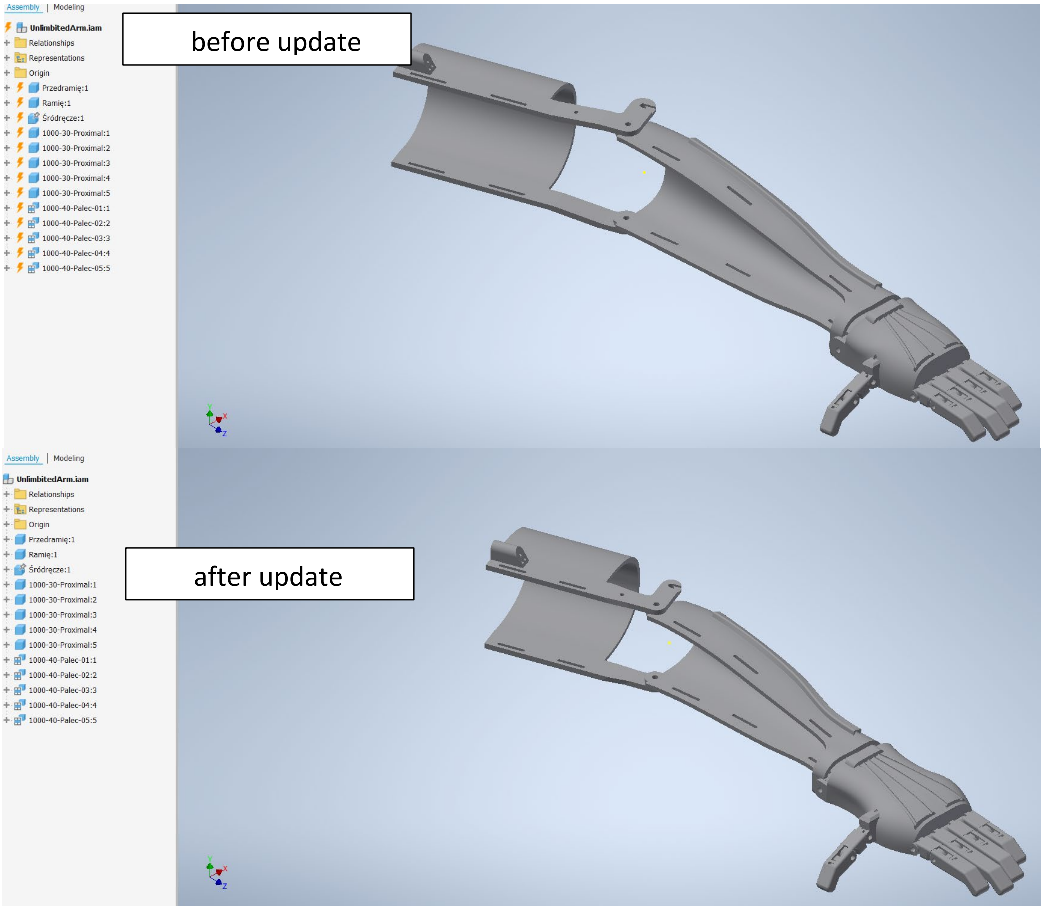


Figure 6. Updating the model with set of data of another patient

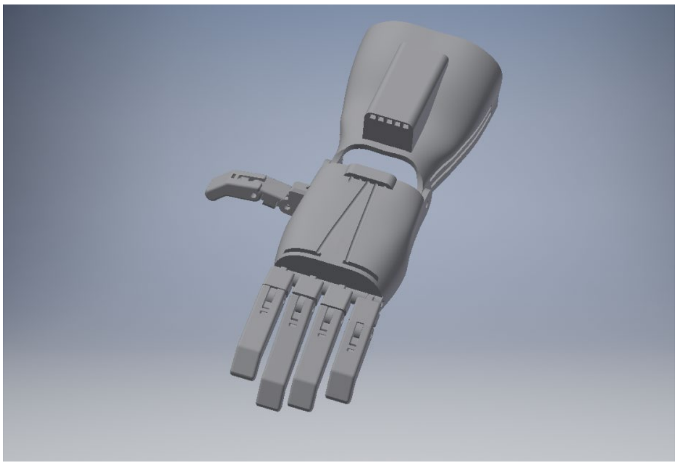


Figure 7. Robotic hand prosthesis – short version (RoboHand)

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 assembly is saved in STP file
- individual parts are saved as STL files for 3D printing.

3.2 CAE simulations

The main objective of the finite element analysis has been to evaluate the strength characteristics of a finger belonging to the prosthesis (Figure 8) by simulating a tensile test. The principle of the test is shown in Figure 9. As one may notice, the upper joint of the finger is supported by a fixed pin, while a downward vertical traction load is applied by means of a prismatic block attached to the lower tip of the finger. The traction load gradually increases from 0 (zero) to 750 N. The contact between the tip of the finger and the traction block takes place along perfectly matching surfaces. The bilateral symmetry of the tensile test (Figure 9) allows performing the finite element analysis on half of the geometric models. Of course, appropriate boundary conditions must be defined on the surfaces generated by the intersection with the symmetry plane (Figure 10).

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

a) The prosthesis finger is made from ABS exhibiting an isotropic linear elastic behaviour defined by the following parameters: elastic modulus E = 1990 MPa, Poisson's ratio v = 0.365, and yield strength Y = 31.2 MPa. The support pin and the traction block are perfectly rigid bodies.

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b) The prosthesis finger and the traction block are bonded together along their contact surfaces. The prosthesis finger is allowed to slide along its contact surfaces with the support pin, the frictional component of this contact interaction being neglected.

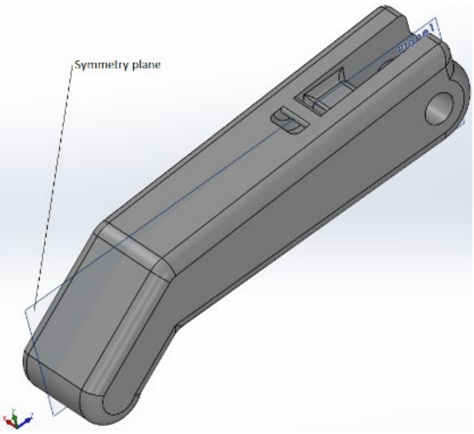


Figure 8. 3D model of the prosthesis finger

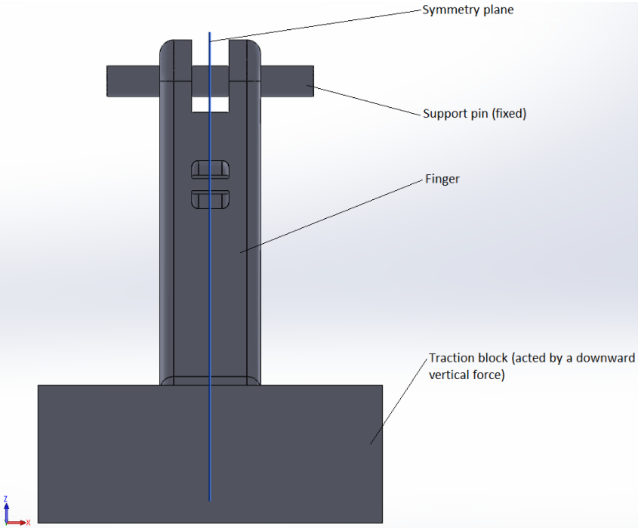


Figure 9. Principle of the tensile test simulated for evaluating the strength characteristics of the prosthesis finger

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

a) Defining the support pin and the traction block as perfectly rigid bodies

b) Associating the ABS material to the prosthesis finger

c) Specifying the contact interaction between the support pin and the prosthesis finger: frictionless sliding contact
d) Specifying the contact interaction between the traction block and the prosthesis finger: bonded contact
e) Defining a full locking kinematic constraint on the red surface shown in Figure 10
f) Defining a symmetry kinematic constraint on the yellow surfaces shown in Figure 10
g) Defining a sliding kinematic constraint on the green surface shown in Figure 10
h) Defining a downward vertical unit force applied to the blue surface shown in Figure 10
Note: The actual values of this force have been specified later as load cases (step (j)).
i) Controlling the local and global dimensions of finite elements and generating the mesh
j) Specifying the actual values of the downward vertical force applied to the blue surface shown in Figure 3: 75 N (load case 1), 150 N (load case 2), 225 N (load case 3), 300 N (load case 4), and 375 N (load case 5).
Note: Because only half of the geometric models have been included in the finite element model, these values correspond to the following forces applied to the traction block in a real tensile test: 150 N, 300 N, 450 N, 600 N, and 750 N, respectively.

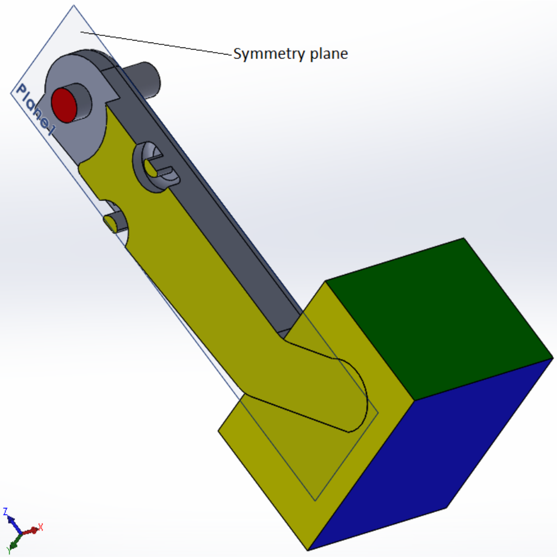
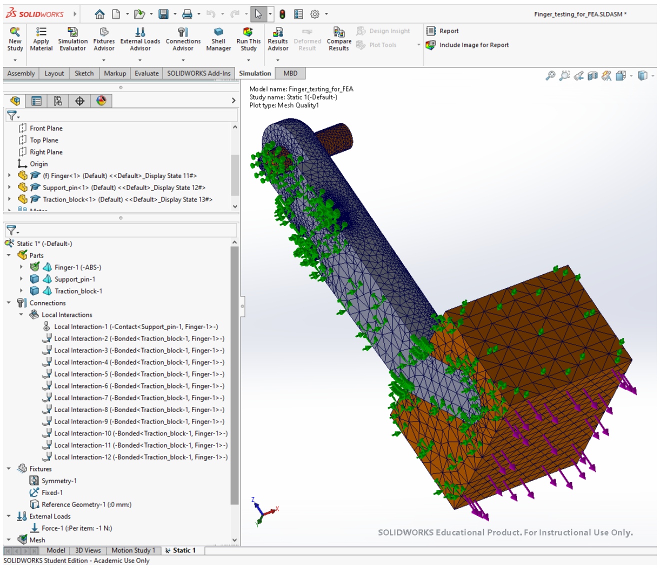


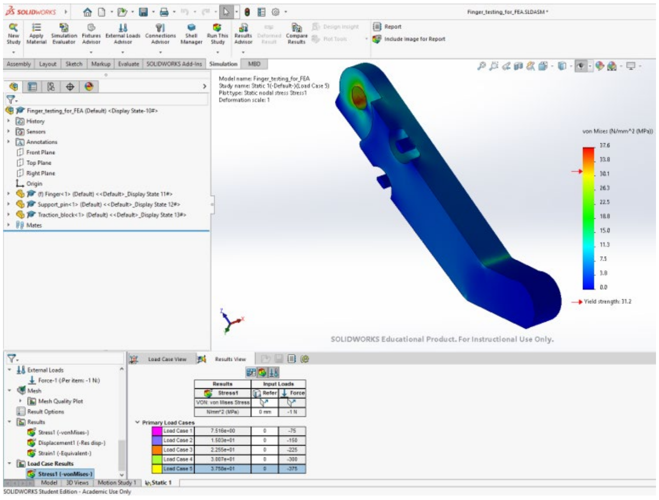
Figure 10. 3D models reduced to half before being used in the finite element model of the tensile test (red surface – cross section of the support pin to be fully locked; yellow surfaces – intersections with the cutting plane to receive symmetry boundary conditions; green surface – region of the traction block to receive a sliding boundary condition; blue surface – region of the traction block to receive the downward vertical load)



Model name: Finger_testing_for_FEA
Study name: Static 1(-Default-)
Plot type: Mesh Quality1

Figure 11. Finite element model of the tensile test simulated for evaluating the strength characteristics of the prosthesis finger

Figure 11 shows the most important result provided by SOLIDWORKS Simulation: distribution of the von Mises equivalent stress in the prosthesis finger for the fifth load case (traction force of 750 N used in a real tensile test). The maximum values of the von Mises equivalent stress $\sigma_{eq,max}$ associated to different load cases are displayed on the diagram in Figure 12 to show their dependence on the traction force *F*.



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

	Results	Input Loads	
	Stress1	Refer	Force
	VON: von Mises Stress		
	N/mm^2 (MPa)	0 mm	-1 N
Primary Load Cases			
🟪 Load Case 1	7.516e+00	0	-75
🟦 Load Case 2	1.503e+01	0	-150
🟧 Load Case 3	2.255e+01	0	-225
🟩 Load Case 4	3.007e+01	0	-300
🟨 Load Case 5	3.758e+01	0	-375

Figure 12. Distribution of the von Mises equivalent stress in the prosthesis finger for the fifth load case – traction force of 750 N used in a real tensile test

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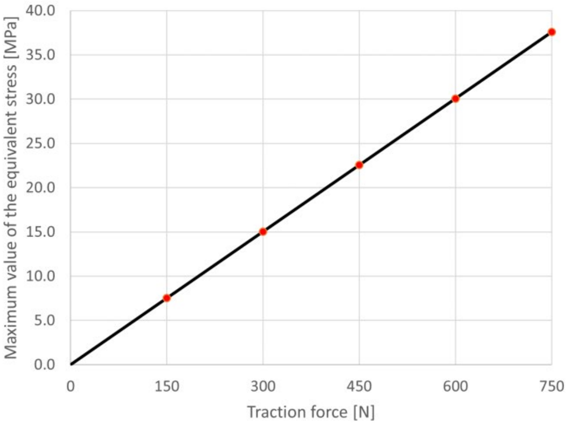

Figure 13. Maximum values of the von Mises equivalent stress associated to different traction forces: red dots – numerical results; black path – linear regression $\sigma_{eq,max} = 5.011 \cdot 10^{-2} \cdot F$

The following conclusions have been formulated after examining the diagram:

a) The mechanical response of the prosthesis finger is well approximated by means of the linear regression $\sigma_{eq,max} = 5.011 \cdot 10^{-2} \cdot F$ (see the black path displayed on the diagram in Figure 13).

b) This regression can be used to determine the testing force at which the maximum value of the equivalent stress equals the yield strength of the ABS material: 622.63 N.

3.3 Manufacturing experiments

The experimental manufacturing of the prosthesis elements was realized using the FDM technology, with different machines and materials. Three different strategies of manufacturing were utilized, as can be noted in earlier works by the author:

- the lowest price (econo), filling 15%, layer thickness 0.3 mm
- highest accuracy (accura), 15% filling, 0.15 mm layer thickness
- the highest strength (strong), filling monolithic (85-95%), layer thickness 0.3 mm

The orientation of the elements in the working chamber adopted one of the three main directions of the axis (i.e. flat, lateral and vertical), compatible with the given manufacturing strategy. The orientations of all parts were predetermined using expert knowledge. Other manufacturing parameters (extrusion speeds, temperatures, the presence of additional raft structures, etc.) have been adapted to the given combination of materials and the geometry of the manufactured element.

For each combination that made up a unique manufacturing process (part, machine, materials, parameters), this process was carried out twice, even in the event of a possible failure in the first attempt.

The manufacturing process was divided into the following elements:

- phalanx (element connecting the fingers with the metacarpus),
- little finger of the thumb,
- biggest finger (middle)
- palm (metacarpus)
- forearm

For each small element (phalanges/fingers), at least two attempts were made to print. In the case of models requiring changes in the parameters of the printing process, more attempts were made to determine the best parameters. In the case of large models, due to their time-consuming nature, one test was performed. The printing was made on 3 types of devices: Anet A8/A8-M - a low-budget device, FlashForge Creator Pro - an intermediate price device and Raise 3D Pro - a high-budget device. In total, the devices produced: 21 phalanges (ABS/PLA), 28 little fingers (ABS/PLA), 25 big fingers (ABS/PLA), 5 metacarpals (PLA) and one forearm (ABS).

Plenty of detailed conclusions were drawn for the models and technology to improve. The most stable process allowing to obtain high surface quality and good shape and dimensional accuracy occurred in the case of small elements made of ABS material in a horizontal position, both in the econo and strong strategies. In the case of ABS material, there is no problem of subcooling the material, so models with high surface quality can be obtained without the need for supports. It is recommended to at least partially close the working space in order to avoid shrinkage of the model.

Figure 14 presents printed and assembled RoboHand. Figure 15 presents examples of manufacturing errors. Also, in the BRIGHT summer school, almost complete UnLimbited Arm model was printed and assembled like shown in Figure 16.

Figure 14. RoboHand prosthesis made of ABS material

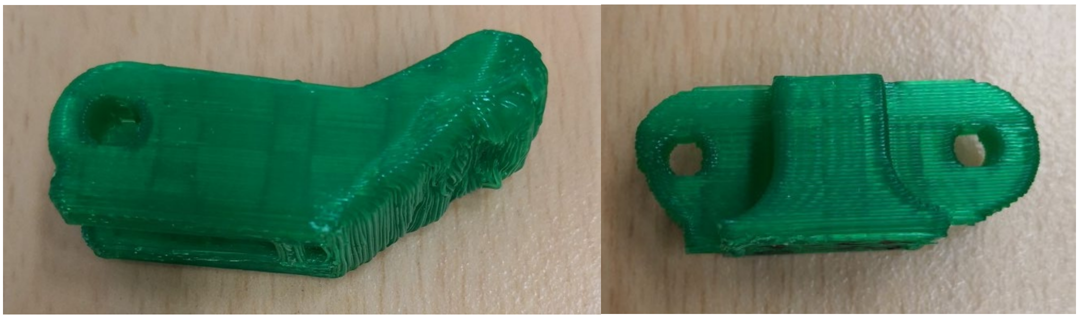

Figure 15. Examples of error in the manufacturing process

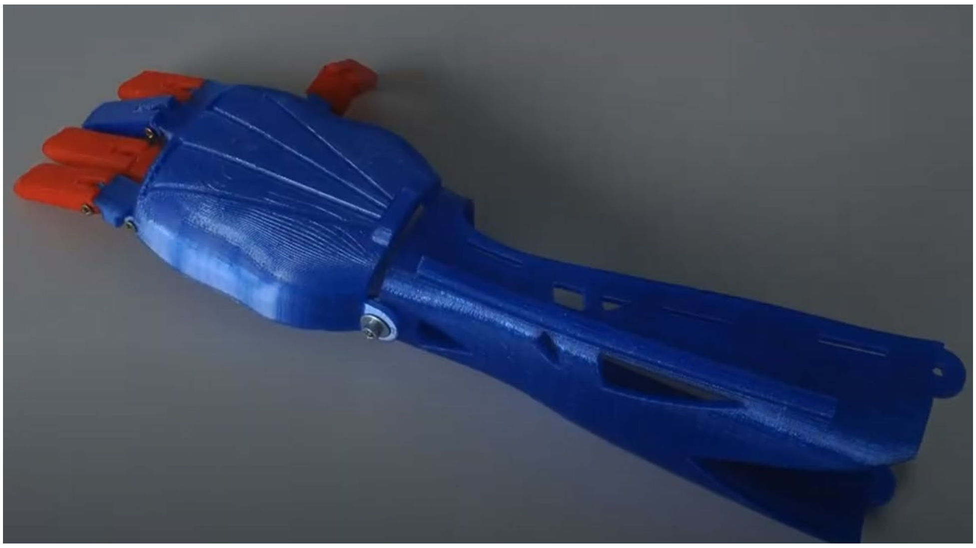

Figure 16. UnLimbited Arm printed during BRIGHT summer school 2021

3.4 Testing

3.4.1. Accuracy and fit

The accuracy of the manufactured elements of the mechanical prosthesis was measured using a caliper and comparing the obtained dimensions to the denomination which is the digital model. The following elements were dimensioned: the largest finger, the smallest finger and the metacarpus. Important dimensions, the accuracy of which could vary with different orientations and manufacturing strategies, are the length of the element and the diameter of the holes (Figure 17). The collected results concerned models made of both PLA and ABS.

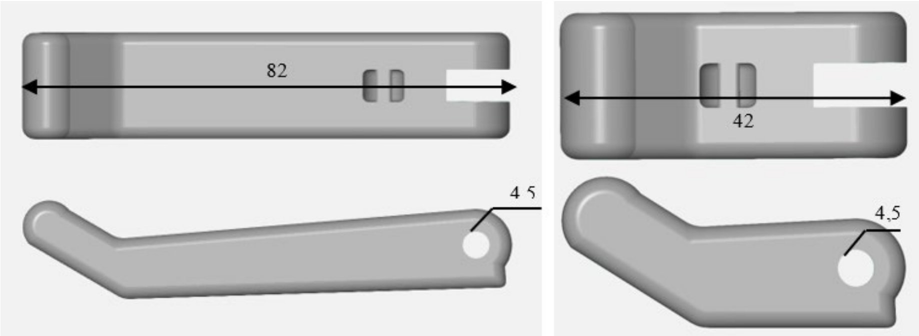

Figure 17. Measured dimensions in accuracy test (examples)

Considering the obtained results for length measurement, for the models manufactured in the accura strategy, the average error is ~0.10 mm, which is below the thickness of one layer and it is a negligible error that does not affect the functionality. In the case of econo small fingers, the error is much higher, but for the model made of ABS material, it is not more than ~0.5 mm, which means that it is still insignificant, because it does not exceed the border of two layers. For a model made of PLA material, the error is much higher and amounts to 0.91 mm. It is the result of very uneven layering at the inclination of the finger. Due to too little cooling directed at the finger, the material was not able to cool down, the model was bent and deformed under the influence of temperature and successively applied layers, which probably contributed to the shape and dimension error. For models created in the strong strategy, the error again does not exceed the boundary of two layers, therefore it does not affect the functionality of the model.

When comparing the measurements of the hole in finger models, a much higher dimensional inaccuracy can be observed, which may be due to several issues. For the Accura little finger models, the error is on average ~0.4 mm, which translates into a layer thickness of more than two layers. The reason why the error in the case of little fingers is higher compared to the big finger may be related to the smaller area and volume of the model. In addition, a measurement error could also have occurred, resulting from applying a caliper in the place of the ejected layer or in the place of the material left at the time of passing the nozzle. For the econo and strong models, there is an error resulting from the orientation of the model, i.e. horizontal positioning relative to the table, which may intensify unevenness in material application, especially for small models at higher speeds. In the case of all models, however, this error is so insignificant that the holes will be quickly made during the assembly of connecting elements and the operation of the prosthesis.

The final stage of accuracy testing was fitting, tested virtually, by superimposing the prosthesis model on a limb of a selected patient – an adult man with forearm amputation. The resulting image is presented in Figure 18.

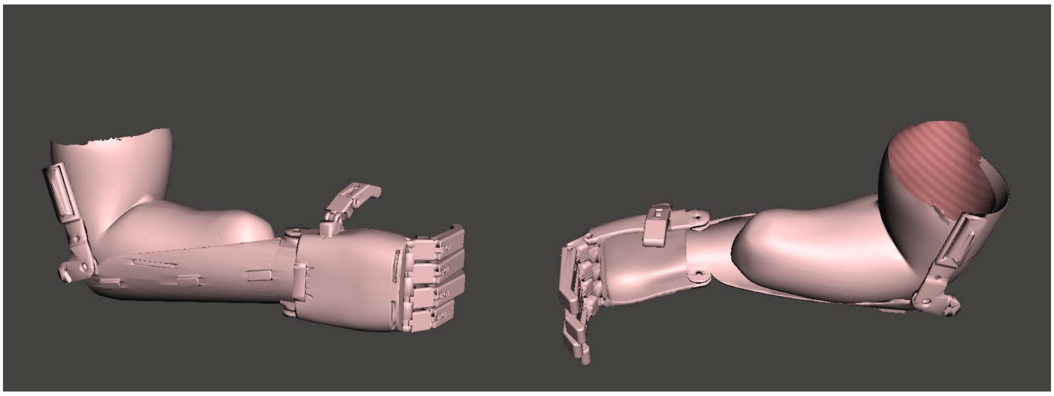

Figure 18. Fit testing of the generated prosthesis

Imposing the model of the entire mechanical prosthesis on the patient's stump made it possible to check the dimensional accuracy of the hand model. When assessing the collision, the plasticity of the hand should also be taken into account, especially under the pressure of tapes / Velcro holding the prosthesis. In the case of the above model, it was found that the shoulder model is correct, while in the case of the forearm section, in order to maintain higher patient comfort, a 5% enlargement of the model and extension of the section connecting the forearm with the metacarpus of the prosthesis can be considered.

3.4.2. Strength test

Strength tests were based on stretching models of the little and big toes and metacarpals. The system has been modeled so that the force falls on the places where the connection with other parts occurs, i.e. on the holes. The finger models were placed directly into the jaws from the end of the phalanx, initially at an angle of its inclination, while on the second trial they were compressed in a vertical position. On the side of the connecting holes, a steel rod was led through the model, which in turn was connected to a steel cable hooked in the jaws of the testing machine. The metacarpal model is finished with connecting exits on both sides, openings for the phalanges at the front, and openings for the distal part of the forearm at the back. This required remodeling of the measuring station. Due to the differences in the diameter of the holes, the larger holes were attached with shackles to a steel cable, which was mounted in the upper jaws of the machine, while a steel rod was led through the lower holes (due to small spaces between the holes) and a steel cable was inserted between it to the lower jaws of the testing machine. The layout is shown in Figure 19.

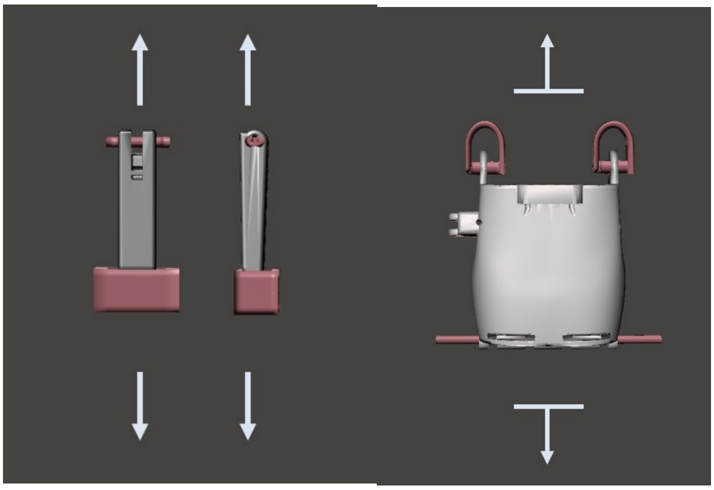

Figure 19. Scheme of tensile tests for prosthesis elements

All models were loaded at a speed of 20 mm/min until they broke or a large drop in force was reached, at which point the machine stops stretching and the jaws are retracted.

Results of the strength test are visible in Figures 20 and 21. In general, lowest obtained values of force at fracture were ~150 N for the fingers and ~400 N for the metacarpus. As such, it can be assumed that the prosthesis could be safely used daily, with designated loads of approx. 20 kg fully bearable by its mechanical components.

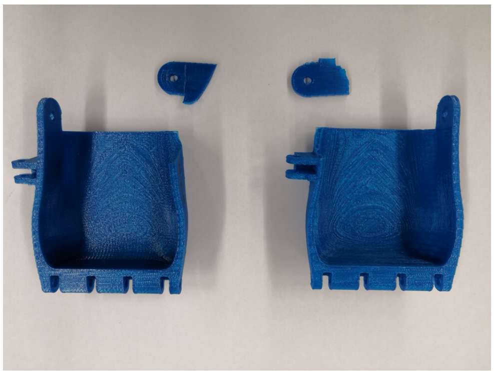

Figure 20. Results of strength test – metacarpus

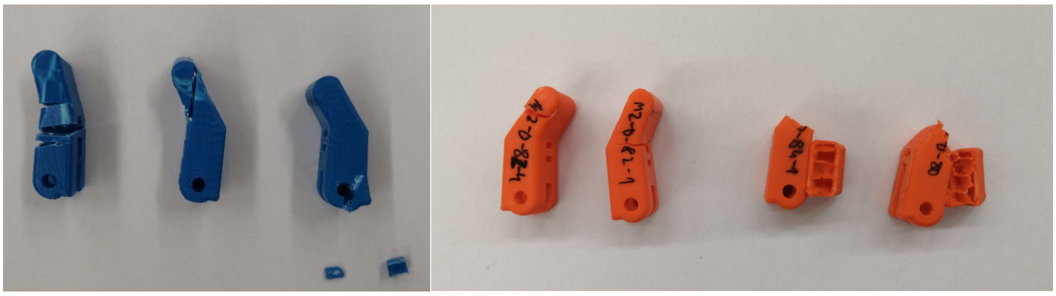

Figure 21. Result of strength test - fingers

3.5 *Dissemination results*

The prosthesis has been used during the BRIGHT summer school in 2021. The group of Cyber Makers, consisting of 6 students from Ukraine was supervised by a teacher from STU (project partner). They selected the prosthesis as their case in the summer school. They prepared a report, which is a part of official materials of BRIGHT summer school 2021. The group suggested certain improvements to the original design of the prosthesis (Figure 22).

Apart from that, during BRIGHT project, the prosthesis was tested by two patients. Virtual test with one patient is presented in Figure 18, while a specialized prosthesis made for another patient is presented in Figure 23. Apart from that, the model was shared with e-Nable Poland (non-profit organization) and its doctors expressed a positive feedback about its use in daily work with prosthetic design. Presentations about the achieved results have been realized during several workshops and seminars with the students as stated in the final Dissemination report of the BRIGHT project and results were integrated in few diploma theses (chapters of theses) that have been realized by students under coordination / supervision / co-supervision of professors coming from BRIGHT project consortium.

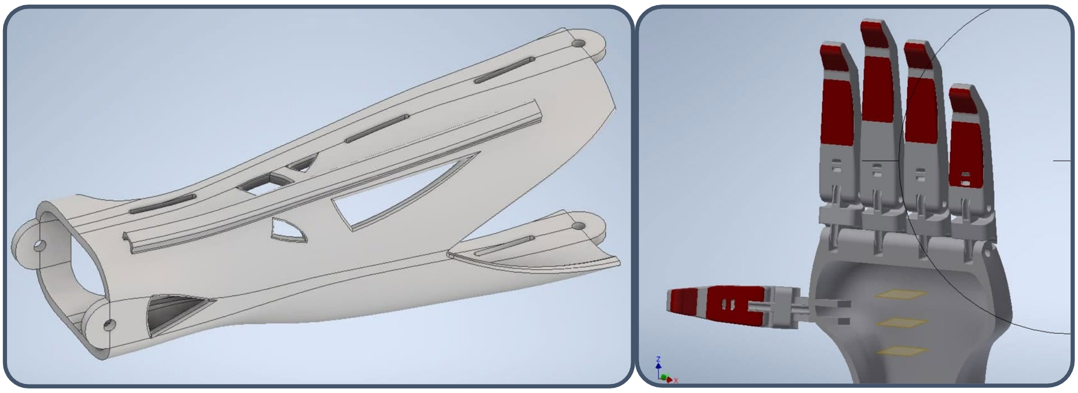

Figure 22. Improvements to prosthesis elements introduced by students of Cyber Makers from Ukraine

Figure 23. Specialized prosthetic for playing percussion

4 Conclusions

The presented case study pertains to open source prosthetic device that can be printed on almost any FDM printer. It was designed and prepared on the basis of available sources 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 2021. 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 and strength testing. Positive feedback was obtained from some patients and doctors. The case was also used to integrate partners from PUT, TUCN and STU during the summer school activities and also in few diploma theses (chapters of theses) that have been realized by students under coordination / supervision / co-supervision of professors coming from BRIGHT project consortium.