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BRIGHT

Erasmus+ strategic partnership for Higher Education

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

O5 - BRIGHT e-case studies for manufacturing of new medical products by 3D printing technologies in pandemic period REPORT

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**
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Version	**FINAL VERSION**

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Content

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1 Introduction

In the context of the pandemic, sharing knowledge, skills, experience and know how transfer are few key factors between stakeholders involved in teaching, but also in the society which might contribute to boost the efficiency of the teaching process, but also the scientific and innovation level in using the right methods that can support hospitals especially in time of pandemic. Professors needs support in sharing their knowledge, experience and teaching methods which can be efficiently used in working with students in the context of the pandemic, while students, after they are being involved in a teaching process that is practically oriented on the needs of the hospitals / public society needs in the context of the pandemic can be involved in project learning activities for being actively engaged in developing, testing and validating of medical parts that are about to be produced by 3D printing in relation with the medical sector in this context. . Using resources developed by BRIGHT project consortium within O1-O4, such as e-courses, e-toolkits, e-virtual laboratory platform & e-webinars (starting from the existing resources) students were able to work under supervision of professors coming from BRIGHT consortium and SMEs in developing, producing & testing of different innovative medical parts that were needed to be 3D printed in concordance with hospital needs in time of pandemic. Not all case studies presented in O5 are directly linked with medical parts (case studies) related to the pandemic. Lack of standardization in medical products realized by 3D printing technologies is limiting the possibilities of realizing and sorting out all medical cases linked with the pandemic (supplementary research activities are needed in this sense still in the next following years). But there were few parts that have been produced directly linked with pandemic (like face shields for protection of doctors). Other needs have been identified in the period of the pandemic when medical sector was under big pressure due to pandemic and there have been identified in this way (together with medical doctors) other way to support them, like for instance in producing some of the parts for real patients in the time of pandemic who needed quick support for the medical doctors who were more focused on people fighting against CoVID. In these sense there have been defined some medical cases like wrist hand orthosis, tongue model with cancer tumor, robotic mechanical hand prosthesis and modular hand prosthesis for bicycle which have represented real needs for some patients in time of pandemic. Having such cases defined with the support of Poznan University of Technology

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(PUT) partner, who have been cooperating very close with hospitals in this period in time of pandemic, students had the opportunity to work in inter & trans-national teams under supervision / co-supervision of professors in the frame of the BRIGHT project. Existing teaching resources which have been conceived by the BRIGHT project consortium in the frame of O1-O4, as well as the existing infrastructure & logistic of the BRIGHT consortium has been used in this sense within the activities of the BRIGHT project. All partners have been actively involved not just for producing the results stated in the intellectual outputs or to perform the activities stated in the project (like summer schools), but also in creating new ideas, improving existing solutions in some cases in terms of CAD design or using new types of 3D printing technologies for material testing specific to the case studies that have been defined. Most of the results that have been achieved in the frame of the BRIGHT project in the work of BRIGHT professors and students, which was done according to each institution experience and expertise in the field of CAD, CAE, 3D printing and testing (with support of the SMEs companies involved in the BRIGHT project) have been used not just for conceiving, producing and testing of medical parts that were made by 3D printing in the time of pandemic to support real patients, but there have been used also for chapters that have been realized by the BSC / MSc students for their diploma theses, publishing of scientific articles in prestigious journals (including ISI journals with impact factor (Q1) or other types of publications like handbooks, toolkit manual, guide project, details about all these achievements being included in the final Dissemination report of the BRIGHT project.

In continuing of this report, there are presented briefly the main achievements in relation with 5 case studies that have been defined in the frame of intellectual output O5 (in synthesis), for more comprehensive understanding of the technical details realized case studies, being created 5 supplementary reports for each case study in particular, that have been provided as supplementary documents for the current report.

In all case studies, there have been comprised all main four steps that have been presented in all teaching documents and resources that have been produced by the BRIGHT project consortium, starting from CAD models, continuing with simulations that have been realized with CAE, continuing with 3D printing technologies and ending with final testing as shown in Figure 1.

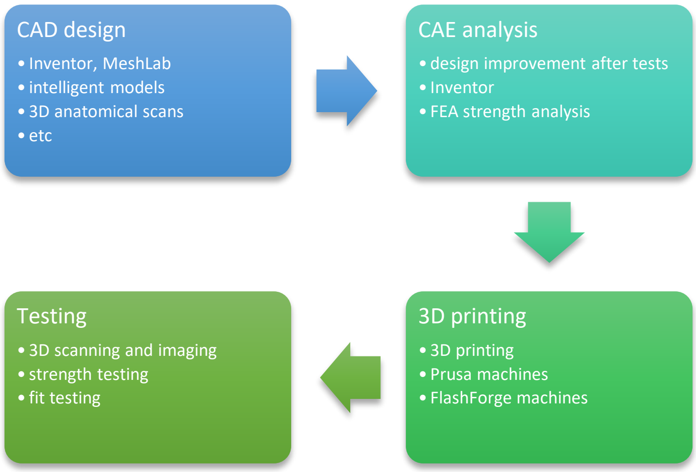

Figure 1. Main stages taken into consideration in relation with realized case studies

2. BRIGHT case studies

2.1. Case study 1 - wrist hand orthosis

The first case study has been represented by an wrist hand orthosis that was used for wrist joint stabilization in time after an injury such as fracture or for patients with conditions that require stabilization (rheumatoid arthritis, muscle atrophy and many others). The orthosis is openwork (with several possible shapes), to enable skin access in both comfort and hygienic reasons (as shown in Figure 2). It is 3D printed using FDM technology, with one of the basic FDM technology materials: PLA, ABS, PET-G and PA-12 (nylon).

Figure 2. Wrist hand orthosis in various versions

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The orthosis model was first designed and created independently, in the AutoMedPrint project realized at Poznan University of Technology with the main aim to be adjusted, realized and further on tested and used in the BRIGHT project. In the BRIGHT project it was then used as an educational tool during both summer schools, the one held remotely in TUCN in 2021 and then the other in Pula, Croatia in 2022. Many groups of students have selected the orthosis for their work and it has been extensively used, have analysed it, have improving it and finally have presented it during the activities realized within the BRIGHT project, as the most substantial example of 3D printed medical part.

The orthosis was in this case customized on the basis of a non-contact measurement of geometry of patient's hand and forearm (or mirror image of the other limb, when the actual limb is damaged and e.g. wrapped in plaster cast). For case study selected patient was a 26-year old man, with an injury to his right wrist, caused by bite of a dog resulting in some bone crush. A full process was undergone and recorded for him (3D scanning shown in Figure 3, finished with obtaining a complete functional orthosis.

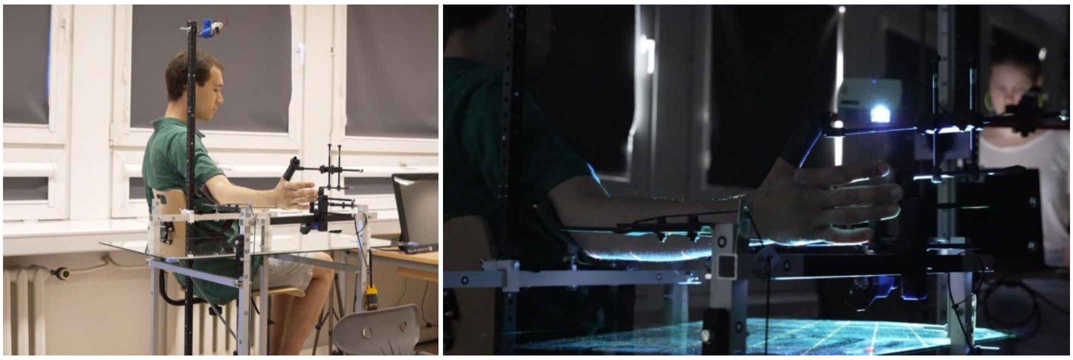

Figure 3. Selected case study – patient with injured hand, patient 3D scanning using AutoMedPrint system at PUT

The measurement was done by optical 3D scanning, usually at the workplace developed as a part of the AutoMedPrint system, developed at Poznan University of Technology, like shown in Figure 4. After measurement, data was processed and model has been designed using dedicated CAD software programs. In the first summer school edition of BRIGHT (2021), an orthosis for a single patient was considered by the students one similar case (for a patients that was a 22-year old female) and task of the students was to create an innovative set of design features (examples can be seen in Figure 5) .

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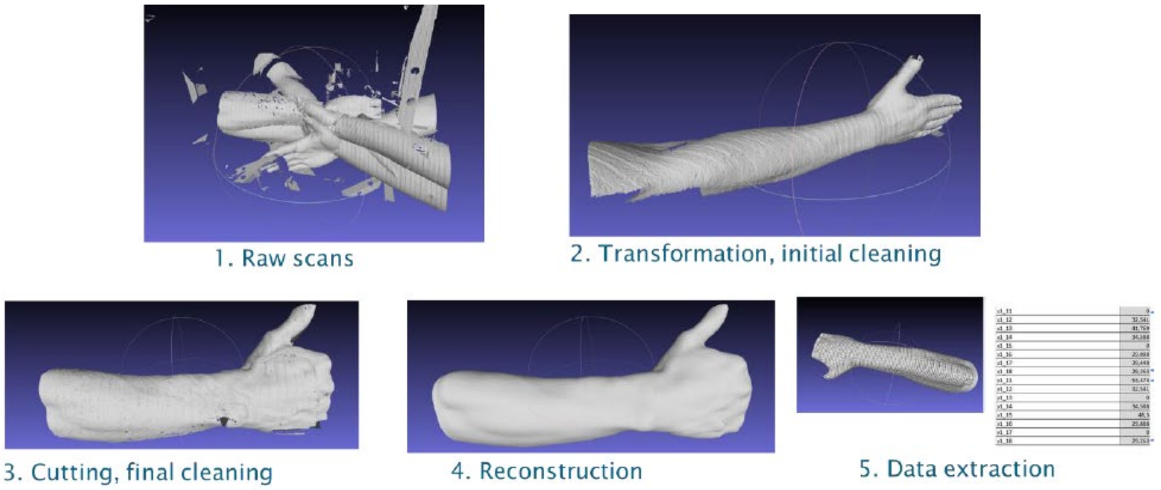

Figure 4. Data processing of 3D scans for the wrist hand orthosis model (AutoMedPrint system materials)

Figure 5. Examples of design features created by the students of first BRIGHT summer school

In the second summer school (Figure 6), the students were given 3D scans of persons present at the site – representatives of consortium partners (teachers and specialists from PUT, Bizzcom and TUCN, 3D scanned during TPM event held earlier in Poznan). The students managed to create customized orthoses and test them with real “patients”.

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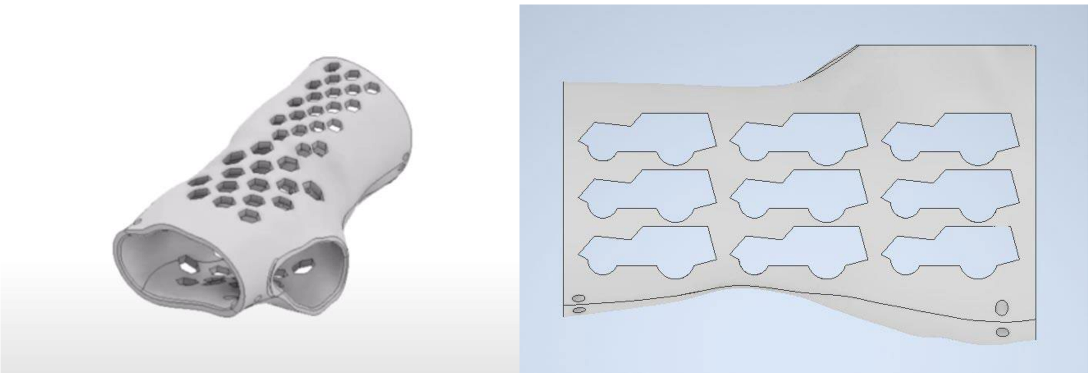

Figure 6. Designs created during the second BRIGHT summer school

In continuing the next step for validating of the result consisted in the analysis of the orthosis that has been realized through CAE analysis. The main objective of the finite element analysis has been to evaluate the strength characteristics of the wrist hand orthosis by simulating a three-point bending test (Figure 7).

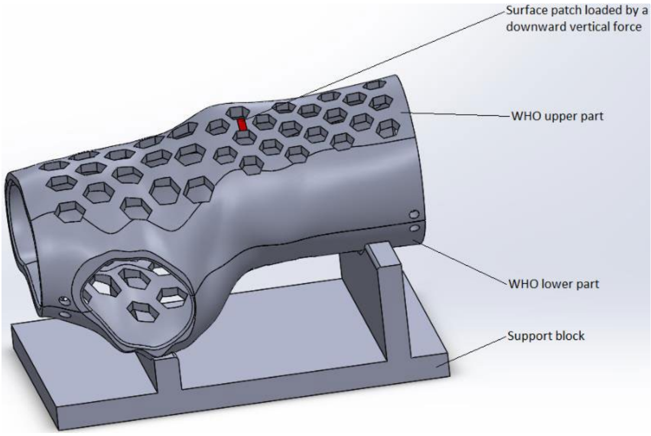

Figure 7. Principle of the three-point bending test simulated
for evaluating the strength characteristics of the wrist hand orthosis

In Figure 8 are shown the most important result that have been provided by SOLIDWORKS Simulation: distribution of the von Mises equivalent stress in the lower and upper parts of the orthosis in case when a loading of 125 N has been used for the testing force.

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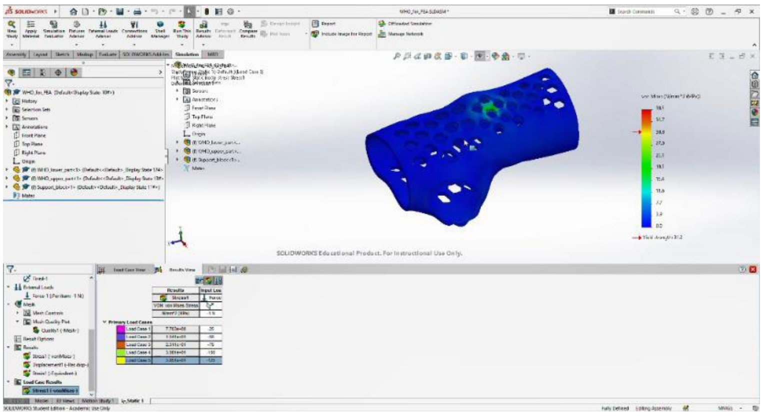

Figure 8. Distribution of the von Mises equivalent stress in the lower and upper parts of the orthosis for the loading case – testing force of 125 N

For the 3D printing, FDM technology was used. For most cases, FlashForge Creator Pro machines were used, in the second summer school, on-site prints were realized using Prusa i3 MK2 (Figure 9). The used materials were PET-G, PLA and nylon, with their temperature and velocity settings as recommended by their respective producers. Different colors were used, mostly white, blue and orange.

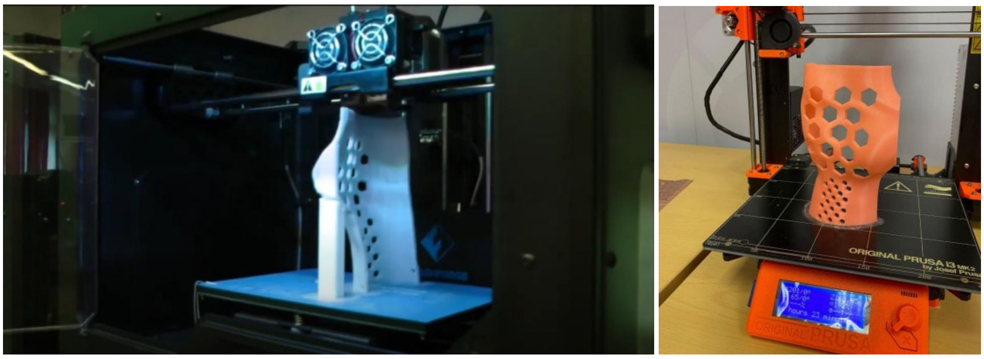

Figure 9. 3D printing of orthosis using FlashForge Creator Pro machine (left), 3D printing of orthosis with Prusa machine (right)

The testing of the orthosis has been divided in this case into non-destructive testing and strength tests. The strength tests mimic the three-point bending test, as in CAE simulations. The orthosis was put in an universal testing machine, with a special 3D printed fixture. Then it was loaded until it broke (Figure 10).

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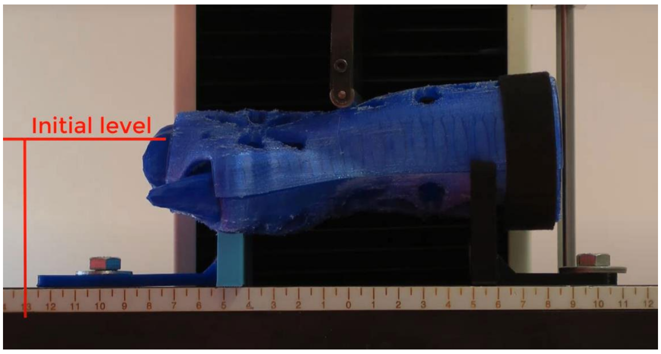

Figure 10. Strength test of orthosis made by summer school participants

The non-destructive part involved accuracy testing done with use of 3D scanning as shown in Figure 11.

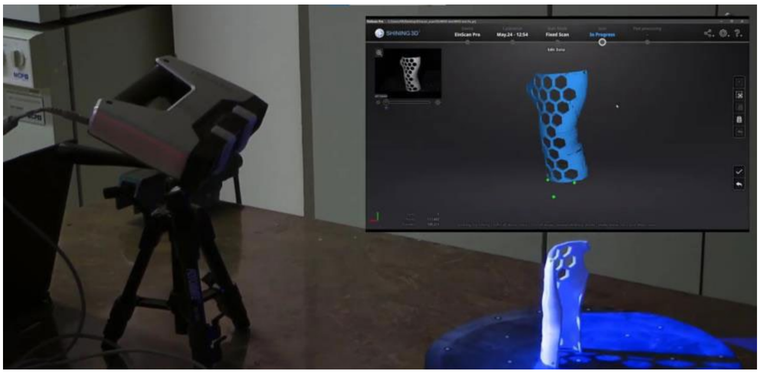

Figure 11. 3D scanning of orthosis for accuracy testing

Also, tests with patients were made for fit and functionality. First of all, virtual tests were made using the MeshLab software. The real patient fit tests are shown in Figures 12 and 13.

Figure 12. Fitting test with patients

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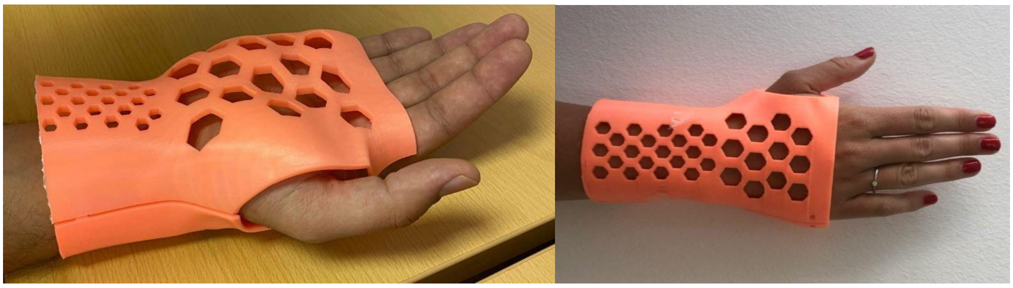

Figure 13. Fitting test with “patients” (BRIGHT International 2022 summer school)

2.2. Case study 2 - tongue model with tumor

Second case study that has been considered for the BRIGHT project has been represented by a tongue model with cancer. Cancer of the tongue is one of the most common malignancies in the oral cavity. A tongue tumor can grow relatively quickly and spread deep into the muscles of the tongue. It is recommended that the resulting lesions undergo tumor resection. This procedure involves radical removal of the tumor, and the operation is highly demanding due to the difficulty of accessing the tumor, it may lead to trismus or massive bleeding. After tumor resection cavity remains and must be reconstructed using the patient’s tissue. The answer to the need for thorough preoperative planning is to create a personalized object that reflects the shape, size and mechanical properties of anatomical structures. One-to-one creation of an individualized model is possible and cost-effective thanks to the additive manufacturing technique.

This was actually the purpose of the second BRIGHT case study that has been defined in the frame of the BRIGHT project. One anatomical model of a tongue with cancer tumor that has been realized in the frame of BRIGHT project is presented in Figure 14. The realized model has also been used for educational purposes.

Figure 14. Models of tongue with tumor

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The product shown in Figure 14 has been customized basing on medical imaging –MRI in this case. STL models have been created by taking data provided in the form of MRI imaging for the conducted research was one of the patients. Segmentation of anatomical structures has been done by using one dedicated software program like InVesalius 3.1. Results of the segmentation of the structures of the tongue and its tumor process are shown in Figure 15.

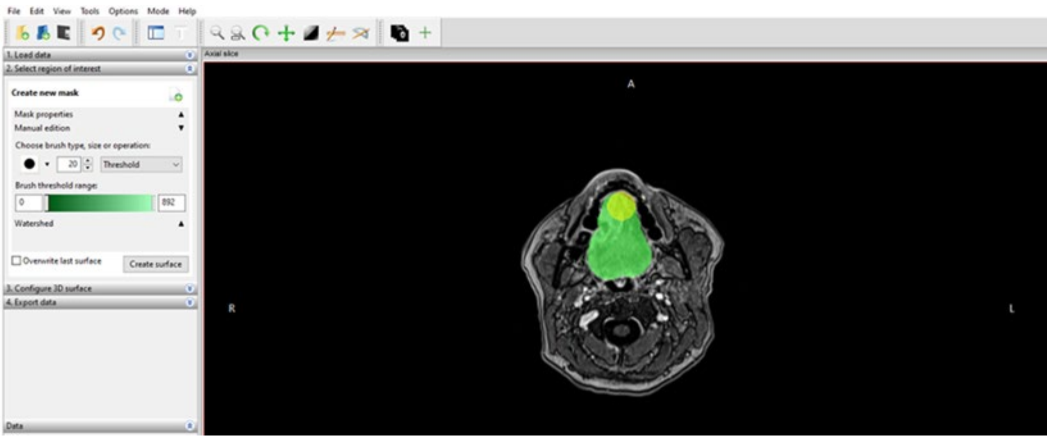

Figure 15. 3D image of a patient's skull with a tongue tumor

The 3D model has been further on processed using the GOM Inspect Suite system like shown in Figure 16 and afterwards one dedicated program called Meshmixer has been used for realizing one mold for the tongue with the tumor and the tumor itself.

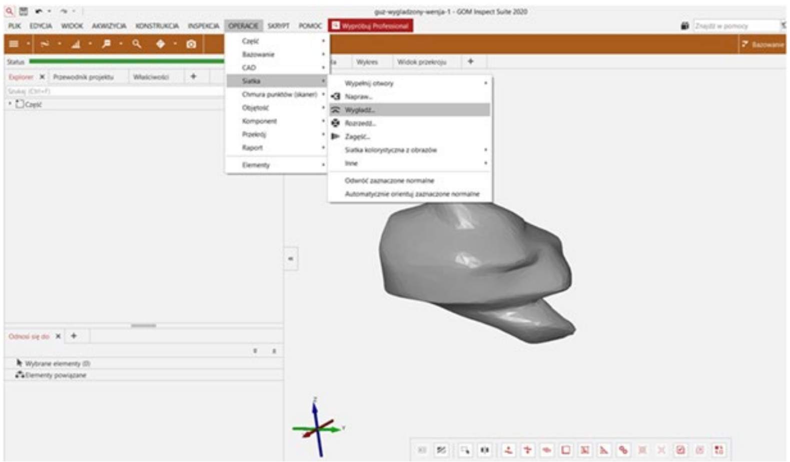

Figure 16. GOM Inspect Suite – smoothing the model

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In continuing one finite element analysis has been realize in order to evaluate the strength characteristics of the mould used for casting the tongue model by simulating a pressurization test. The principle of the test is shown in Figure 17. As one may notice, the inner surfaces of the mould parts are loaded by pressure after being clamped between two rigid plates in their assembled configuration.

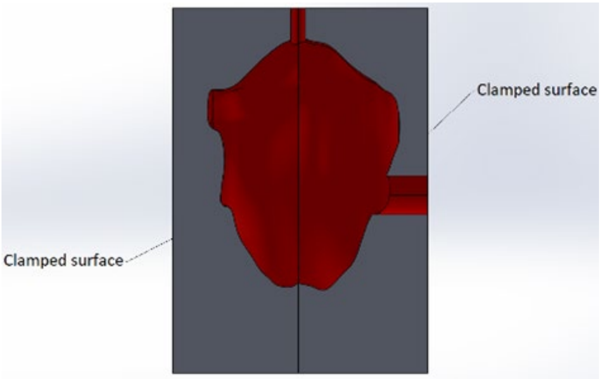

Figure 17. Principle of the pressurization test simulated for evaluating the strength characteristics of the tongue casting mould (inner pressure acting on the red surfaces)

Figures 18 shows the most important results provided by SOLIDWORKS Simulation: distributions of the von Mises equivalent stress in the mould parts for the highest stressing variant that has been considered in this case.

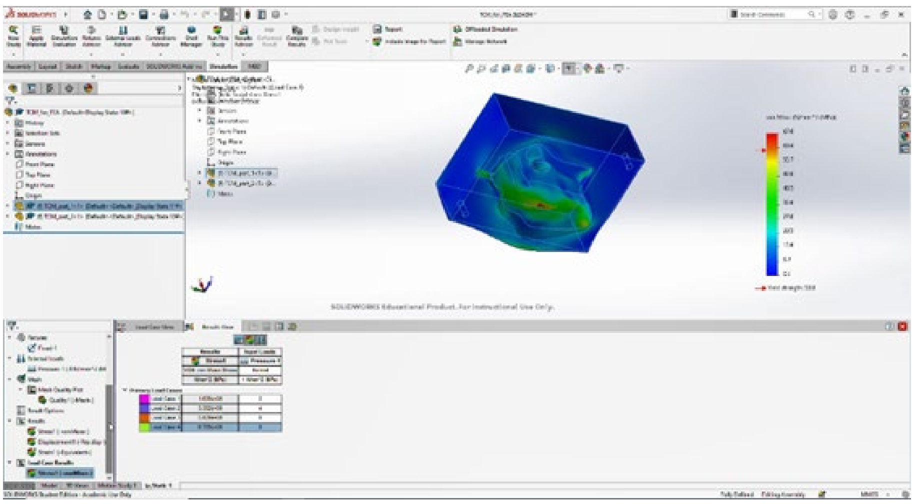

Figure 18. Distribution of the von Mises equivalent stress in the upper part of the mould

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Regarding the Manufacturing steps the case, FDM process has been selected to realize the tongue and tumor (hard, operative model), by using the FlashForge Creator Pro equipment shown in Figure 19.

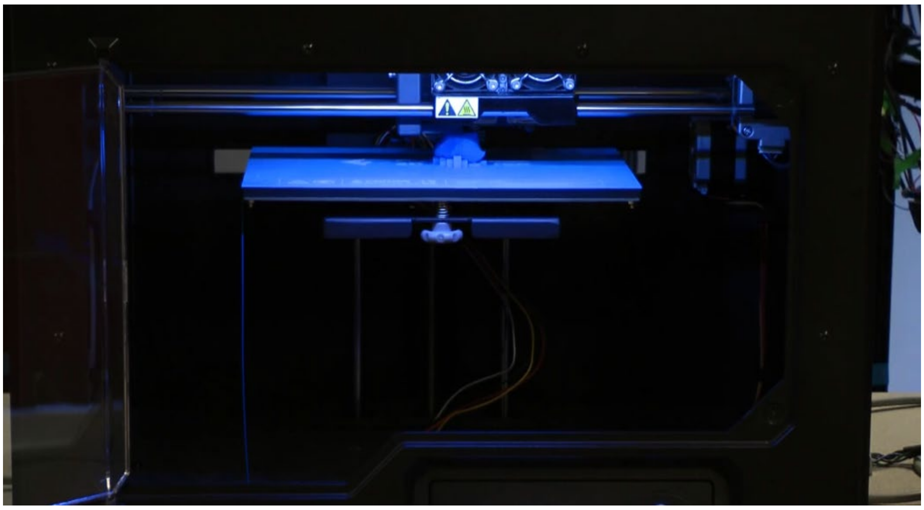

Figure 19. FDM 3D printing of tongue – FlashForge Creator Pro

Molds were printed with the Prusa i3 MK3S printer in the 3D printing laboratory of Poznan University of Technology (see Figure 20).

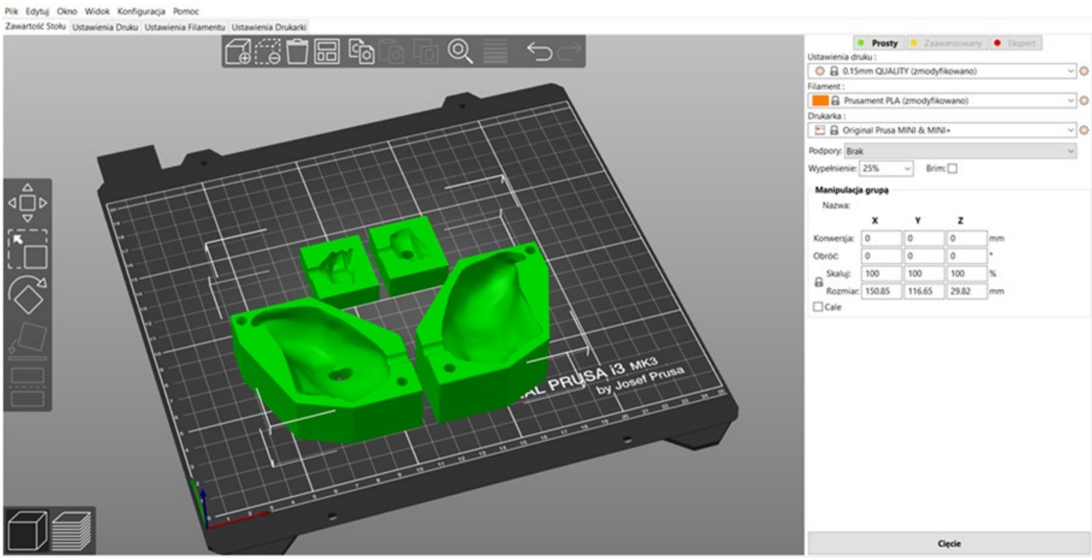

Figure 20. Screenshot of PrusaSlicer with casting

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Figure 21 presents final results of hard models 3D printing – FDM, PolyJet and SLA printouts after post processing, before sterilization and clinical use.

Figure 21. Hard 3D printed models of tongue with cancer – FDM, PolyJet and SLA technology

In terms of casting, the first step in all the operations was to locate the tumor of the tongue in the cast mold. As the tumor is inside the tissue, its location was arbitrary, selected on the basis of photos taken during the design. The location of the tumors in a casting mold is shown on Figure 22.

Figure 22. Placing the tumor model in larger mold

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Ultimately, three different models of the tongue will be created along with its tumor. The materials were selected in consultation with the medical staff, based on the presentation of samples of various materials. The semi-finished product intended for the casting of the tongue in all cases was - Sorta Clear 12. However, the tumors were made of materials such as Fiberflex (printed), Dragon Skin 10 and XTX 45 DRY (cast) as shown in Figures 23 and 24.

Figure 23. The resin casting process

Figure 24. Three cast models of tongue, with use of various materials

In terms of testing, one of the first stages of the simulated operation was the preparation of surgical instruments, which included a surgical vice, surgical tweezers and surgical knives. Then the models were inspected and the selected area was marked with a marker, as it is usually done in the operating theatre (Figure 25).

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Figure 25. Operation simulation - marking

The next step was (Figure 26) to incision the area marked at that time and then excises the tumor model. The operation was performed jointly by two surgeons on the tongue with the tumor cast from Dragon Skin 10 silicone material and the tumor cast from XTX 45 DRY silicone material (dyed).

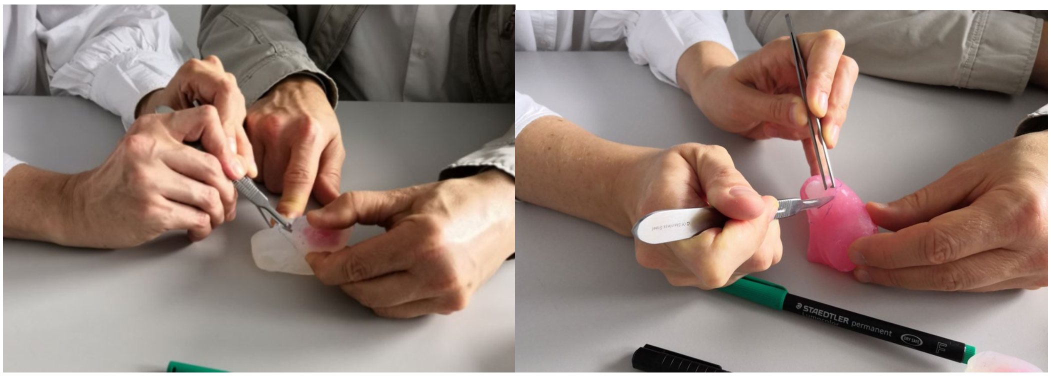
Figure 26. Operation simulation - incision

The doctors who performed a simulated operation confirmed that the faults are not a problem if they are not in the desired location, in this case within the tumor and its margin. The color of the silicone models turned out to be a very important factor during the planning and during the simulated operation. The transparency of the tongue model together with its colored tumor allowed a better view of the tumor visibility and its correct excision. These types of models were assessed as very good in terms of didactic value, intended for students and less experienced doctors. The operation carried out on the colored model was closer to the actual operation, it reflects the difficulty of the operation. In this case, the tumor was excised with too small a margin and part of it remained in the tongue.

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2.3. Case study 3 - face shield

The product that has been selected for case study 3 that has been realized in the frame of intellectual output 5 was a 3D printable face shield, that was used in times of COVID pandemic as a quick-resort disposable protection device for medical personnel dealing with the infected (see Figure 27). The 3D printed part is the head section, to which a transparent shield is attached, along with a rubber band holding the whole shield at user's head, like shown in Figure 28.

Figure 27. 3D printed face shields, supplied to medical personnel

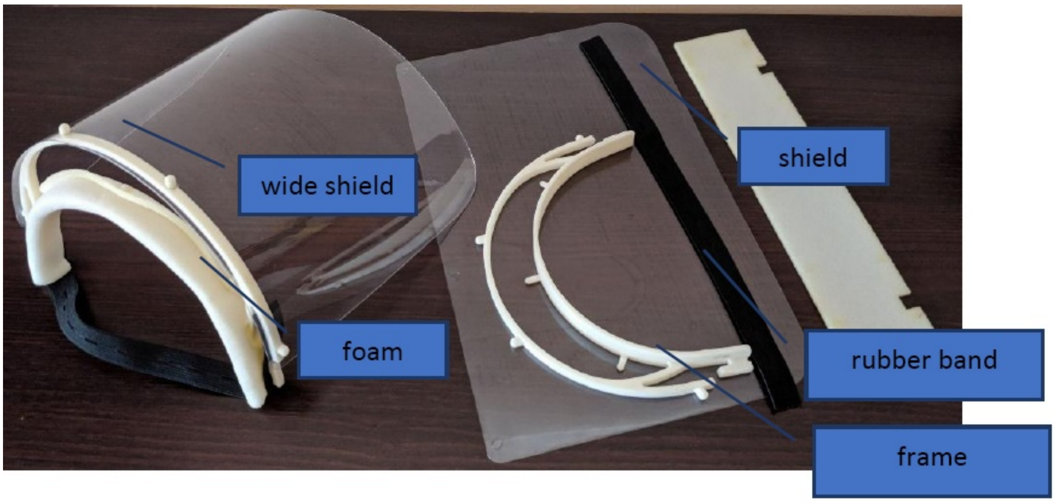

Figure 28. Structure of the shield

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The design of the shield can be prepared in any software – originally, it was Autodesk Inventor CAD system, where the models were prepared by PUT team (Figure 29).

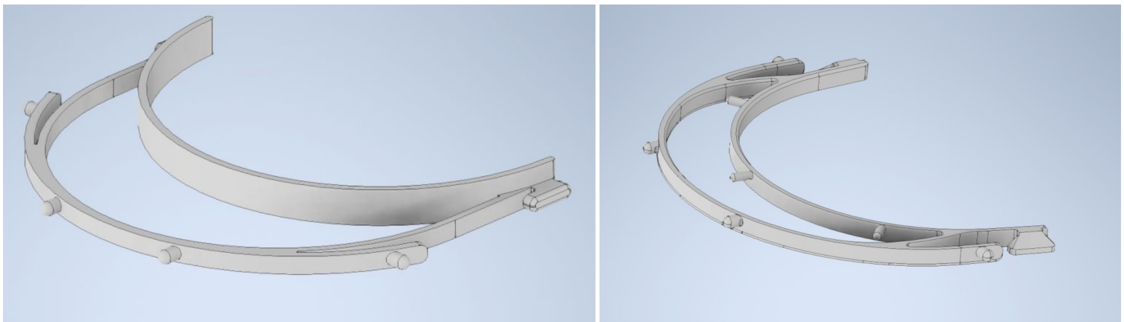

Figure 29. Face shield model, basic (Prusa) version (top) and final model designed in Autodesk Inventor

In terms of CAE simulation, the main objective of the finite element analysis (performed by scientific team but also by the students in the summer school) has been in this case to evaluate the strength characteristics of the face shield base (see Figure 30) by simulating a dimensional adjustment procedure. The dimensional adjustment procedure consists in enforcing the rear ends of the shield base to approach the symmetry plane.

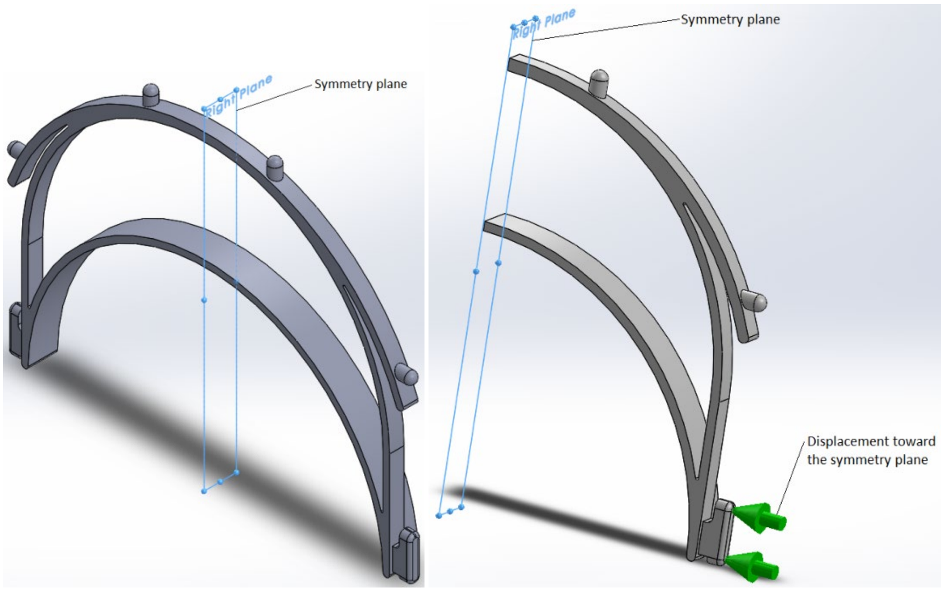

Figure 30. 3D model of the face shield base (right), dimensional adjustment simulated for evaluating the strength characteristics of the face shield base

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The finite element model has been prepared assuming that the face shield base is made from PETG characterised by an isotropic linear elastic behaviour. The finite element model has been elaborated and solved with SOLIDWORKS Simulation (Figure 31).

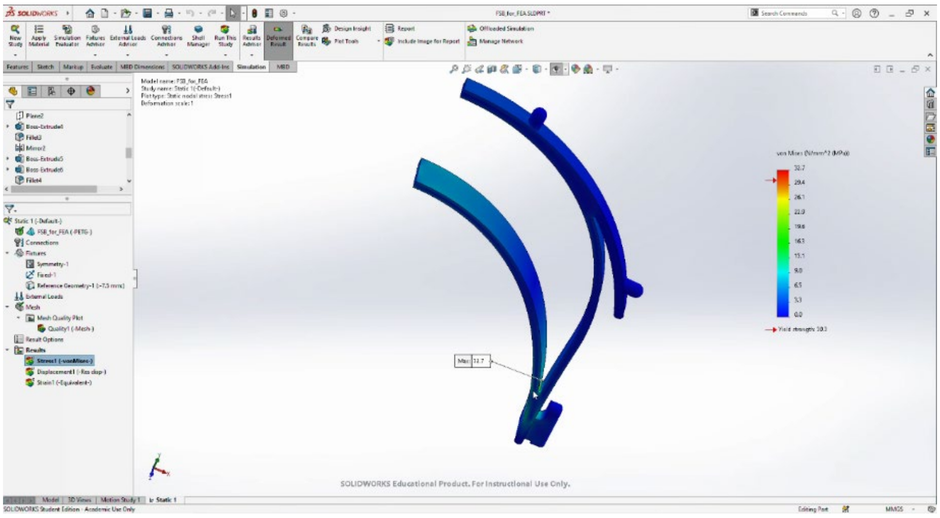

Figure 31. Distribution of the von Mises equivalent stress in the face shield base corresponding to the 7.5 mm displacement of its rear end

In terms of 3D printing, the shield was generally manufactured using the FDM technology using the following equipment items: Prusa i3 MK2 (Figure 32), FlashForge Creator Pro (Figure 32) and Anycubic Chiron (Figure 33)

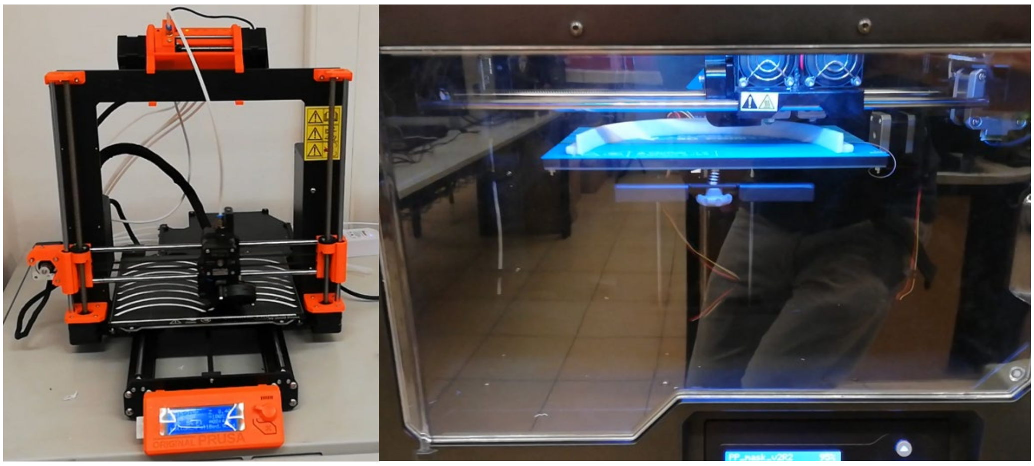

Figure 32. FDM 3D printing of face shield – Prusa (left) and FlashForge Creator Pro (right)

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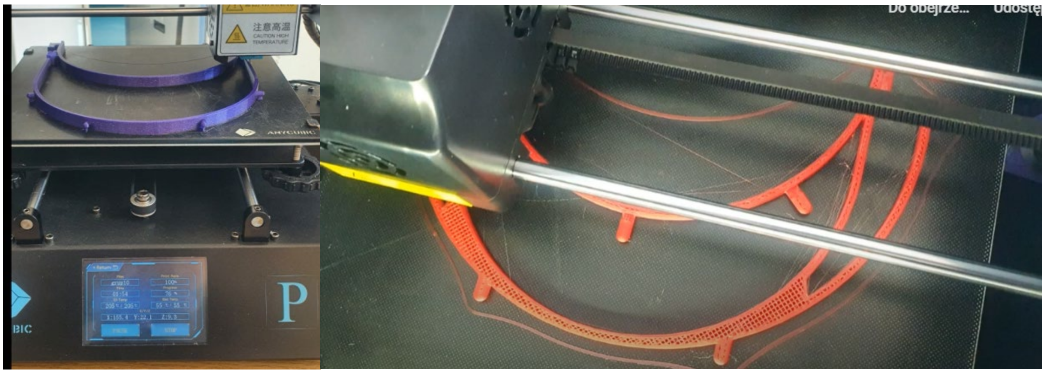

Figure 33. Face shield printing using Anycubic Chiron machine

Part has been also produced by injection molding - the injection molding process was planned and realized in the facilities of the industrial partner of the BRIGHT project – the BM Plast company (Croatia) (Figure 34 and 35).

Figure 34. Productive moulds preparation/ quality inspection

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Figure 35. Manufacturing equipment for production in batch series

In terms of testing - the following activities were realized for the face shields:

- non-destructive testing – 3D scanning and quality check measurement (Figure 36),
- destructive testing – tensile test (Figure 37) and
- testing with medical personnel (Poznan University of Technology with hospital doctors) – Figure 38.
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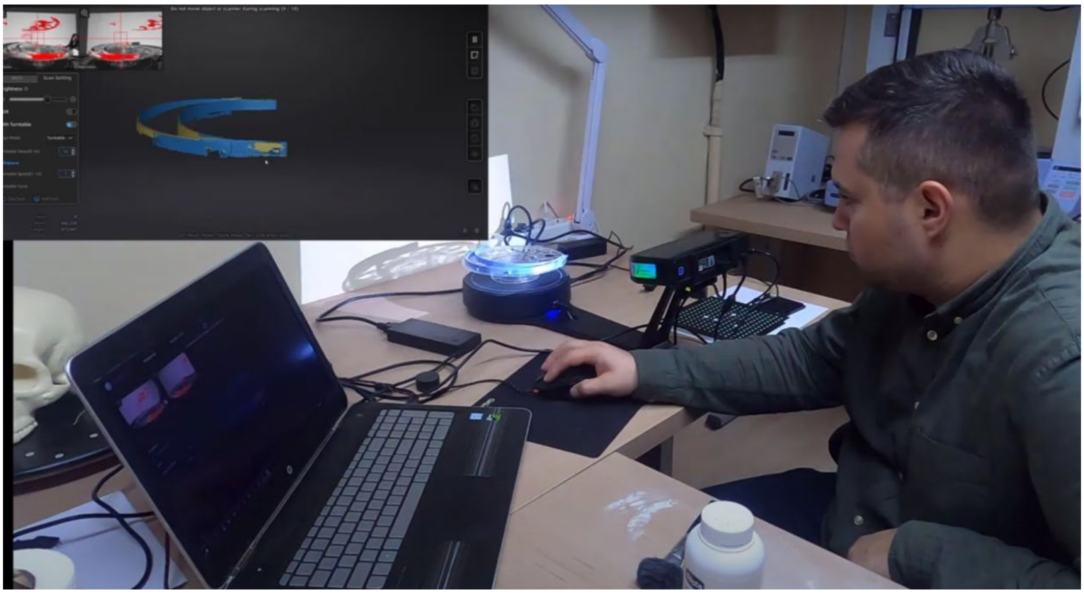

Figure 36. 3D scanning for accuracy measurement (NiS, Serbia)

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Figure 37. Tensile test of the face shield base

Figure 38. Testing in clinical conditions – 3D printed version (left) and injection mold version (right)

Most tests were realized with participation of students, or recorded for their use in the educational process, to maximize reach and possible teaching effect.

2.4. Case study 4 - robotic mechanical hand prosthesis

The UnLimbited Arm prosthesis that has been considered for the case study 4 (Figure 39) 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

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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, stretched from the arm to the prosthetic hand. When the forearm stump is straightened, the fingers are open – when it is bent, the fingers close.

Figure 39. UnLimbited Arm Prosthesis

The basic, open source version of the prosthesis has been customized on the basis of several dimensions of a patient in the frame of BRIGHT project case study 4.

The complete model of a customizable prosthesis in CAD design 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 consists of four main component types (Figure 40):

- 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).

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 41) and the UnLimbited Arm part (Figure 42).

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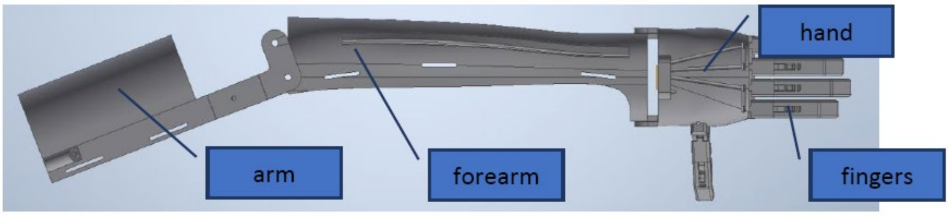
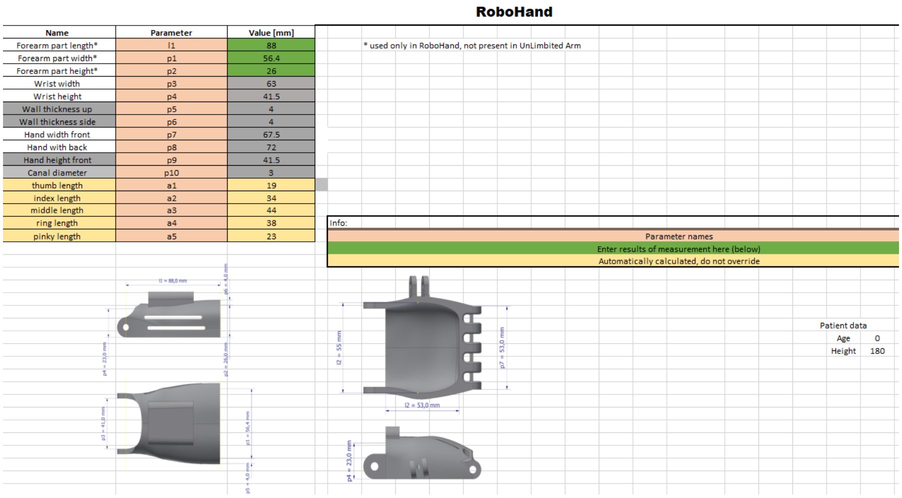


Figure 40. Robotic hand prosthesis - parts



RoboHand

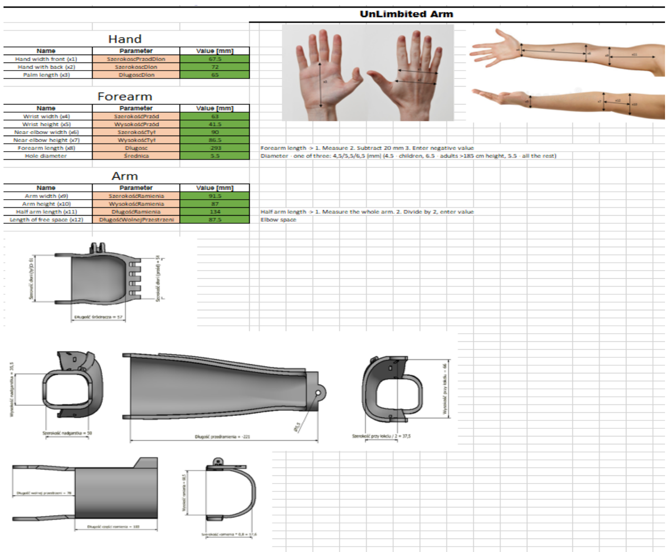
Name	Parameter	Value [mm]
Forearm part length*	l1	88
Forearm part width*	p1	56.4
Forearm part height*	p2	26
Wrist width	p3	63
Wrist height	p4	41.5
Wall thickness up	p5	4
Wall thickness side	p6	4
Hand width front	p7	67.5
Hand with back	p8	72
Hand height front	p9	41.5
Canal diameter	p10	3
thumb length	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 41. 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 42. Excel spreadsheet – UnLimbited Arm part

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After introducing a set of parameters, the model redesigns itself. Example of model in the shorter version is presented in Figure 43.

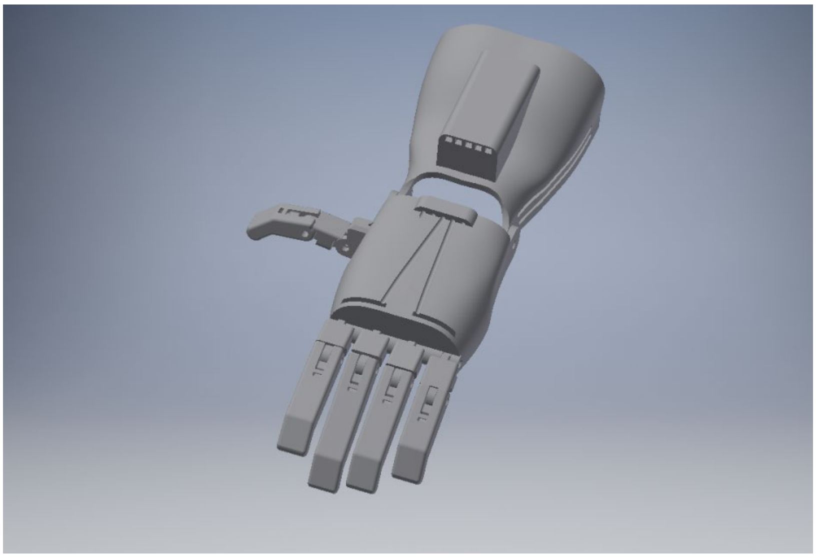

Figure 43. Robotic hand prosthesis – short version (RoboHand)

In terms of CAE simulation, the main objective of the finite element analysis consisted in the evaluating of the strength characteristics of a finger belonging to the prosthesis (Figure 44) by simulating a tensile test.

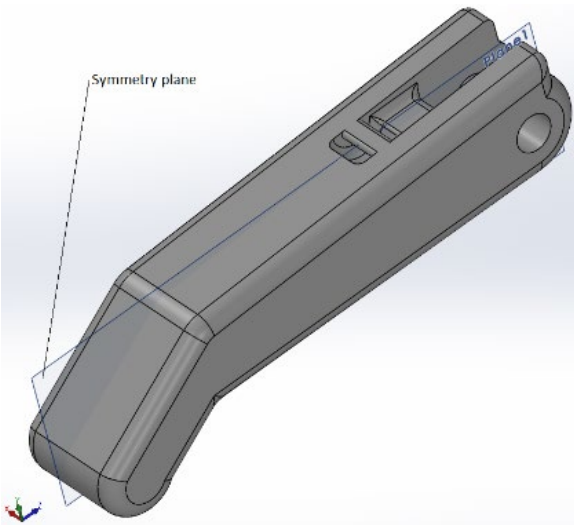

Figure 44. 3D model of the prosthesis finger

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The finite element model of the tensile test has been elaborated and solved with SOLIDWORKS Simulation as shown in Figure 45

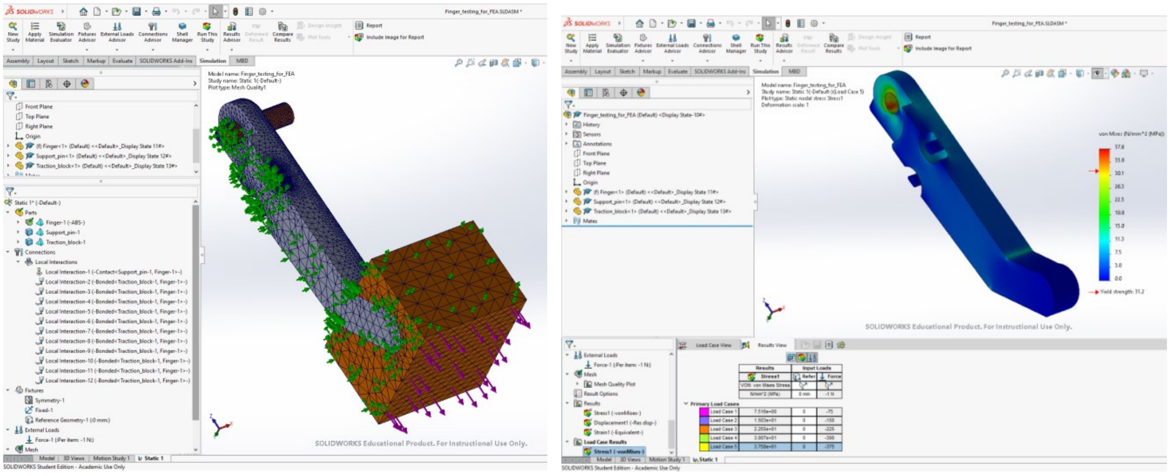

Figure 45. Finite element model of the tensile test simulated for evaluating the strength characteristics of the prosthesis finger

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. 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 fingers (ABS/PLA), 5 metacarpals (PLA) and one forearm (ABS) - Figures 46, 47.

Figure 46. RoboHand prosthesis made of ABS material

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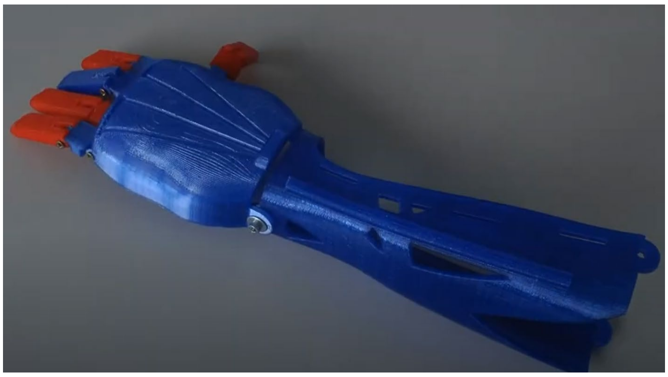

Figure 47. UnLimbited Arm printed during BRIGHT summer school 2021

In terms of testing, 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 – Figure 48.

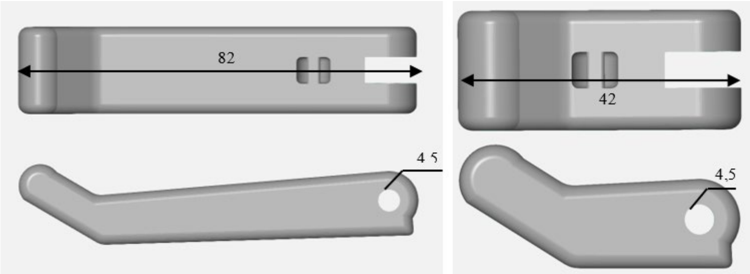

Figure 48. Measured dimensions in accuracy test (examples)

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 49.

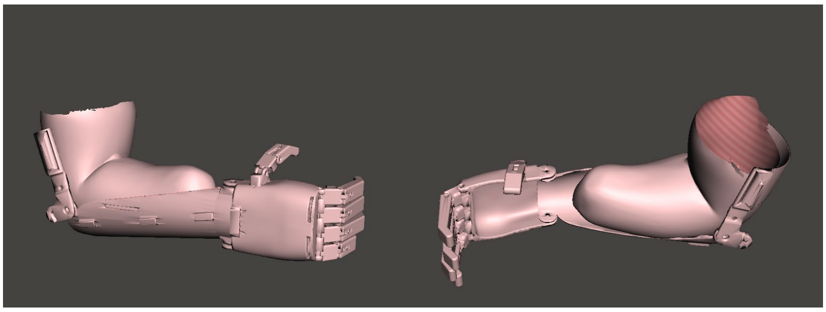

Figure 49. Fit testing of the generated prosthesis

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Strength test was also realized 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 Figures 50 and 51.

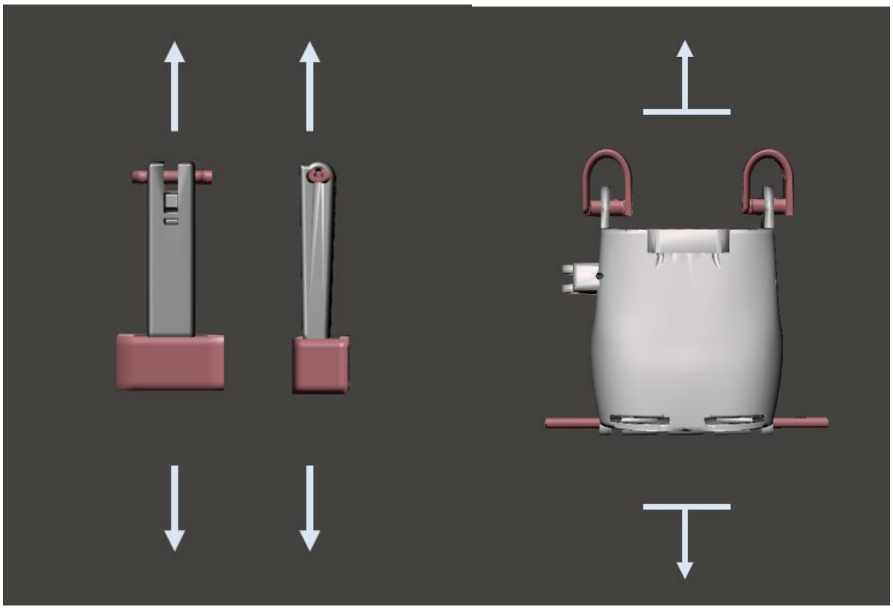

Figure 50. Scheme of tensile tests for prosthesis elements

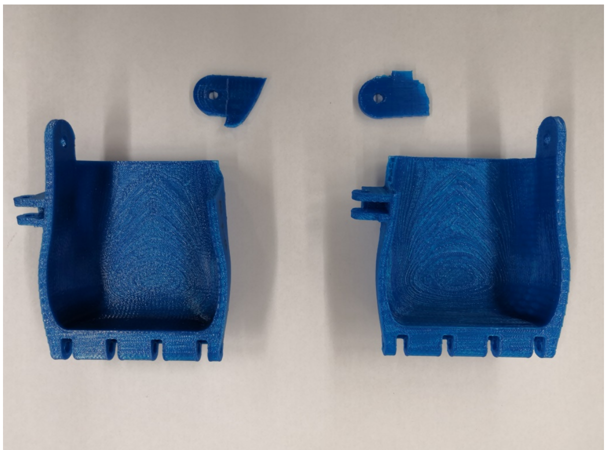

Figure 51. Results of strength test – metacarpus

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2.5. Case study 5 - modular hand prosthesis for bicycle

The product that has been defined as case study 5 in the frame of intellectual output 5 with support of the medical doctors has been a 3D printable mechanical prosthesis (Figure 52), that has been 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 52. Bicycle hand prosthesis

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. 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 below:

The complete model of a customizable prosthesis has been designed in Autodesk Inventor CAD software (Figure 53). The parameters (dimensions) were entered through an Excel spreadsheet (which could be edited using MS Excel or Google Sheets, alternatively Open Office package) shown in Figure 54. The prosthesis preparation is based on anatomical data.

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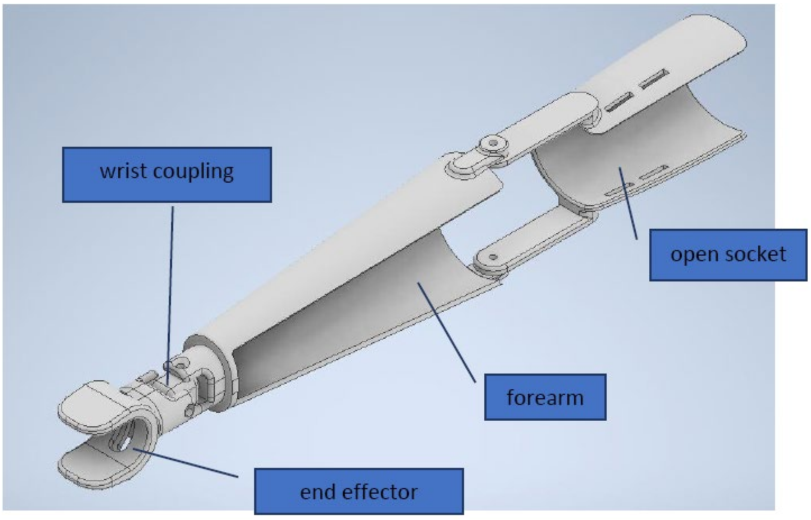

Figure 53. Bicycle hand prosthesis - parts

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

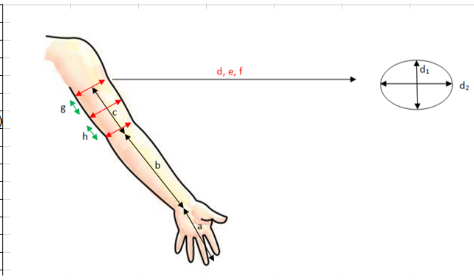

Figure 54. Excel spreadsheet – bicycle prosthesis

After introducing a set of parameters, the model redesigns itself, results of which are presented in Figure 55.

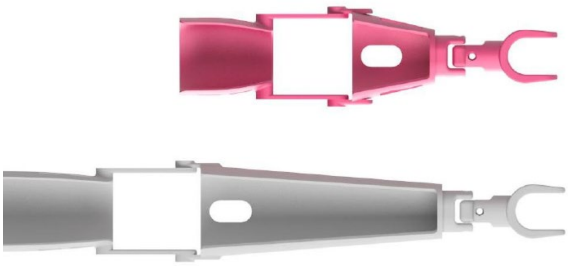

Figure 55. Update of model with different patient data

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In case of CAE analysis, the main objective of the finite element analysis consisted in the evaluation of the strength characteristics of the improved design of bicycle prosthesis made for the adult patient (Figure 56) by simulating a distal tensile test. The principle of the test is shown in also in Figure 56, results of the CAE analysis being presented in Figure 57. 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.

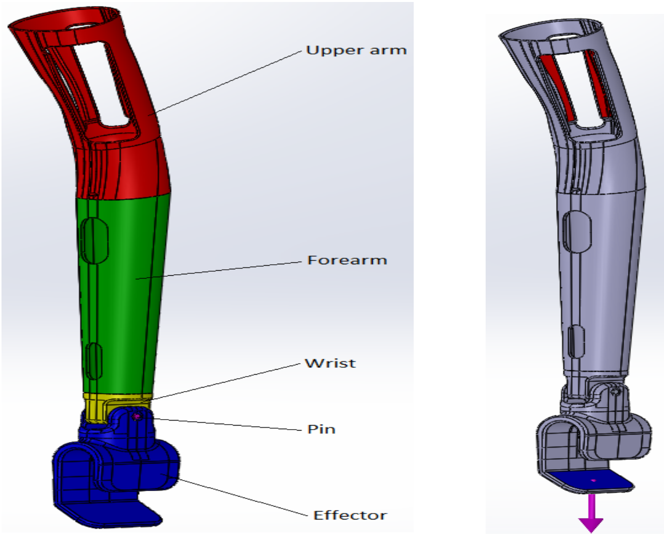

Figure 56. 3D model of the bicycle prosthesis (left), principle of the distal tensile test simulated for evaluating the strength (right)

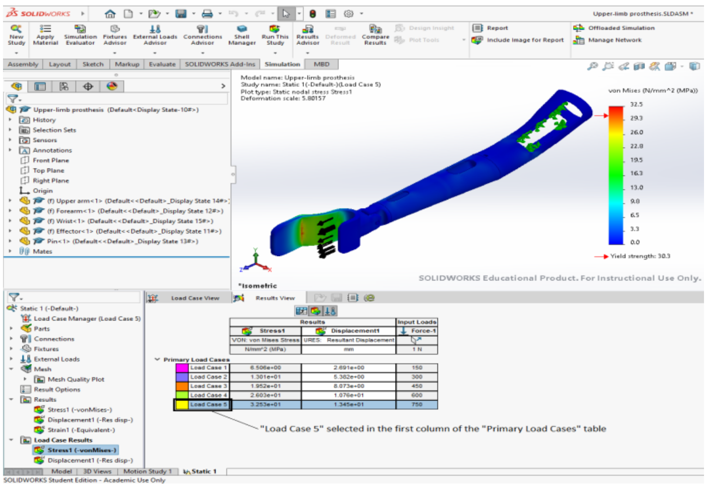

Figure 57. Distribution of the von Mises equivalent stress in the bicycle prosthesis

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The manufacturing of the prosthesis elements has been realized using the FDM technology different equipment and materials. For the summer school, Prusa i3 MK2 equipment was used, with the Prusa Slicer software used for programming (see Figures 58 and 59).

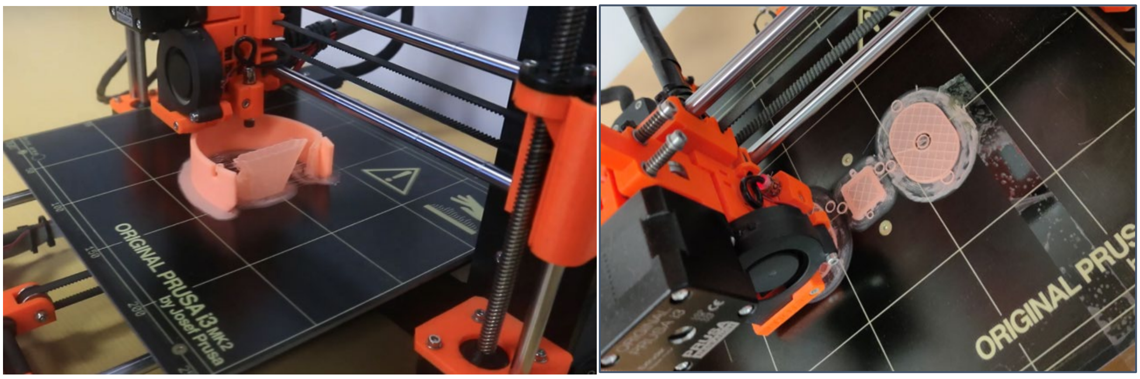

Figure 58. 3D Printing of prosthesis parts using Prusa FDM machine

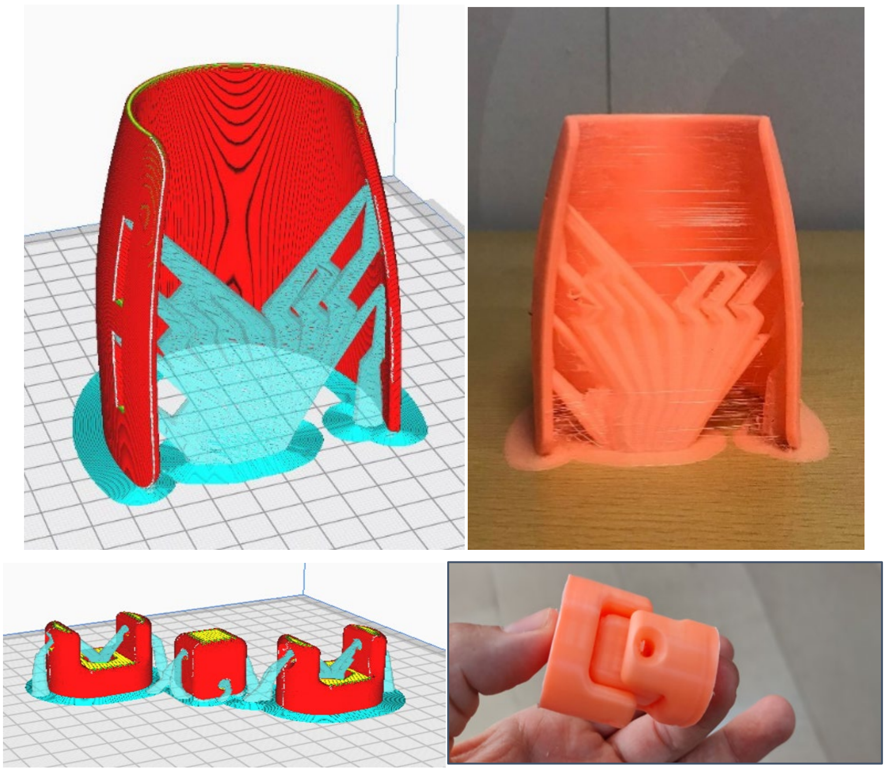

Figure 59. Process planning (left) and result (right)

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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 60. For the adult version of the prosthesis (Figure 61), other machines have to be used, with slightly larger build chamber.

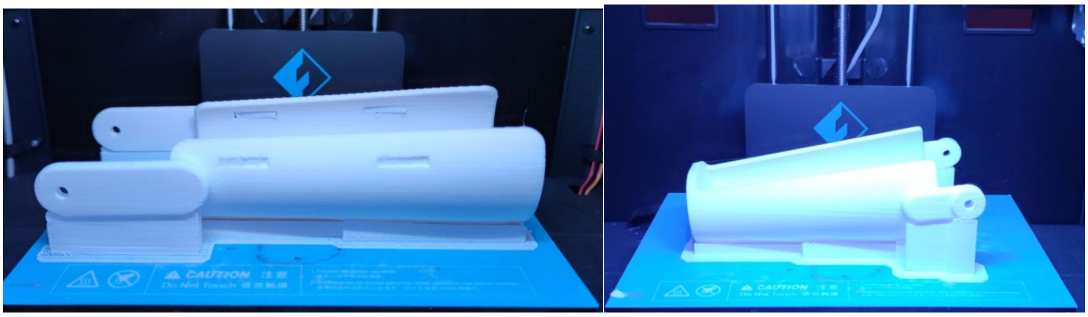

Figure 60. Parts of prosthesis (socket and forearm) made using FlashForge Creator Pro machines

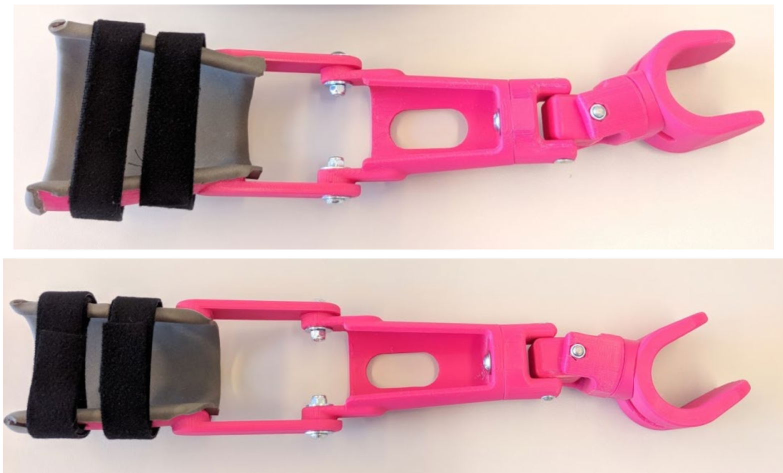

Figure 61. Prostheses made for different patients

In terms of testing, 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 required to be tested in laboratory conditions and in real-life conditions (see Figure 62, 63).

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).

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Figure 62. Testing of prosthesis by children patient

Figure 63. Testing of prosthesis by adult patient

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3. Dissemination activities and conclusions

In terms of disseminating activities, more than couple dozens of students had the experience with CAD design, CAE simulation 3D printing, simulation and testing of the customized orthosis during both summer schools as presented in the Final dissemination report of the BRIGHT project. Educational materials in the project were prepared on that basis (CAD, CAE, 3D printing and testing instructions and educational videos) and were used with great feedback. Presentations about the achieved results in relation with all case studies 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. Beside all these achievements, most of reached results that have been developed by BRIGHT professors in collaboration with students have been published in scientific articles within prestigious journals (including ISI journals with impact factor (Q1) or other types of publications like handbooks, toolkit manual, guide project, details about all publications related to the realized case studies and results reached with support of BRIGHT project resources being presented in the final Dissemination report of the BRIGHT project in the end.

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