Intellectual Output_O1:
EMERALD e-book for developing of biomimetic mechatronic systems

MODULE 7
3D PRINTING AND RAPID TOOLING METHODS

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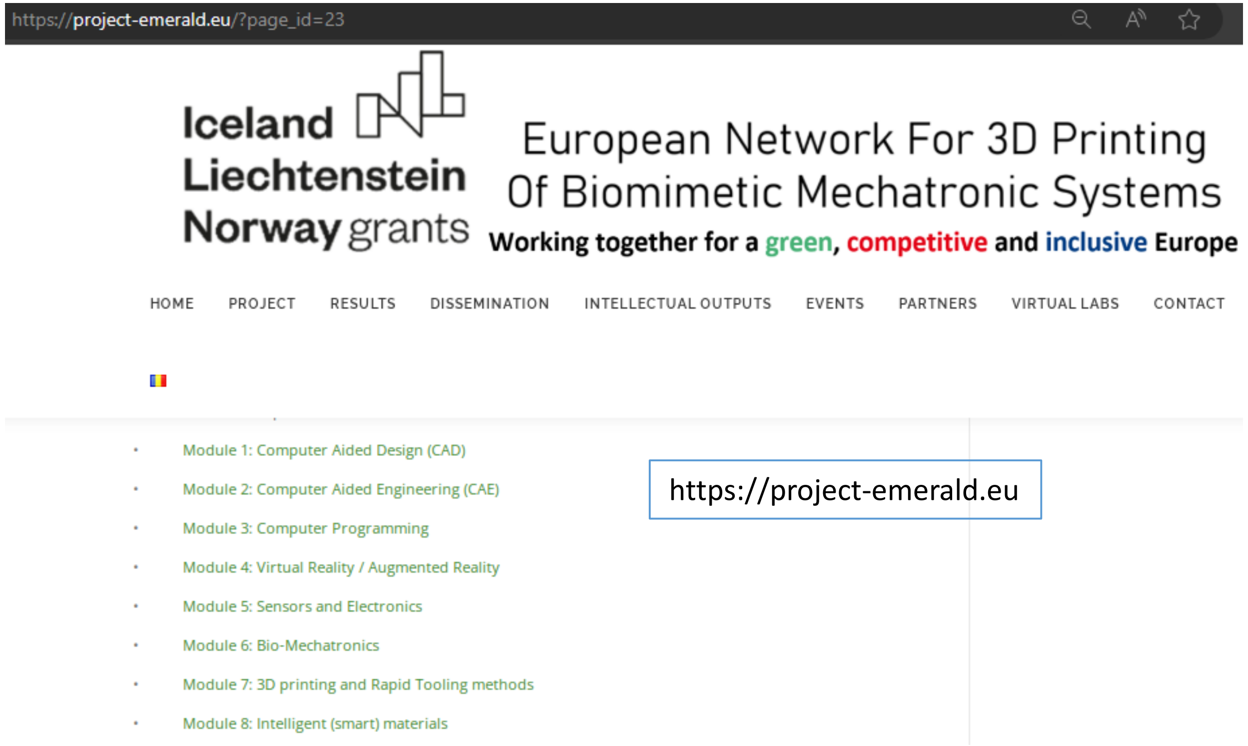

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EUROPEAN NETWORK FOR 3D PRINTING OF BIOMIMETIC MECHATRONIC SYSTEMS

MODULE 7 – 3D PRINTING and RAPID TOOLING methods

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1.Introduction

Additive manufacturing technology (AMT), also known as 3D printing, has revolutionized various industries, including medicine. It is transforming the way medical devices and implants are manufactured, leading to significant advancements in patient care. 3D printing has the ability to create intricate and complex structures, which was not possible with traditional manufacturing techniques .

The medical applications of 3D printing are numerous and include the creation of prosthetics, implants, surgical tools, and even human tissues and organs. Another area where 3D printing is making a significant impact is in the creation of implants, such as spinal and joint replacements. With 3D printing, implants can be created that are tailored to the specific requirements of each patient. 3D printing is also revolutionizing the field of biomechatronics, which combines biomechanics and electronics to develop advanced prosthetics and exoskeletons.

This module presents basic knowledge on 3D printing. Some basic concepts and definitions have been presented, as well as some descriptions of fundamental and derivative processes. Along with basic knowledge, also examples of use in the field of personalized prosthetic and orthotic devices are presented.

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2. *Basics of 3D Printing technology*

1.Additive Manufacturing

2.Rapid Prototyping

3.Rapid Manufacturing

4.Rapid Tooling

5.3D Modeling Software

6.Build Volume

7.Layer Height

8.Resolution

9.Post-Processing

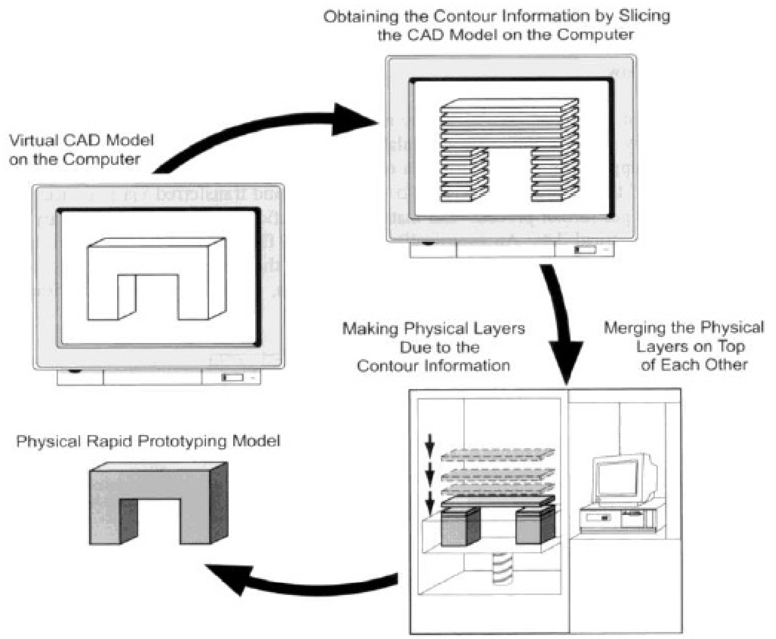

Figure 2.1. Basic scheme of additive manufacturing [1]

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2.2 3D Printing technologies

2.2.1 Review of available technologies

The ISO/ASTM 52900 standard defines the following seven categories of additive manufacturing processes (Fig. 2.2):

- extrusion,
- sintering of powders (powder bed fusion),
- photopolymerization,
- material jetting,
- binder jetting,
- sheet lamination,
- directed energy deposition

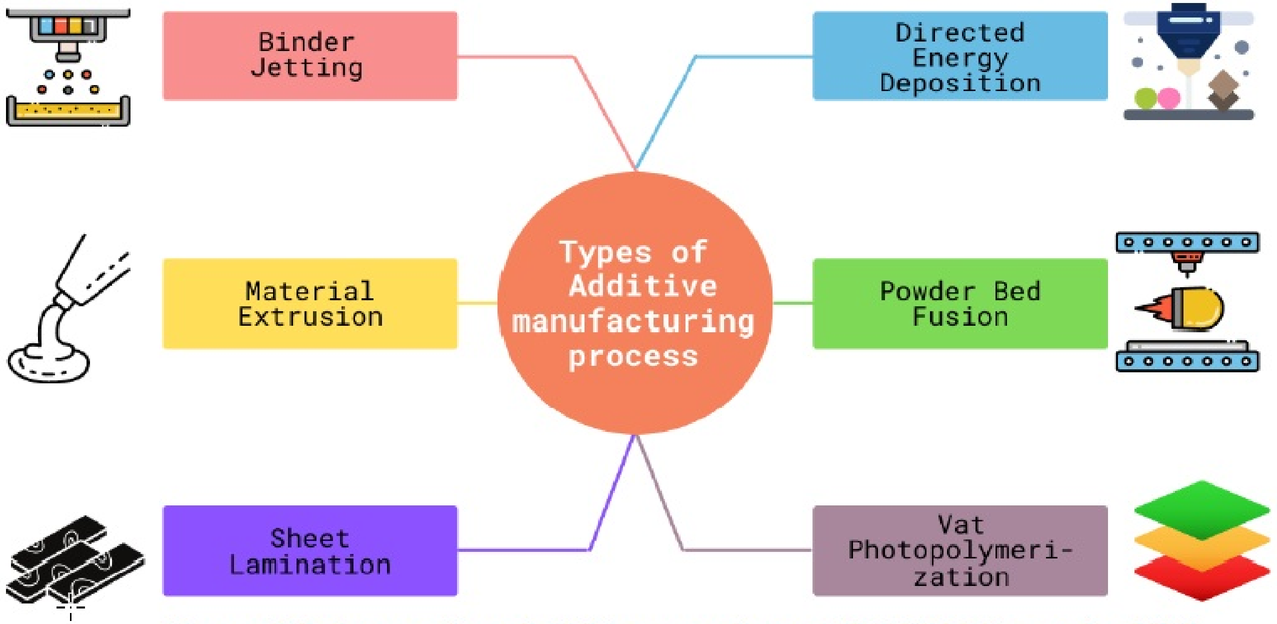

Figure 2.2.Categories of AMTs according to ISO 52900 standard [3]

2.2.2 Fused Deposition Modelling

Fused Deposition modeling is a process consisting in layered deposition of plasticized build and support material supplied in form of a wire by an extrusion head . Numerically controlled device deposits build and support material on the model base, with data about head positioning coming from horizontal cross-sections of the part, prepared on the basis of the 3D CAD model.

Obtained models are considerably strong and can be subjected to further treatment by machining, gluing or painting, to obtain desired surface quality. Produced part is ready for use immediately after support material removal

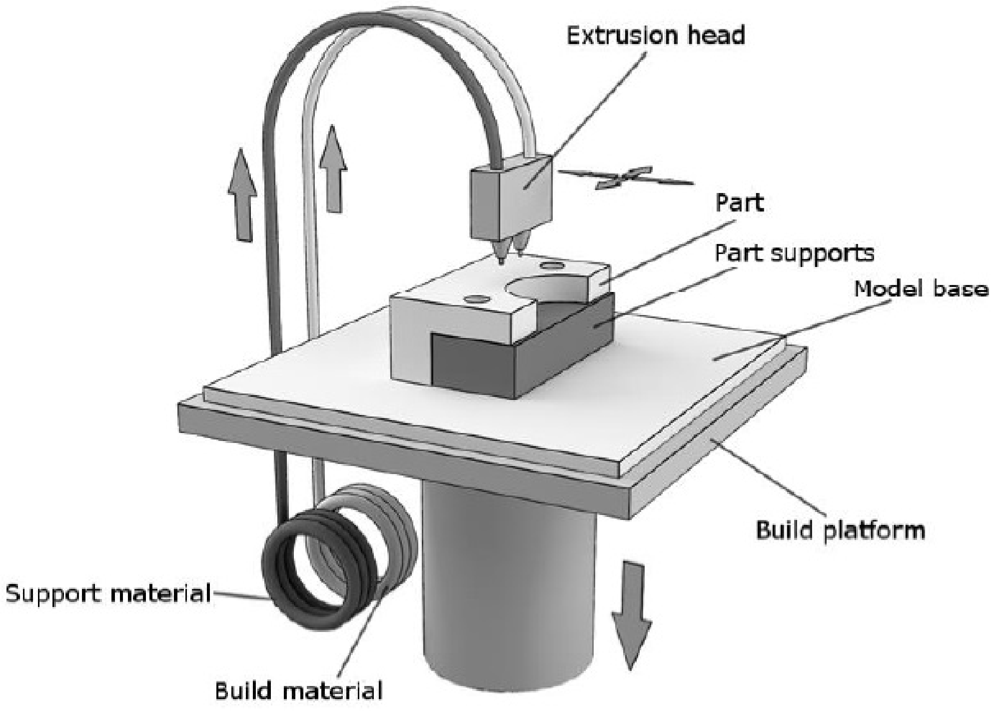

Figure 2.3. Scheme of FDM technology [5]

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The process utilizes mostly thermoplastic materials, or composites based on them. Below, the most frequently used and specific materials are mentioned.

Standard:

•ABS - Acrylonitrile butadiene styrene, (poly(acrylonitrile-co-butadiene-co-styrene))-the most popular, good strength properties

•PLA - polylactide, polylactic acid - cheap, biodegradable, easily processed

Often used:

•PETG ("HD glass") - transparent, durable, easy to process,

•TPU ("flex") - thermoplastic polyurethane, flexible, soft

•PA12 (nylon) - abrasion resistant

•HDPE - polyethylene - cheap, available

Specialized:

•PC - polycarbonate – durable

•PPSF - polyphenylsulfone (polyphenylsulfone) - increased resistance

•PEEK (polyetheretherketone) - rigid, durable, resistant to high temperatures

Soluble supports:

•PVA - polyvinyl alcohol, soluble in water

•HIPS - polystyrene - soluble in limonene,

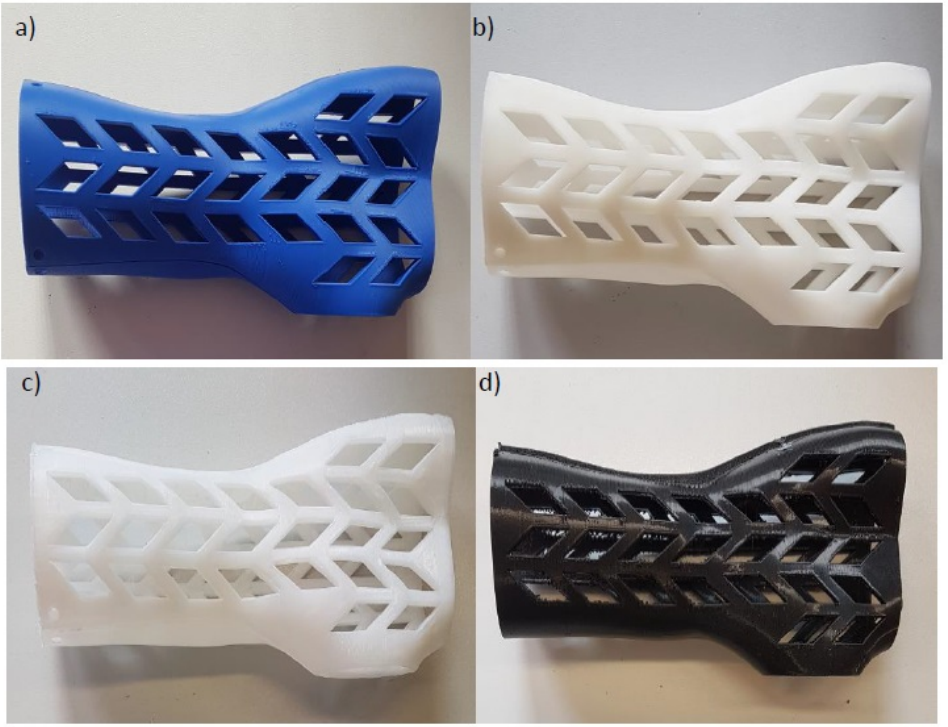

Figure 2.4 presents single anatomical product (hand orthosis) made of different materials using FDM technology.

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2.2.3 Stereolithography and UV technologies

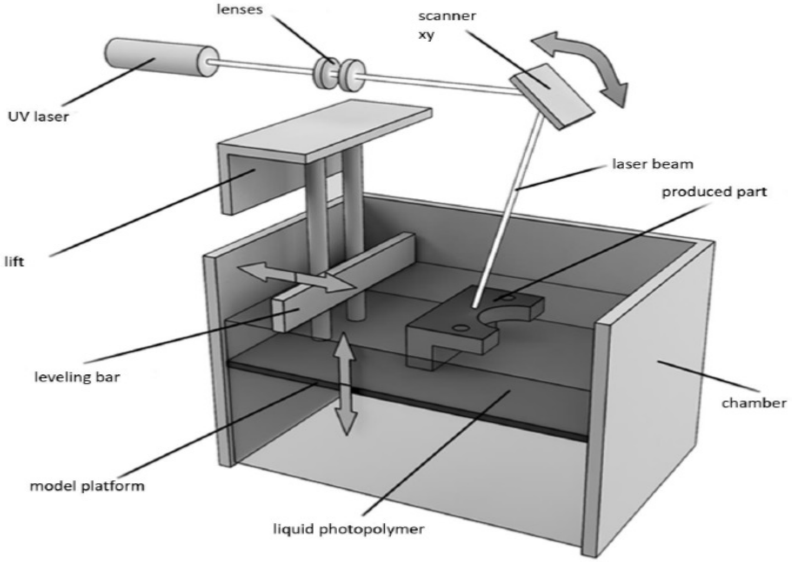

Figure 2.5. Scheme of SLA technology [5]

There are two main kinematic variants of SLA technology:

•standard process, in which laser is positioned above the resin tank (as presented inFig. 2.5), and the model platform is going down after each layer,

•inversed process, in which laser is positioned below the resin tank and the modelplatform is rising up after each layer, with the product being fabricated upsidedown.

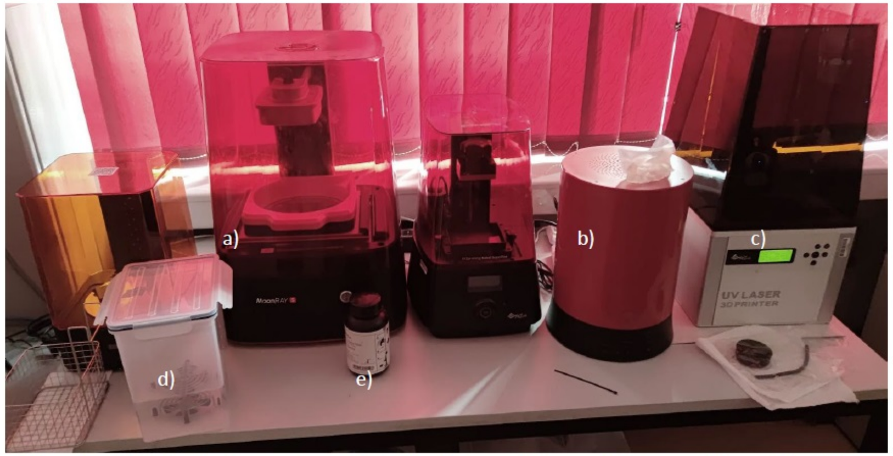

Figure 2.6. SLA technology setup: a) & c) desktop machines with inverse kinematics, b) post-curing station, d) cleaning tank, e) photopolymeric material

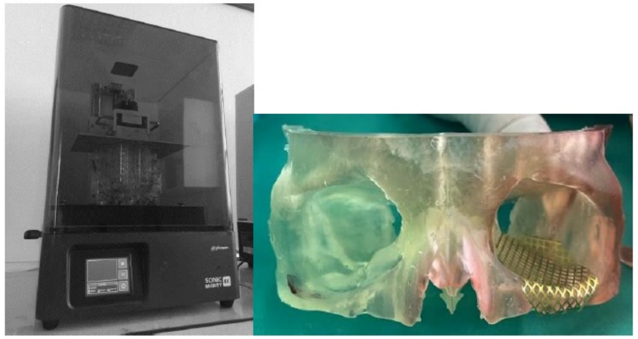

Figure 2.7. Anatomical part printed with SLA (inside the machine) and its clinical use for implant shape adjustment [9]

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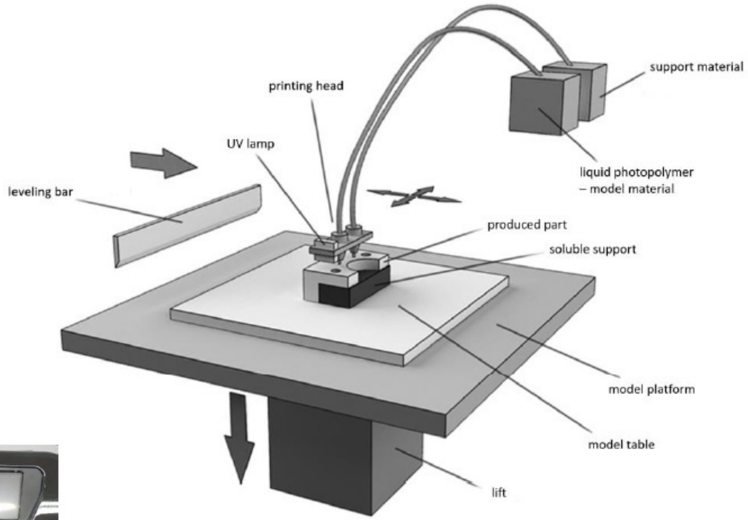

ure 2.7. Scheme of PolyJet technology

Support structures are necessary as in the inverse kinematic SLA method, as the projector is located at the bottom of the resin tank (Fig. 2.10). DLP is a useful method for intricate shapes, but current generation of machines have very small build chamber and the process takes very long – its usability is therefore limited.

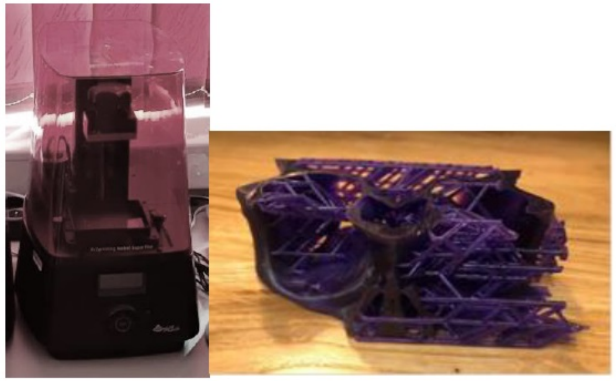

Figure 2.10 DLP machine and example of anatomically shaped product [10]

Figure 2.8. PolyJet machine – Stratasys MediJet J5

PolyJet technology is very useful for building multi-material, very detailed physical representations of complex intricate shapes, especially anatomical ones. It is suitable for representation of very thin structures and minor details, such as eye socket bone (Fig. 2.9) or arteries and nerves in a brain. Larger machines, such as MediJet J5 (Fig. 2.8) can be used to produce useful structures and objects, such as mechanisms of bioinspired prostheses, as well as large anatomical interconnected structures, such as liver or heart.

Figure 2.9. Example of anatomical models produced by PolyJet [9]

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2.2.4 Selective Laser Sintering

Intensive development work on the SLS method led to the creation of similar methods: Direct Metal Laser Sintering (DMLS) and Selective Laser Melting - SLM. All three methods are considered as one family. They differ mainly in the range of materials used, as well as in the fact that in the SLS and DMLS method only the outer layer of powder grains is melted, and in SLM the powder grains are fully melted

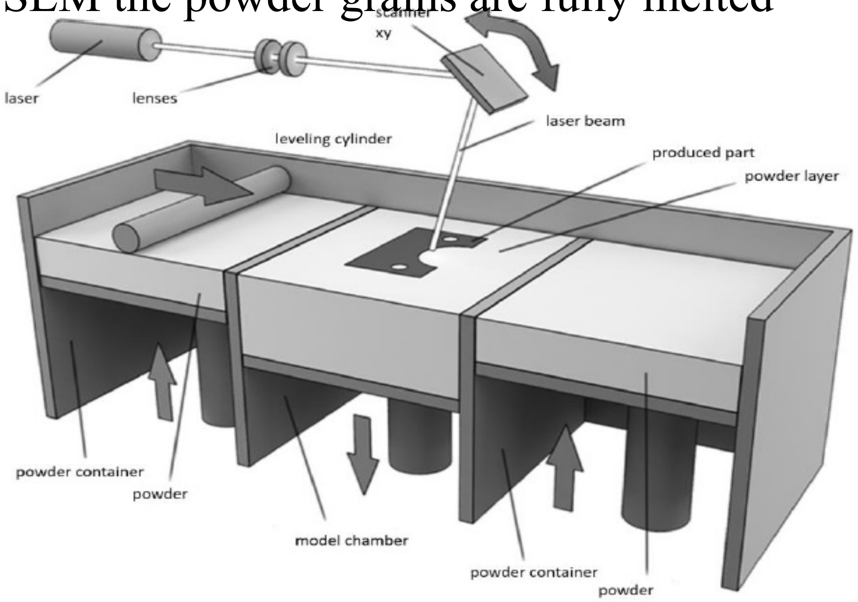

Figure 2.11. Scheme of SLS technology [5]

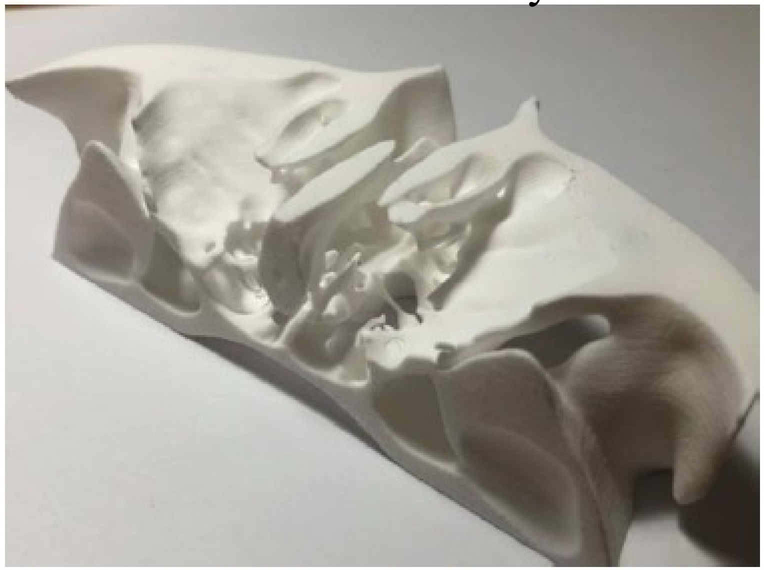
Figure 2.12. Example of anatomical object produced by SLS technique [11]

The SLS method uses both one-component powders and two-component powders - of which only one component material is a melting binder and the other is a filler. The size of a single grain is usually in the range of 20-70 micrometers, and the smaller it is, the better the strength properties and the greater the dimensional and shape accuracy of the manufactured element.

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2.2.5 Other noteworthy technologies

Among literal dozens of other additive technologies available on the market, the following might be interesting from the viewpoint of producing biomimetic devices intended for medical use:

- 3D bioprinting is one of the additive manufacturing techniques (AdditiveManufacturing) intended for medical applications and tissue engineering. Itconsists in the layered production of tissues (groups of cells). However, 3Dbioprinting technology can be described as the future of medical printing,especially in the field of biomimetic solutions.

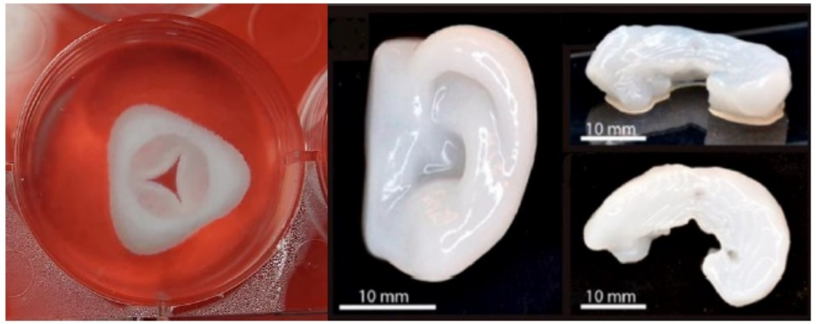

Figure 2.13. Examples of bioprinted objects [12] [13]

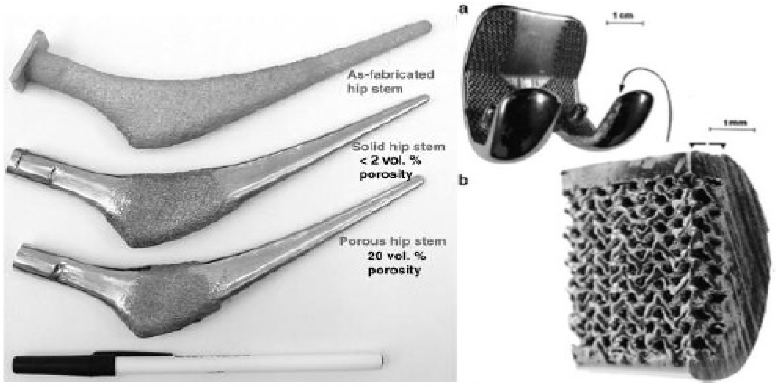

Figure 2.14. Products obtained by laser powder forming (a) [14] and electron beam melting (b) [15]

- Laser powder forming - LPF - this is a group of methods which use a high-powerlaser beam to deposit metallic materials in a targeted manner. The characteristic feature of the LPF is that it is the work table on which the model isformed that moves at most in the XY axes, and does not move in the Z axis.
- electron beam melting - EBM - allows for the production of models from metal powders melted using an electron beam in high vacuum conditions. The process iscarried out at a high temperature (even up to 1000 degrees Celsius), which gives a measurable benefit in the form of a model structure free of thermal stresses. EBM is the most similar to SLM, because in both cases the powder is fully melted, thanks to which the elements do not have a porous structure and do not require further heat treatment.

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2.3 Preparing 3D printing processes

2.3.1 Data formats

There are several file formats that are directly related to the additive manufacturing [16]. They differ significantly from one another. Some additive manufacturing software can also import CAD-specific file formats, which is an ongoing trend.

proteza00_Zosia__stl

```
solid STL generated by MeshLab
  facet normal   9.994322e-03 -4.197675e-02 -9.990687e-01
    outer loop
      vertex  -5.937941e-01  3.377039e+01  3.400025e+01
      vertex  -8.860629e-01  3.359167e+01  3.400483e+01
      vertex  -1.287003e+00  3.360526e+01  3.400025e+01
    endloop
  endfacet
  facet normal   1.001812e-02 -4.128383e-02 -9.990972e-01
    outer loop
      vertex  -1.287003e+00  3.360526e+01  3.400025e+01
      vertex  -8.860629e-01  3.359167e+01  3.400483e+01
      vertex  -1.880865e+00  3.335046e+01  3.400483e+01
    endloop
  endfacet
  facet normal   1.019512e-02 -4.169602e-02 -9.990783e-01
    outer loop
      vertex  -1.287003e+00  3.360526e+01  3.400025e+01
      vertex  -1.880865e+00  3.335046e+01  3.400483e+01
      vertex  -1.906565e+00  3.345367e+01  3.400026e+01
    endloop
  endfacet
```

Figure 2.15. STL file structure – ASCII encoding

STL (initially Stereolithography, now – Standard Triangulation Language) is the first and still one of the most widely used file formats for additive manufacturing. STL files are widely supported by most 3D printing software and hardware, making them an ideal choice for most applications.

OBJ (standing just for Object) is another widely used file format for additive manufacturing. OBJ files are widely supported by many 3D printing software these days, making them a good choice for applications that require more information

AMF (Additive Manufacturing File) is a newer file format that has been developed specifically for additive manufacturing, in 2011. It was called "STL 2.0", as it addresses to many of the shortcomings of the STL format.

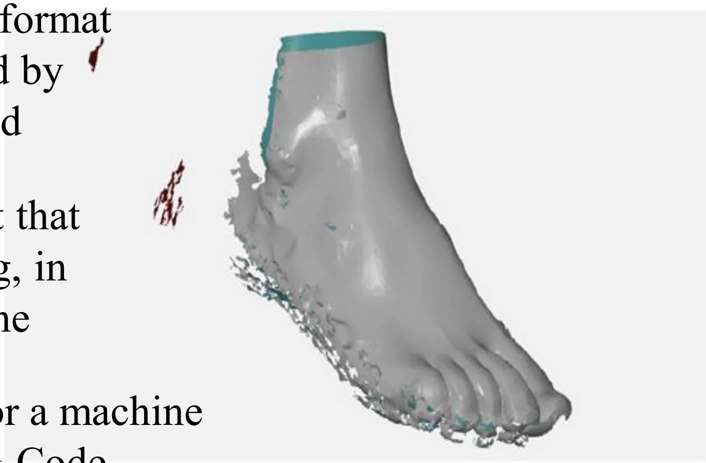

Figure 2.16. STL mesh editing process

CNC (computer numerical control) machines, including 3D printers. G-Code files contain instructions for a machine to follow, including movements, speed, and temperature. sually, software for slicing (CAM) deals with G-Code preparation and the user does not have to interfere or deal with the format in any way

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2.3.2 Software – slicers

Slicer software usually allows to adjust various parameters that affect the final quality and accuracy of the 3D printed object, as well as course of the additive manufacturing process. One of the most significant benefits of using slicer software is the ability to generate accurate estimates of print time and material usage.

An example of universal slicer is Simplify3D software, that can be used for almost any FDM machine and material which is available on the market.

A very important function of slicer software, mentioned above, is the ability to generate G-code, which is the machine language used by 3D printers to build objects

There are many slicer software options available, including both open-source and commercial options. Some popular slicer software options include Cura, PrusaSlicer, and Simplify3D.

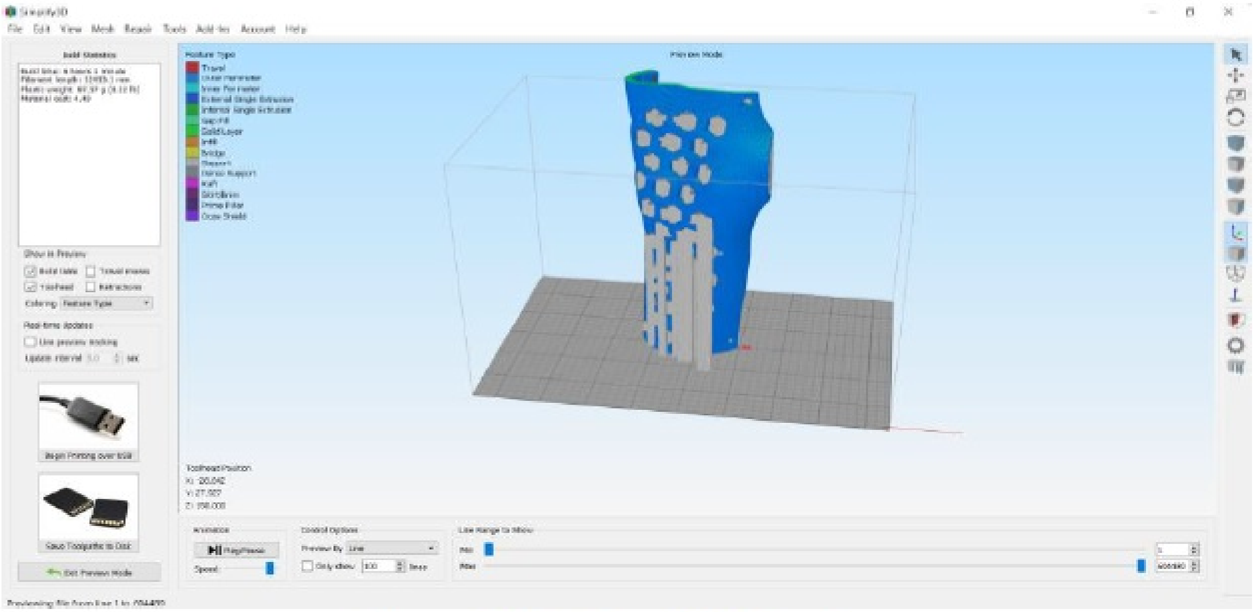

Figure 2.17. Simplify 3D slicer

2.3.3 Guidelines for 3D printing of anatomical shapes

Below, a set of general guidelines is presented for 3D printing of anatomical shapes – including biomimetic products. These are just a general set of remarks, which have to be considered carefully, depending on a specific case of a product suited for people with special needs.

1. Accuracy: It must be ensured that the 3D model used for printing is accurate andhas been verified by a medical professional
2. Material Selection: a material that is safe and appropriate for the intended useshould be selected, ideally a biomaterial.
3. Layer Thickness: The layer thickness should be small enough to produce a smoothsurface but not so thin that the print is weak and prone to breakage. A commonlayer thickness for biomedical and biomimetic applications is 0.1-0.2mm for the FFFtechnology
4. Print Resolution: High-resolution prints produce better details and improvedaccuracy. Using a 3D printer with a high resolution capability should be consideredto produce the best results.
5. Post-Processing: Depending on the intended use, it may be necessary to performpost-processing techniques such as sanding or polishing to improve the surfacefinish and accuracy, especially if surface of a product will be in touch with humanbody parts.
6. Sterilization: If the 3D print is intended for use in a medical setting, or for peoplewith special needs (e.g. immunocompromised) it must be sterilized to eliminateany potential contaminants or microbes.
7. Quality Control: Quality control checks before using the 3D print in a medicalsetting must be performed, to ensure that it meets the necessary standards and specifications.
8. Legal Considerations: It is important to consider any legal or regulatoryconsiderations when 3D printing anatomical shapes. This may include obtainingnecessary certifications and complying with applicable regulations

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In terms of guidelines for design of 3D printed parts, there are also plenty of things to consider, when switching from conventional manufacturing technologies into 3D printing, mostly regarding easier post processing, strength and usability of fabricated parts. Many guidelines are available in the community of 3D printing professionals, an example is shown in Fig. 2.18.

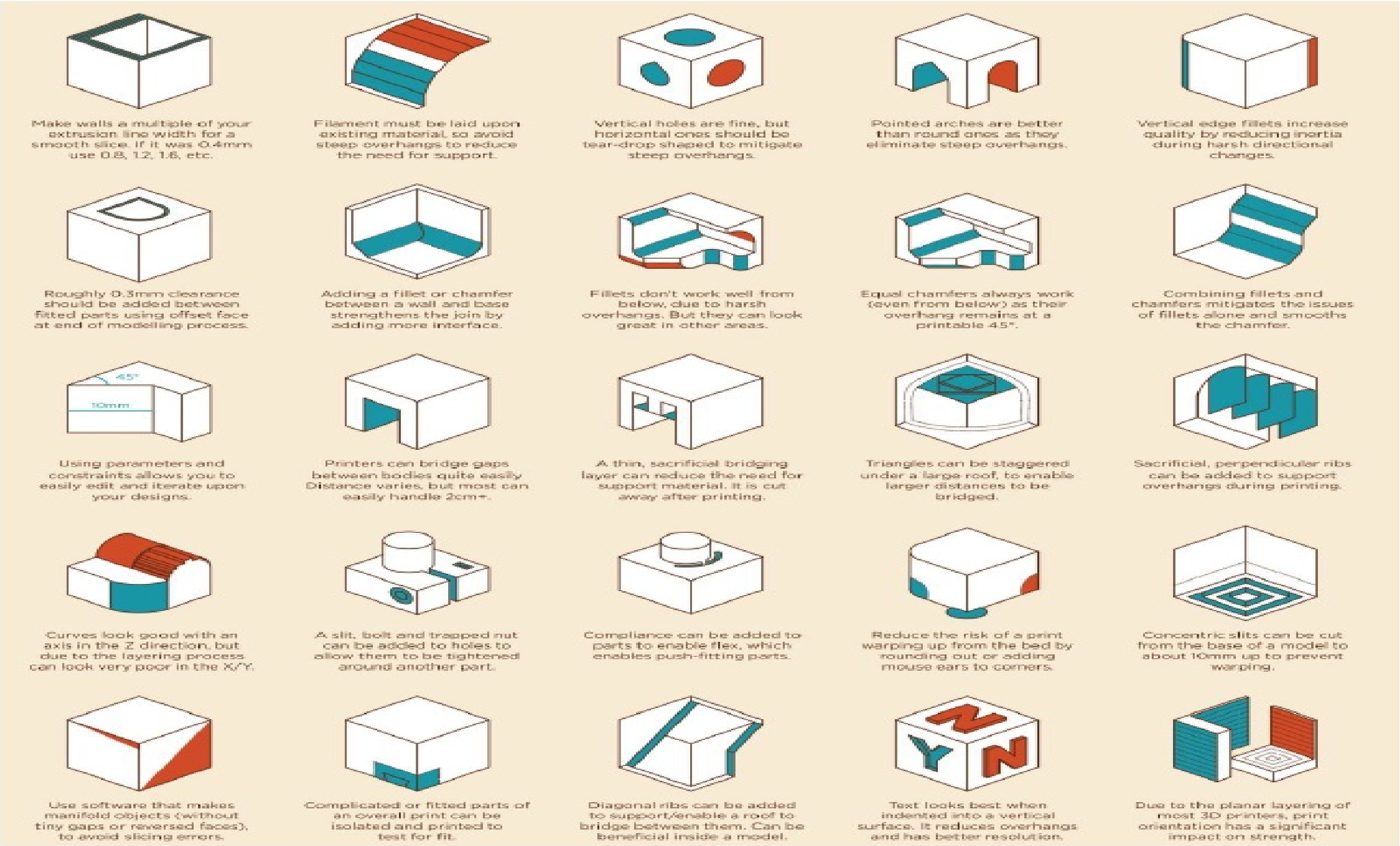

Figure 2.18. Example of guidelines for design for 3D printing [17]

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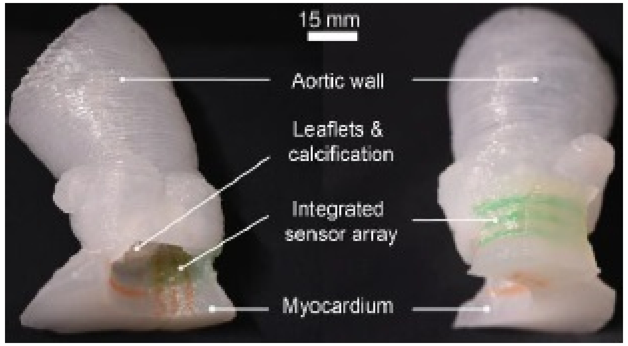
3.Examples of 3D printed biomimetic devices

3.1 Review of applications of 3D printing for biomimetic devices

Figure 3.1. 3D Printed knee personalized implant versus traditional implant [18]

1.Artificial Joints: 3D printing is increasingly used to produce customized artificialjoints, such as hip and knee replacements, with shapes and structures that mimicthe natural anatomy (Fig. 3.1).

2.Heart Valves: 3D printing has been used to produce heart valves with structuresand materials that mimic the natural anatomy, offering improved functionality andpersonalization. For example, researchers at Minnesota University created patient-specific model, which includes the anatomy of the damaged leaflets of the aorticvalve, where the replacement valve will be inserted



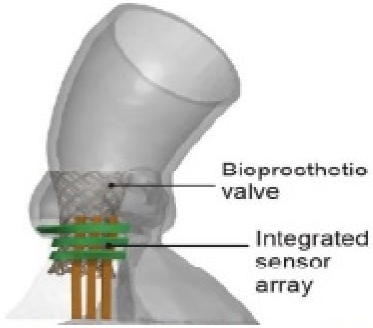


Fig. 3.2. 3D-printed model of a patient's aortic region [19]

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3.Skin Tissue: Researchers have developed 3D printed skin tissue that mimics thestructure and function of natural skin, offering a promising solution for burn victimsand people with skin conditions .

4.Bones: 3D printing has been used to produce customized bones for use in medicalprocedures. The 3D printed bonesmimic the structure and mechanical properties of natural bone, e.g. by infusing them with antibiotics (Fig. 3.3)

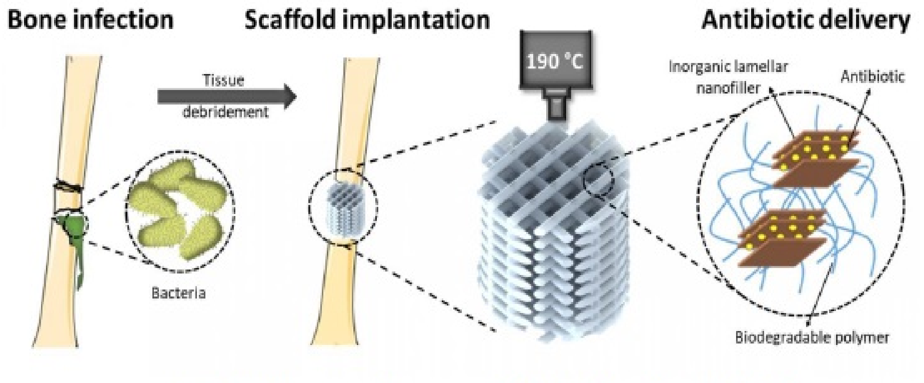

Fig. 3.3. 3D-printed bone scaffold with antibiotics [21]

5.Cartilage: Researchers have developed 3D printed cartilage that mimics thestructure and function of natural cartilage, offering a promising solution for people with conditions such as osteoarthritis (Fig. 3.4)

6.Blood Vessels: 3D printing has been used to produce functional blood vessels witha structure that mimics the natural anatomy, offering a promising solution forpatients with cardiovascular disease

7.Prosthetic Feet: 3D printing has been used to produce prosthetic feet withstructures that mimic the natural anatomy, offering improved balance and stability for users

8.Orthoses: 3D printing has been used to produce customized orthoses that mimicthe shape and structure of the body, offering improved comfort and functioncompared to traditional equipment, often by implementation of mechatronicsolutions [25].

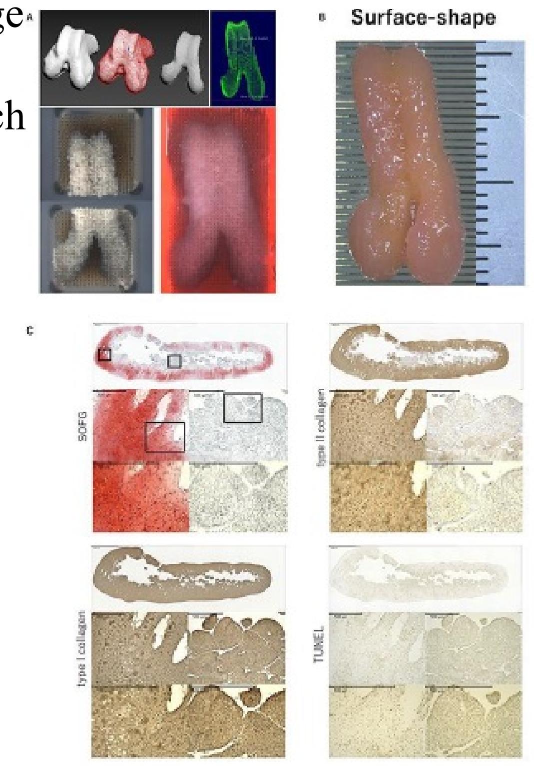

Fig. 3.4. Bio-3D printer design data and images of the articular surface-shape construct of cartilage tissue [22].

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3.2 Biomimetic example – therapeutic wrist hand orthosis

As a custom example of 3D printed product for people with deficits, a hand orthosis intended for realization of therapeutic and rehabilitation purposes will be described in this chapter. It can be used for wrist joint stabilization in time after an injury (fracture) or for patients with conditions that require stabilization, as rheumatoid arthritis, muscle atrophy and many others. It can be 3D printed using one of the basic FDM technology materials: PLA, ABS, PET-G and PA-12 (nylon), of which PLA and PA-12 are recommended due to proper combination of mechanical and processing properties. Shape of the orthosis is shown in Fig. 3.5. The first stage of the process of additive manufacturing of the orthosis in the FDM technology was the import of 3D models of the STL files to the selected slicer software in order to create instructions for the device in the form of a G-code file.

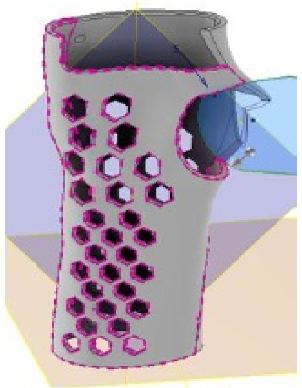

Figure 3.5. Shape of the wrist hand therapeutic orthosis

Figure 3.7. 3D printed test orthoses, PLA (left) and TPU (right)

Processes for both materials were executed using similar parameters. Layer thickness of 0,25 mm was used and 30% of internal filling was applied with default pattern. 3D printing of PLA took approximately 4 hours per one part of the orthosis, with TPU taking above 7 hours. First printouts were not subjected to full post-processing, as they were only intended to check

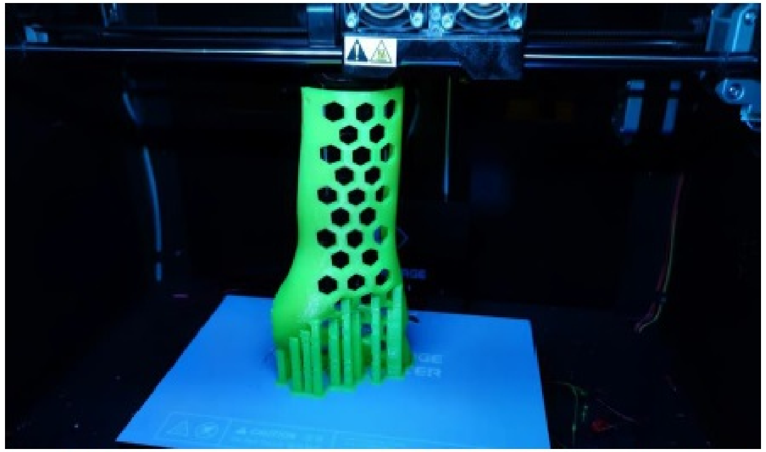

Figure 3.6. 3D printed orthosis (single part) in the machine chamber

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Improved final version of the orthosis was 3D printed only of PLA material, in a similar time, approximately 8 hours of continuous printing for both parts (one after another). Full post processing was applied, consisting of the following activities:

•removal of support,
•manual grinding, removing sharp edges,
•lining the orthosis with the EVA medical foam in specific places – mostly aroundthe edges but also in locations where corrective shape of the orthosis would makeit squeeze patient’s muscle tissue.

Figure 3.8. Tests of orthoses with the patient

The orthosis was evaluated as usable and helpful in therapy. Olso, orthoses for other patients with similar condition were made. The orthosis produced in this way is equal to, and in many respects even better than typical solutions. The first key aspect here is individualization, the 3D printed one described here is precisely adapted to the human body, which increases its rehabilitation effectiveness. Another important feature is the very short production time - only a week passed from the start of measurements to the first tests of the device by the patient. It also translates to reduction of costs.

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4.Summary

In this e-learning module, 3D printing technologies were presented. Basic concepts, ideas and principles were described, along with context of biomedical applications, especially having in mind the main topic of the EMERALD project, which is production of biomimetic mechatronic devices using 3D printing. The performed review of processes and applications prove that it is fully justified to use the additive technology as means of fabrication of usable, anatomically personalized (biomimetic) devices for people with disabilities or other special needs.

Basic knowledge contained in this module, along with knowledge on CAD, computer programming and biomechatronics should allow the learner to get acquainted with basic set of technologies necessary in the work of modern biomedical engineer, dealing with design and production of customized mechatronic medical devices.

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