Prototype of hand prosthesis components manufactured with biocompatible material using PolyJet Matrix technology

Prototyp elementów protezy dłoni wykonanych z biokompatybilnego materiału z zastosowaniem techniki PolyJet Matrix

PAWEŁ SZCZYGIEŁ *

DOI: https://doi.org/10.17814/mechanik.2022.7.10

This paper presents a procedure for developing a components of the hand prosthesis using reverse engineering. The hand model was obtained using a plaster cast and a 3D scanner. The 3D model of the prosthesis was remodelled using selected CAD software. The prosthesis was made of MED610 polymer material using PolyJet Matrix (PJM) technology. The MED610 material was chosen for its biocompatible properties. The printed model of the finger prosthesis was subjected to a bending test.
KEYWORDS: MED610, PJM, 3D printing, prosthesis, reverse engineering

W artykule przedstawiono procedurę projektowania elementów protezy dłoni z wykorzystaniem inżynierii odwrotnej. Modele dłoni odwzorowano w postaci odlewów gipsowych. Korzystając ze skanera 3D otrzymano chmurę punktów, którą przekonwertowano do pliku STL. Model 3D protezy przebudowano w oprogramowaniu CAD. Protezę wykonano z materiału polimerowego MED610 z zastosowaniem technologii PolyJet Matrix (PJM). Materiał MED610 został wybrany ze względu na biokompatybilne właściwości. Wydrukowany model protezy poddano próbie zginania.
SŁOWA KLUCZOWE: MED610, PJM, druk 3D, proteza, inżynieria odwrotna

Introduction

Currently, manufacturing companies are adopting additive manufacturing due to their flexibility and product customization, combined with non-dramatic increases in per unit cost [1]. The components obtained through 3D printing technology are characterised by high anisotropy [2–4].

3D printing techniques offer medical applications in many areas such as neurosurgery, cardiovascular, orthopaedic, dentistry and pharmaceutic [5]. The FDM (Fused Deposition Modelling) technology is used for the manufacture of parts coming into contact with skin, food and medicines (Acrylonitrile-butadiene-styrene), also in field of pharmaceutical industry, biomedical engineering (Polycarbonate), dental implants, surgical sutures (Polylactide), surgical and dental instruments (Polyetherimide, Polyetheretherketone). The Polyjet technique has been applied in area of dentistry, orthodontic laboratories (Acrylic resins e.g. VeroDent MED670) such as the Selective Laser Sintering (SLS) technology (Polyamide e.g. PA 2105). The Stereolithography (SLA) is used to produce precise surgical measures and dental models (Acrylic resins e.g. Accura ClearVue). The Selective laser melting (SLM) is used to produce implants (titanium alloy) [6]. The Digital Light Processing technology serves to produce prosthetic models, gingival masks, surgical templates, orthodontic model (Acrylic resins e.g. 3Delta Model 320) [7]. The 3D printing has found applications in limb fracture imaging, preoperative planning [8] and drug formulation, which is becoming a novel approach for many patients since it brings the manufacturing close to them and offers individualization of therapy [9].

Polyjet printing is achieved utilizing state-of-the-art, layer-by-layer, extrusion of photo-polymer materials in ultrathin layers of 16 μm on a build-in tray before the model is finished. Each photopolymer layer is cured by UV light directly after it has been injected, providing completely cured versions that can be treated and used immediately without post curing [10]. Models made with PolyJet technology use additional material for support structures. They are formed by a separate group of heads, which can be removed using pressure washers, solutions or mechanical separation using water.

This paper undertook to produce a model of a prosthesis by interdisciplinary involvement of reverse engineering and 3D printing. The earliest prosthesis were found come from ancient age [11]. One of the earliest written references to prosthetic were found in a book from XVI century. The author designed functional limb prosthesis [12]. The art of prosthesis design was in its golden age after the First World War [13]. Each of these cases arose out of the need to restore the body to its functionality. Moreover, the people of the ancient era believed that without a limb, they would also live without it in the afterlife. During designing a prosthesis, three most important factors can be determined: the functionality, the appearance and the comfort of use. These aspects has largely influence the acceptance of the prosthesis. A group of respondents in 2009

* Mgr inż. Paweł Szczygieł – pszczygiel@tu.kielce.pl, 0000-0002-3113-3557 – Faculty of Mechatronics and Mechanical Engineering, Kielce Univeristy of Technology, Kielce, Poland

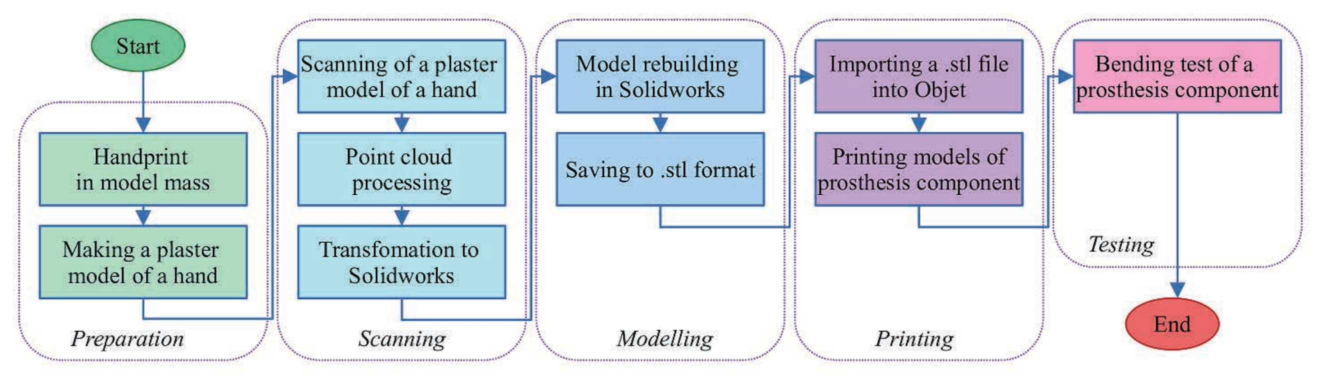

Fig. 1. Adopted scheme

showed that only 55% of prostheses users wear them regularly. The rest of the group indicated that the lack of full acceptance was due to one of the three factors mentioned [14].

This paper describes the method of prosthesis preparation *via* reverse engineering produced with 3D printing technology of Polyjet Matrix made of MED610 photo-curable material.

The first research results were presented during the 4th scientific conference Rapid Prototyping on 23 September 2021 in Rzeszów (Poland). The article is an extension of this research presented under the title "Analysis of the possibility of using the MED610 photocurable resin for 3D printing of hand prosthesis components" [15].

Materials and Methods

The prosthesis was made by following the diagram shown in Fig. 1. This scheme includes in successive stages: preparation, scanning, modelling, printing and testing. The model was rebuilt using SolidWorks (Dassault Systemes SolidWorks Corp., Waltham, MA, USA) software and saved in STL format. The STL file was placed in Objet Studio. The components of the prosthesis were printed using a machine Connex 350 (Stratasys corp. Rehovot. Israel).

Preparation

The manufacture of the hand prosthesis elements was initiated by a patient who, as a result of an accident at work, had four fingers severed. The fingers were sewn to the hand but only one survived intact. The other fingers got necrosis and were shortened. The left hand suffered an accident.

In Fig. 2*b* the patient's hand bone structure is shown. The handprint models of right and left hand were made using commercially available chromatic alginate which is intended for taking impressions. The mass for duplicating body parts is a mass of natural origin created from plants and is therefore completely non-toxic. The plaster models (Fig. 3) were made using synthetic, modelling gypsum in grey colour which filled the impressions. It is used in dental laboratories for making models but due to its properties and high hardness it is perfect for casting figurines, casts, stuccoworks.

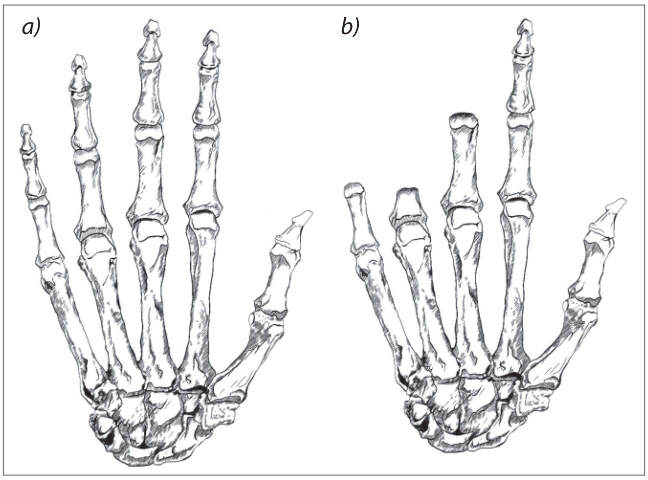

Fig. 2. The skeletal system of patient left hand of: *a*) before the accident and *b*) after the accident

Fig. 3. The plaster models

A plaster cast of the right hand was used to reproduce a prosthetic of the left hand finger. Using the right hand to reconstruct the prosthesis will contribute to the owner's acceptance of the prosthesis. Personalisation in this case not only includes wearing comfort and fit, but the prosthesis was also designed to the shape of the owner's hand.

Scanning

The plaster models of the hands were scanned (Fig. 4) using a machine Atos II (GOM. Braunschweig. Germany). Reference points were pasted on the scanned items. The obtained point clouds were subjected to polygonisation (Fig. 5) using GOM Professional software (GOM. Braunschweig. Germany). The scan of the right hand model was mirrored. This allows it to be used for reconstruction of missing left hand parts. The little finger was then isolated from the resulting model, saved as STL file and transferred to Solidworks as a solid object (Fig. 6).

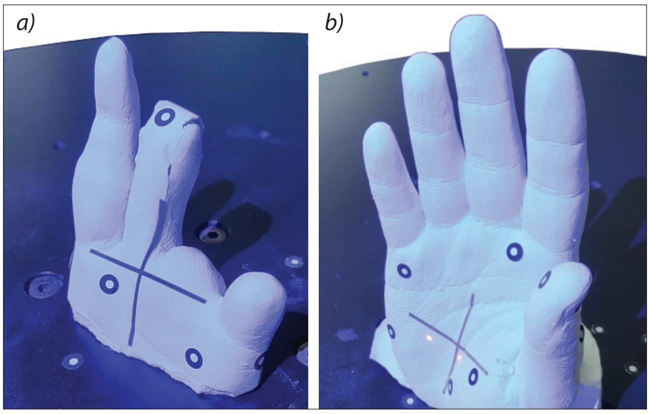

Fig. 4. Scanning the model of: *a)* damaged left hand and *b)* right hand

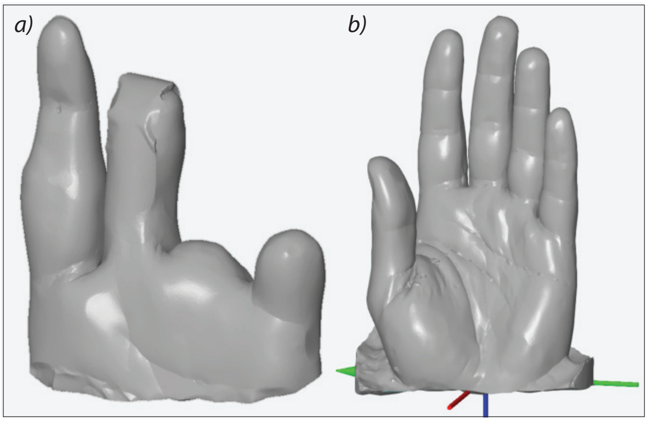

Fig. 5. Poligonised model of: *a)* damaged left hand and *b)* mirrored right hand

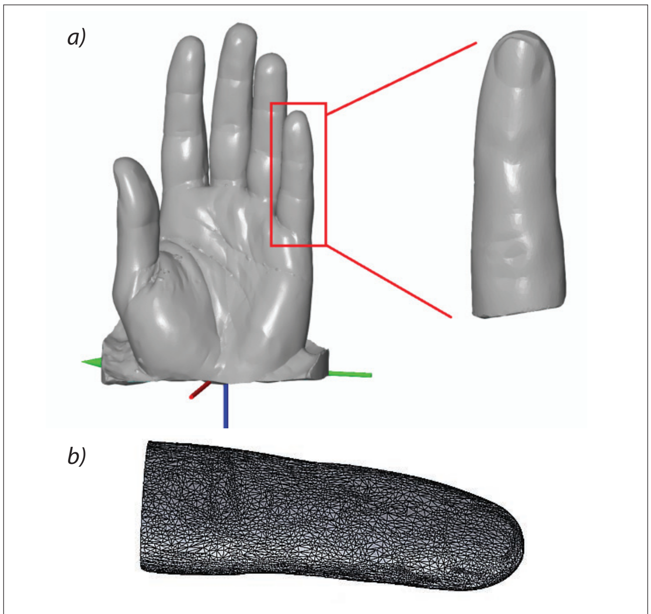

Fig. 6. Little finger in: *a)* GOM Professional, *b)* SolidWorks

Modelling

Solidworks software was used to rebuild the solid model of the little finger. A simple sleeve shape was used at the base of the little finger, which will be used to apply the prosthesis as an overlay (Fig. 7). The model was exported in STL file format. The dimensions of the sleeve ensure that the prosthesis fits the stump of the little finger. The stump was dimensioned using GOM Professional software.

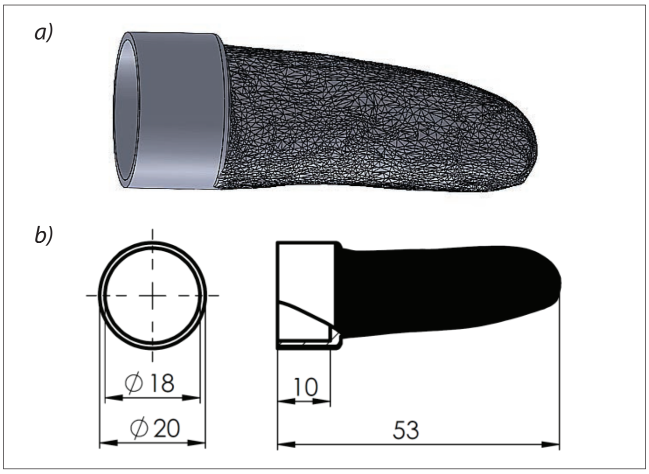

Fig. 7. Rebuilt model of the little finger: *a)* Solidworks part, *b)* little finger dimensions

Printing

The STL files of the models of the little finger and test samples were placed in Objet Studio on the virtual work of the Connex 350 printer. The printout was made in high quality mode. The printing time of one finger is 1.5 h. The output of the main material (MED610) of one finger is 19 g and the output of the support material (FullCure 705) is 17.3 g. All printed parts were placed on a virtual work platform in Objet (Fig. 8).

The MED610 (Stratasys corp. Rehovot, Izrael) material was used in the printing process. MED610 is a biocompatible material used in PolyJet printing technology for medical and dental applications. The manufacturer states that the material may remain permanently in

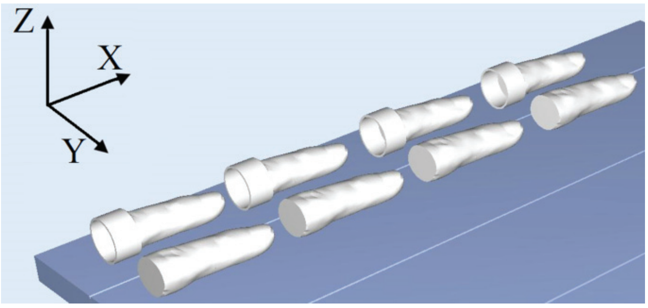

Fig. 8. Arrangement on the work platform

contact with the skin more than 30 days and for a limited time in contact with the oral mucous membrane (up to 24 h). The characteristics of the material are included in Table I. The printout parameters of the build tray are shown in Table II. The printouts are shown in Fig. 9.

TABLE I. Properties and chemical composition of MED610 material [16, 17]

Properties		
Property	Standard	Value
Tensile strength	D-638-03	50÷65 MPa
Ultimate elongation	D-638-05	10÷25%
Young's modulus	D-638-04	2000÷3000 MPa
Bending strength	D-790-03	75÷110 MPa
Modulus of elasticity in bending	D-790-04	2200÷3200 MPa
Poisson ratio*	ASTM D638-10	0.41
Deflection temperature (under load of 0.46 MPa)	D-648-06	45÷50°C
Water absorption	D-570-98 24HR	1.1÷1.5%
Shore hardness	D Scale	83÷85 D
Rockwell hardness	M Scale	73÷76 M
Biocompatibility	PN-EN ISO 10993-1:2017	Skin contact: permanent Contact with mucous membrane: up to 24 hours
Chemical composition		
Component	% of weights	
Isbornyl acrylate	15÷30	
Acrylic monomer	15÷30	
Urethane acrylate	10÷30	
Acrylic monomer	5÷10; 10÷15	
Epoxy acrylate	5÷10; 10÷15	
Arylate oligomer	5÷10; 10÷15	
Photoinitiator	0.1÷1; 1÷2	

* Note: The Poisson ratio value was obtained by e-mail from Stratasys at the author request.

TABLE II. Printout parameters

Printing time	Consumption of model material MED610	Consumption of support material FullCure705	Print mode
2 h 50 min	122 g	89 g	High Quality

Testing

The Inspekt Mini strength testing machine from Hegewald and Peschke MPT GmbH with the LabMaster software (Hegewald and Peschke, Nossen, Germany) was used to perform test at the maximum load of 3 kN. The bending test of the finger is shown in Fig. 9.

The printed little finger only deflected by just over 2.5 mm at a force of 2900 N (Fig. 11). It should be noted that the applied pressure was quasi-perpendicular to the surface of the stacked print layers, when the best strength results are achieved. Due to the limited measurement range of the testing machine, only a small fragment of the bending diagram of the little finger can be observed.

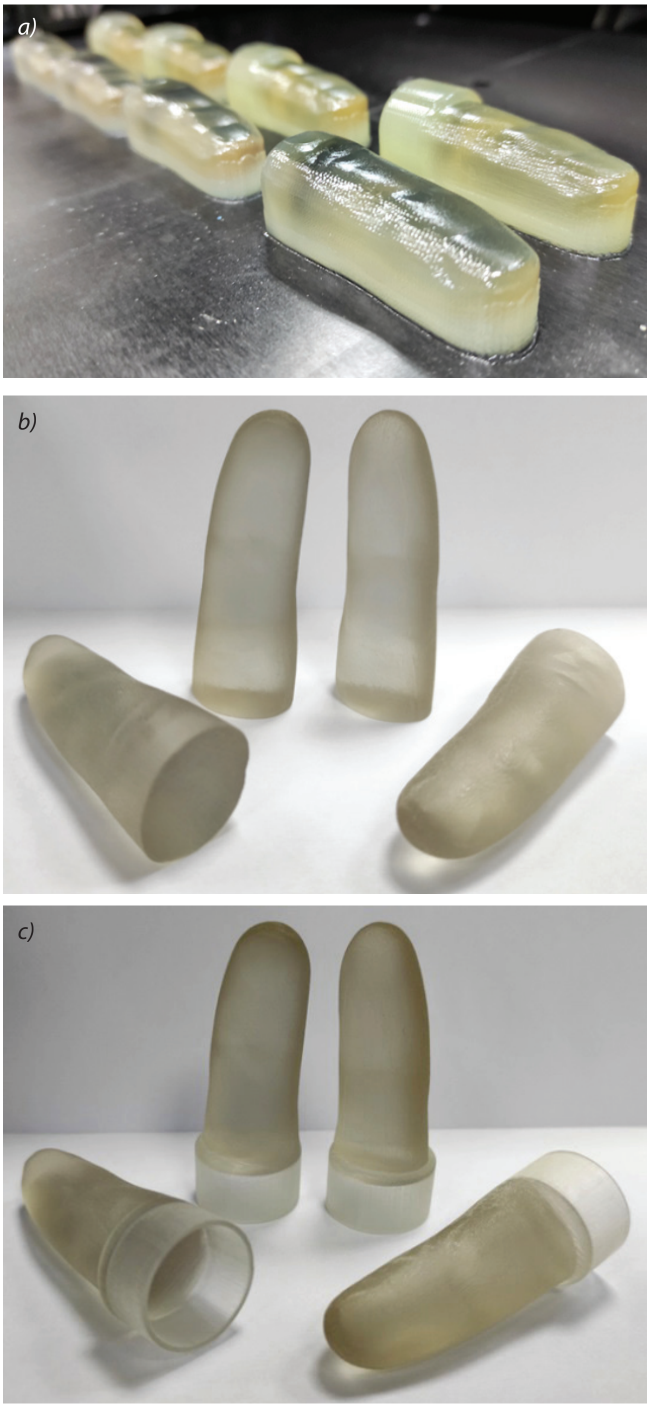

Fig. 9. Printout: *a)* before removing support material, *b)* cleaned fingers, *c)* cleaned fingers with sleeve

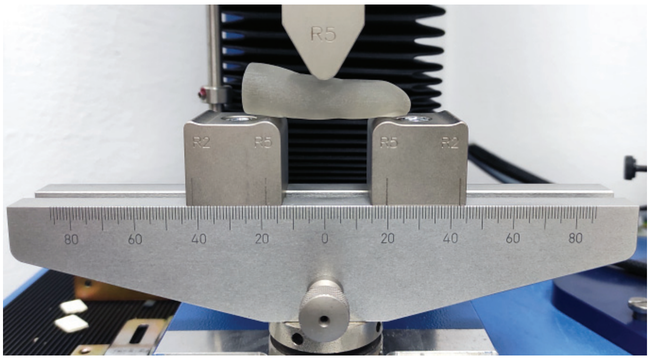

Fig. 10. The position of the finger during bending test

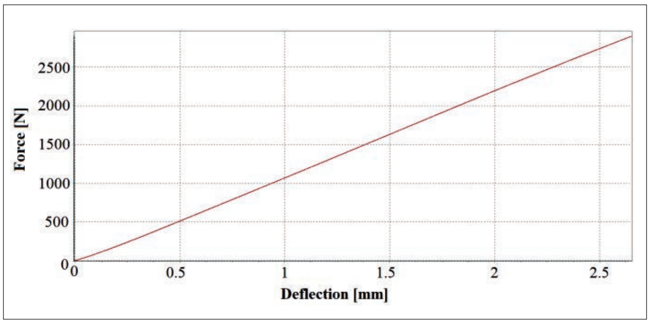

Fig. 11. Bending chart force-deflection

Conclusions

The performed procedure of making models of prosthetic elements indicates the possibility of using MED610 material for this purpose. The first stage, i.e. mapping and making a plaster model of the hand, is of significance as it does not expose the patient to direct scanning operations. The processing of the obtained point cloud and the subsequent reconstruction of the model with the SolidWorks programme also enables further work on the remaining elements of the prosthesis. High strength of the material and transfer of a high bending force by the model encourage further reconstruction works improving the functionality of the prosthesis.

The applied solution favourably influences the acceptance of the prosthesis by the disabled person due to the fact that it was designed on the basis of the owner's body.

References

[1] Verna E., Maisano D.A. "A benchmark analysis of the quality of distributed additive manufacturing centers". *Int. J. Qual. Reliab. Manag.* 39, 6 (2022): 1488–1505, https://doi.org/10.1108/IJQRM-07-2021-0214/FULL/XML.

[2] Mehdipour F., Gebhardt U., Kästner M. "Anisotropic and rate-dependent mechanical properties of 3D printed polyamide 12 – A comparison between selective laser sintering and multi jet fusion". *Results Mater.* 11 (2021): 100213, https://doi.org/10.1016/j.rinma.2021.100213.

[3] Kozior T., Bochnia J., Gogolewski D., Zmarzły P., Rudnik M., Szot W., Szczygieł P., Musiałek M. "Analysis of Metrological Quality and Mechanical Properties of Models Manufactured with Photo-Curing PolyJet Matrix Technology for Medical Applications". *Polym.* 14 (2022): 408-2022, https://doi.org/10.3390/POLYM14030408.

[4] Kozior T., Bochnia J. "The Influence of Printing Orientation on Surface Texture Parameters in Powder Bed Fusion Technology with 316L Steel". *Micromachines*. 11 (2020): 639, https://doi.org/10.3390/MI11070639.

[5] Kholgh Eshkalak S., Rezvani Ghomi E., Dai Y., Choudhury D., Ramakrishna S. "The role of three-dimensional printing in healthcare and medicine". *Mater. Des*. 194 (2020): 108940, https://doi.org/10.1016/J.MATDES.2020.108940.

[6] Gogolewski D., Kozior T., Zmarzły P., Mathia T.G. "Morphology of models manufactured by SLM technology and the Ti6Al4V titanium alloy designed for medical applications". *Materials* (Basel). 14 (2021): 6249, https://doi.org/10.3390/MA14216249.

[7] Turek P., Budzik G., Oleksy M., Bulanda K. "Polymer materials used in medicine processed by additive techniques". *Polymers*. 65 (2020): 510–515, https://doi.org/10.14314/POLIMERY.2020.7.2.

[8] Hovis J.P., Ahlers C.G., Dilbone E.S., Pennings J.S., Henry A.L., Gauger E.M., Desai M.J., Lee D.H. "Efficacy of utilizing 3D printed models for preoperative surgical planning of open reduction, internal fixation of distal humerus fractures". *Ann. 3D Print. Med.* 5 (2022), https://doi.org/10.1016/J.STLM.2022.100047.

[9] Mohammed A.A., Algahtani M.S., Ahmad M.Z., Ahmad J., Kotta S. "3D Printing in medicine: Technology overview and drug delivery applications". *Ann. 3D Print. Med.* 4 (2021), https://doi.org/10.1016/J.STLM.2021.100037.

[10] Antoniou P.E., Bamidis P.D. "3D printing and virtual and augmented reality in medicine and surgery: tackling the content development barrier through co-creative approaches". *3D Print. Appl. Med. Surg.* 2 (2022): 77–99, https://doi.org/10.1016/B978-0-323-66193-5.00004-6.

[11] Nerlich A.G., Zink A., Szeimies U., Hagedorn H.G. "Ancient Egyptian prosthesis of the big toe". *Lancet*. 356 (2000): 2176–2179, https://doi.org/10.1016/S0140-6736(00)03507-8.

[12] Hernigou P. "Ambroise Paré IV: The early history of artificial limbs (from robotic to prostheses)". *Int. Orthop.* 37 (2013): 1195–1197, https://doi.org/10.1007/S00264-013-1884-7.

[13] Biernoff S. "The Rhetoric of Disfigurement in First World War Britain". *Soc. Hist. Med.* 24 (2011), https://doi.org/10.1093/SHM/HKQ095.

[14] Biddiss E. "Need-Directed Design of Prostheses and Enabling Resources. Amputation, Prosthes. Use, phantom limb pain an interdiscip". *Perspect.* (2009): 7–21, https://doi.org/10.1007/978-0-387-87462-3_2.

[15] Bochnia J., Szczygieł P. "Analiza możliwości zastosowania żywicy fotoutwardzalnej MED610 do wykonania technologią druku 3D elementów protezy dłoni". *Materiały Konferencyjne – IV Krajowa Konferencja Naukowa Szybkie Prototypowanie*. (2021): 20.

[16] Stratasys MSDS Clear Bio-Compatible MED610. Available online: https://www.sys-uk.com/wp-content/uploads/2016/01/MSDS-Clear-Bio-Compatible-MED610-English-US-1.pdf (access: 15 March 2022).

[17] Stratasys Biocompatible Clear MED610. Available online: https://cadxpert.pl/wp-content/uploads/2019/03/spec_PolyJet_ MED610_MED620.pdf (access: 15 March 2022).