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3D printing: clinical applications in orthopaedics and traumatology

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- Advances in image processing have led to the clinical use of 3D printing technology, giving the surgeon a realistic physical model of the anatomy upon which he or she will operate.
- Relying on CT images, the surgeon creates a virtual 3D model of the target anatomy from a series of bi-dimensional images, translating the information contained in CT images into a more usable format.
- 3D printed models can play a central role in surgical planning and in the training of novice surgeons, as well as reducing the rate of re-operation.

Keywords: 3D printing; orthopaedics; traumatology; 3D reconstruction; image segmentation; patient-specific model

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Introduction

Surgical planning has gone through many different stages in the evolutionary history of modern medicine, moving simultaneously with the progression of the available technologies for diagnostic imaging. From the simple radiographs of the early 1900s, we arrived at modern acquisition systems such as computed tomography (CT) and magnetic resonance imaging (MRI) which provide the surgeon with detailed reconstructions of the patient anatomy, in combination with advances in image processing. Today, thanks to 3D printing (3DP) technology, we can make a further step, moving from the virtual world to the physical one.

Although 3DP was born in the mid-1980s, only in recent years has it started to become widely known in both surgical and non-surgical worlds. 3DP is based on an additive manufacturing (AM) process that can realise objects by adding material layer by layer, rather than by subtraction from the raw material as is the case with conventional technologies. 3DP has recently been defined as the third industrial revolution; this definition seems to be particularly suitable in relation to the huge number of possibilities offered by this technology in various fields, including the medical one. To date, 3DP has begun to have an emerging role in some medical fields, such as dentistry, orthopaedics and traumatology. Its great success in these fields stems from the ease of medical image processing as it mainly involves bone structures, offering clear visiblity and contrast. The segmentation process that allows translation from medical images to the virtual model consists of extracting the specific structure in each layer of the image dataset. Once this process is completed, the final model is exported to a suitable format for 3DP and prototyped. At the end of a post-processing phase articulated according to the specific production technology, it is possible to provide a replica of the anatomy of interest. Parenchymatous organs, such as in the abdomen, are much less contrasted and with very low differences between the various structures. For this reason, unlike bones or vascular contrasted structures, the algorithms that perform automatic segmentation or contrast-based projections are not sufficient to improve the presentation of clinical data.

The advent of minimally-invasive techniques such as laparoscopic surgery, or - more recently - robotics, have completely changed surgeons' approach to intervention. There is a need for greater understanding of the specific anatomy in order to plan not only the various phases of the intervention, but also the access of surgical instruments. For this reason, it is necessary to provide surgeons with facilities that allow them to properly investigate the clinical situation. Moreover, in the orthopaedic or traumatology fields it is possible to let the surgeon test in advance the specific procedure on a 3D printed model, applying screws or plates, or testing the drilling path.

In current clinical practice, however, medical images such as CT and MRI, or in some cases, projections or 3D reconstructions, are normally used as essential support for pre-operative planning. 3D printed models are useful for transferring information to the surgeon in a more informative way and allow for improved, more detailed surgical planning. They can help to illustrate intervention procedures to novice surgeons and patients, and can be useful for testing the procedure on patient-specific (PS) anatomy through the use of printing materials able to resemble the mechanical properties of bone.

Materials and methods

Image analysis

The first step in the generation of a PS model is the extraction of the target geometry from medical images. This image segmentation process partitions an image area or volume into non-overlapping, connected regions, homogeneous with respect to certain signal characteristics.[1]

The main objective is to reduce the complexity of the original image, leaving a comprehensive representation of the characteristics of interest. The level of partitioning of the image depends on the complexity of the problem being faced. The segmentation should end when the object of interest has been located. From a practical point of view, the segmentation of a picture consists of assigning to each pixel a label, which establishes the membership of a particular group. Many segmentation algorithms can be found in the literature, classified in various ways, but none of them can be applied without substantial modifications to the anatomical area in question, so the choice of appropriate method depends on the nature of the matter.[2,3]

In relation to our goals, we can divide the segmentation procedures in to the following categories:

a) manual, where the outline of the image portion to be assigned a specific label must be drawn by hand;
b) automatic, where the algorithm automatically divides the image into regions that show similar characteristics within these areas, and differ from one region to the other for the same characteristics, and
c) semi-automatic, which represents a compromise between the two previous techniques.

This last approach requires a modest interaction with the user, who is asked to set some parameters to control the evolution of the algorithm. Modern multi-detector computed tomography (MDCT) equipment is able to provide up to several hundred images for each phase: thus, a manual approach is not compatible with the quantity of images to be processed. Moreover, it is also highly operator-dependent. Automatic segmentation systems have been developed for different anatomical regions, such as bones, liver and colon. These structures are characterised by greater homogeneity on the radiological image, but the algorithm is based on several assumptions that sometimes limit the range of applications. Semi-automatic algorithms seem to be the best option, since they require limited interaction with the user, yet they are more flexible and thus can be applied in a variety of clinical situations.

Within all the three cited categories, many types of algorithm are listed (see survey of the different techniques typically applied to medical images).[4-6] Many different commercial software programmes allow medical image segmentation.[7-11] In order to give an overview of the process, we will take as an example the image segmentation performed using the commercial software, ITK-Snap[12] (Philadelphia, PA). The software implements a semi-automatic procedure based on a simple region-growing algorithm. The segmentation process of each structure begins from the definition of a grey level window including all the grey shades of the structure of interest. The second step is to define one or more starting points on the images; the spherical surfaces from which the algorithm will start its evolution. The algorithm develops within and through each MDCT slice, until the user stops its evolution. If the structure is well-contrasted with respect to its surroundings, the user can also allow the algorithm to evolve until the region identified will not evolve any further. The evolution is based on various parameters, including: a) an expansion factor which controls the forces acting inwards and outwards upon the segmentation surface; and b) a curvature factor that controls how the 3D surface is able to lose its sphericity and adapt to the details of the image. When the algorithm has completed its evolution, the resulting label set is rendered to achieve a 3D surface. The virtual model is navigable and the user can interact with it, changing the transparency or colour of each structure in the 3D rendering, as well as providing a detailed view of the interaction among the different anatomical structures. The next step is to move to a suitable format for successive 3DP purposes.

The worldwide accepted standard for 3DP is the standard triangulation language (STL) file. An STL file outlines the geometrical representation of the object through a mesh (for example a series of oriented triangles). The higher the number of oriented triangles, the better the object will be described in terms of surface quality. Depending on the specific clinical case, some additional post-processing on the final 3D virtual model may be necessary, such as surface smoothing, ensuring that clinical information is not compromised during this process.

3D prototyping

Additive manufacturing is the formalised term for what used to be called rapid prototyping (RP), and what is popularly called 3DP. The term RP is used in a variety of industries to describe a process for rapidly creating a system or part representation before final release or commercialisation.[13] Thus, from a technical point, 3DP is a subset of AM. A now-prevailing categorical view of AM processes was developed by the ASTM International Committee F42 using AM technologies.[14] The Committee was formed in 2009 and the current version of 3DP technologies classification was released in 2010. ASTM identified seven categories with more than 30 variations on the basic theme, each with its advantages and disadvantages.[15] In Table 1 an overview of process classes is presented, along with examples of leading

Table 1. Additive manufacturing: seven categories as identified by ASTM, with some examples of companies that provides the specific technology, compatible materials and field of application

Process	Ex. companies	Materials	Market
Vat photopolymerisation	3DSystems (USA), Envisiotec (Germany)	Photopolymeric	Prototyping
Material jetting	Objet (Israel), 3DSystems (USA), Solidscape (USA)	Polymers, waxes	Prototyping, casting patterns
Binder jetting	3DSystems (USA), Ex-One (USA), Voxelijet (Germany)	Polymers, metals, foundry sand	Prototyping, casting moulds, direct part
Material extrusion	Stratasys (USA), Bits from Bytes, RepRap	Polymers	Prototyping
Powder bed fusion	EOS (Germany), 3DSystems (USA), Arcam (Sweden)	Polymers, metals	Prototyping, direct part
Sheet lamination	Fabrisonic (USA), Mcor (Ireland)	Paper, metals	Prototyping, direct part
Direct energy deposition	Optomec (USA), POM (USA)	Metals	Repair, direct part

companies that produce machines for each process, typical materials classes and the most popular markets for use. Companies highly specialised in medical prototyping are a developing market.[16,17]

The first step to printing a PS model in 3D is the slicing process, which consists of cutting the virtual model into thin bi-dimensional layers, each layer equal in thickness. Each slice is then sent to the 3D printer which deploys the corresponding layer of material. The building plate then lowers to the same thickness of the layer, and the printer deploys a new layer. Printing technologies differ in the way layers are laid down and cured: each technology is characterised by a layer and in-plane resolution which affects the tolerance of the final printed object with respect to the virtual model. Since we are applying this technology to the medical field, the best option would be to use high-resolution printers, although they commonly have high costs. Depending on the specific application it is possible to choose between Stratasys FDM® (Eden Prairie, MN) or fused filament fabrication (FFF) technology, characterised by a low resolution (300-100 µm), or photopolymer or chalk-based printers (100-10 µm).

Applications

Orthopaedics and traumatology have been among the first medical fields to use 3DP technology to build PS models, along with maxillofacial surgery. This stems from the straightforward elaboration required by radiological images of the involved structures. Bone structures are well-contrasted with respect to the surrounding structures, thus they can be simply segmented from medical images using automatic or semi-automatic algorithms. Moreover, the advent of selective laser sintering (SLS), an AM technology able to process metal and ceramic powder, allowed the production of personalised prostheses, to be tailored to the specific geometry of each clinical case. The introduction of materials for 3D printers which can be sterilised also paved the way to the prototyping of personalised instrumentation for orthopaedic and traumatology surgery.

In Table 2, the presented applications and related bibliography are summarised.

Table 2. Summary of 3DP applications in traumatology and orthopaedics

Applications	References
PS models	
Orthopaedics	18-25
Traumatology	18, 26, 27
PS Implants and orthoses	
Implants	28, 29, 30-38
Biomaterials	39-42
Orthoses	43, 44
Personalised instrumentation	
Templates	45, 46
Surgical guides	47

PS models

The main goal of a 3D-printed PS model is to resemble the clinical case, in order to give a more detailed overview to the surgeon. The 3DP material also plays a central role, especially when the model can be used for the testing of the procedure in advance. Where bone models are concerned, chalk-based printers can be useful, since they are able to give the surgeon the feeling and the mechanical response of a real bone while drilling or applying screws or plates. Operations can also be made on plastic models in order to visualise the final outcome of the intervention.

In the following, key literature on the usage of 3DP will be presented, with a special focus on orthopaedics and traumatology applications.

Orthopaedics

Orthopaedic surgery can present considerable challenges in cases with extensive primary injuries with multiple bone fragmentation, as well as in those presenting bone deformities. Radiographs are used routinely for orthopaedic surgical planning, yet they provide inadequate information on the precise 3D extent of bone defects.[18-19] Examples of the application of 3DP within the orthopedic field have spread rapidly in the last few years and include the use of a 3DP model to assess the surgical approach for corrective osteotomies, in order to gain a more informative overview of the anatomy and to improve the detail of planning, especially in cases of minimally-invasive surgery. The approach has been employed in a case of forearm deformity (Fig. 1),[20] to plan a corrective osteotomy

Fig. 1 3DP model for planning the surgical correction of a forearm deformity.[20]

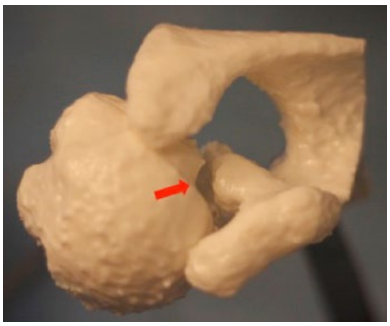

Fig. 2 3DP model of a right shoulder in external rotation with the Hill-Sachs lesion fully engaged.[22]

for cubitus varus[21] and in the treatment of recurrent anterior shoulder instability (Fig. 2).[22]

The availability of a 3D printed model can also be a fundamental aid in the placement of screws or surgical plates, mainly thanks to the possibility of testing in advance of the procedure; examples include pedicle screw placement in a clinical case of severe congenital scoliosis[23] or, more in general, applications to spinal surgery[24,25] with the aim of designing PS surgical guides.

Traumatology

3DP models can also aid the visualisation of traumatic situations, such as complex bone fragmentation. This is one of the most widely-used applications of 3DP to PS model prototyping. Orthopaedic surgeons at the Walter Reed Medical Center (Bethesda, MD) have developed models of the human knee using 3DP technologies. These models have been used for surgical procedures where a wound is near a nerve or arterial junction, with little tolerance for error.[26-27] Other examples include: a) shoulder models, to help design implants to correct fractures of the head of the humerus; b) hip models, which can act as an important treatment planning tool in complex cases to aid the chances of successful surgical outcome and long-term implant stability and to aid the design of custom-made acetabular sockets that fit into the remaining bone stock; and c) knee models to design a custom-made knee prosthesis that required fixation stems in an unusual configuration relative to the displaced tibial plateau.[18]

Maxillofacial surgery

One of the most established applications concerns maxillofacial/craniofacial surgery. Here, 3D printed models appear to be held in high regard. In many cases this type of surgery can take place over many years resulting in numerous operations to correct deformity. A superior treatment plan resulting from the use of medical models can lead to enhanced surgery with the prospect for better primary care and fewer follow-up procedures to correct for irregularities.[18]

Oncology

Tumour resection can benefit significantly from 3D printed models. An example is the resection of a cranial tumour.[28] The applied technique is based on a custom model of the tumour and surrounding skull, reconstructed from medical images from which the resection of the tumour and shape of the cranioplasty can be determined. The technique facilitated accurate surgical resection of the tumour and subsequent reconstruction. The surgeon reported several advantages of the technique including increased confidence, reduced operating time (by at least 60 minutes), excellent cosmetic results, accuracy and simplicity. The patient reported that the opportunity to see the 3D printed model improved their understanding of the procedure.[28] A model constructed to aid surgery in the case of a 6-year-old patient with a largescapular osteochondroma is also reported in Tam et al's 2012 paper.[29]

PS implants and orthoses

Another important field of application is the 3DP of PS prostheses thanks to the introduction of metal 3D printers based on powder bed fusion or direct energy deposition technology (Table 1). The possibility of building customised objects in stainless steel, titanium, ceramics or high-performance plastics like poly-ether-ether-ketone (PEEK) paved the way for the creation of customised prostheses. At present, many companies that produce metal prototypes also provide PS implants (for example, LayerWise (Leuven, Belgium).[30] Specialist orthopaedic companies are now also present in the market (such as Lima Corporate (Assago, Italy).[31] The prosthesis can be created using CAD software with the ability to design the product based directly on the virtual PS geometry retrieved from medical images (Fig. 3).

3DP is not only useful to tailor the prosthesis based on specific anatomy but also to recreate an exact surface finish or a controlled porosity able to aid osteointegration. 3D printed implants are reported in several clinical cases, like total hip arthroplasty[32] or total calcanectomy (Fig. 4).[33] They are also extensively used in maxillofacial surgery[34,35] and cranio-maxillofacial surgery.[36,37] Absorbable materials have been used to realise bone fixation implants.[38] The more recent introduction of biocompatible materials for RP allowed the production of grafts for bone reconstruction or the building of bio-scaffold, for tissue engineering. Biocompatible materials include metals, ceramics and polymers. Bioceramics such as hydroxyapatite are currently the preferred material for bone reconstruction.[39,40] Bone graft substitutes created in the use

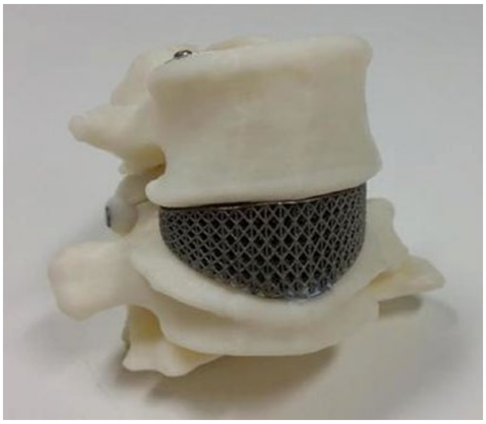

Fig. 3 Spinal implant cage for a case of severe back pain.[41]

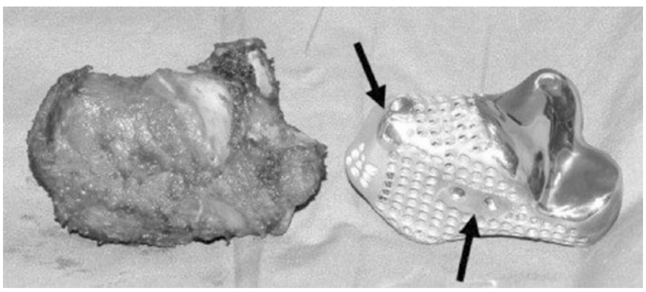

Fig. 4 3DP calcaneal prosthesis to replace a totally removed calcaneum.[33]

of 3D printed scaffolds are usually made from a composite of polycaprolactone (PCL), poly-lactic-co-glycolic acid (PLGA), and β-tricalcium phosphate (β-TCP). Improvements to the biological functionality of 3D-printed synthetic scaffolds have been attempted by ornamenting them with a cell-laid mineralised extracellular matrix (ECM) that mimics a bony microenvironment.[42] Metals like titanium can be used particularly in load-bearing areas, such as for hip reconstruction. Tissue engineering aims to aid in the repair and/or regeneration of bone defects by using a scaffold as a platform for carrying cells or therapeutic agents to the site of interest. An ideal scaffold aims to mimic the mechanical and biochemical properties of the native tissue. In order to effectively achieve these properties, a scaffold should have a suitable architecture favouring the flow of nutrients for cell growth. It should also have osteoconductive properties, supporting cells through a suitable surface chemistry.[43]

Another interesting application of 3DP is the realisation of PS orthoses; created using a reverse engineering approach based on 3D scanners, PS orthoses are able to capture the area of interest. This approach allows a seamless fitting to the patient's anatomy and optimisation in the selection of the design and materials. Personalised orthoses have been applied to ankle-foot complex motion restoration,[44] and for the healing of fractured limbs.[45]

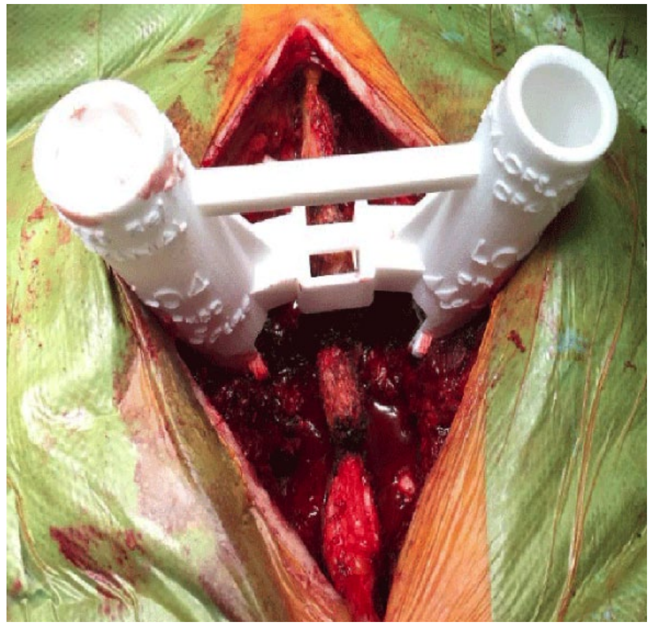

Fig. 5 Intra-operative placement of tubular guides for spinal neuronavigation.[48]

Personalised instrumentation

3DP plays also an important role in the design and production of personalised instruments and surgical guides, thanks to the availability of sterilisable and biocompatible printing materials. Orthopaedic surgery in particular benefits from this technique. Examples come from the creation of a personalised osteotomy template for the surgical treatment of cubitus varus deformity,[46] and for total knee arthroplasty and the prototyping of PS instruments during simulated pelvic bone tumour surgery.[47] Guides for pedicle screw placement have also been created through 3DP techniques[48] (Figs 5-7). The main benefit of this approach comes from the reduction of intra-operative time, since the surgeon has already planned the most suitable position of all the instruments before the intervention.

Conclusions

The use of physical models for treatment planning and visualisation, instead of the sole use of CT, MRI data or virtual reconstruction, has a number of distinct advantages. Software methods which give the illusion of 3D volumes on a 2D screen can cause problems regarding the viewing angle, depth, transparency and lighting anomalies that manifest as viewing orientation uncertainties.[18] Successful surgical correction of deformities such as of the hip joint before the onset of osteoarthritis requires the accurate characterisation of anatomical deviations as the first step in the planning of a corrective osteotomy. Pedicle screws inserted with a standard surgical technique have sometimes penetrated the outer bony wall or even missed the pedicle.[49] Complex anatomical

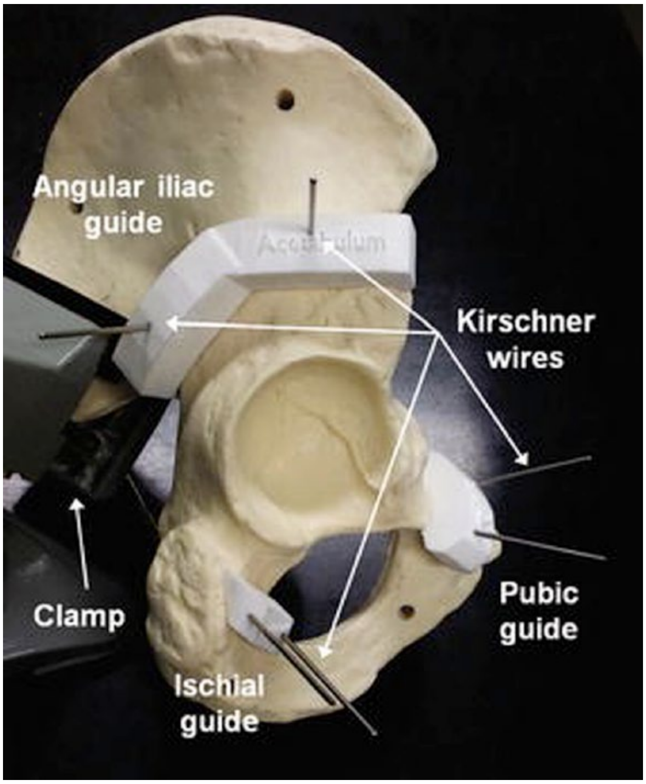

Fig. 6 PS surgical guides mounted on a PS pelvic bone model.[47]

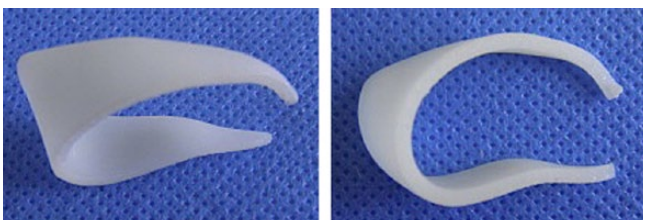

Fig. 7 Osteotomy template for surgical treatment of cubitus varus.[46]

relationships (bone fragments in the vicinity of fracture sites, for example) can be better appreciated on 3D solid models ‘in hand’. Touch seems to recalibrate the visual perception so that it is better able to infer depth from the retinal projection.[50] The sensory information exploited by the haptic system for the recognition of real objects is made by kinaesthetic and cutaneous inputs. While kinaesthetic inputs refer to the perception of the spatial configuration of the hand and fingers, the cutaneous inputs deal with the perception of the contact conditions between the human hand and the real object.[51] Vision and touch generate functionally overlapping, but not necessarily equivalent, representations of 3D shape. Within the orthopaedic and traumatology field, 3DP also enables advance testing of the surgical procedure; this possibility can lead to a better intervention outcome and a reduction of operation time. 3D-printed models can be a useful tool for the teaching and training of novice surgeons, improving the quality of training and the learning curve.

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REFERENCES

1. **Pham DL, Xu C, Prince JL.** A survey of current methods in medical image segmentation. *Annu Rev Biomed Eng* 2000; 2:315-38.

2. **Raut S, Raghuvanshi M, Dharaskar R, Raut A.** Image segmentation - a state-of-art survey for prediction. ICACC '09 Proceedings of the 2009 International Conference on Advanced Computer Control, 2009; 420-4.

3. **Gonzales RC, Woods RE, Eddins SL.** *Digital image processing using Matlab*. Upper Saddle River, New Jersey: Pearson Prentice Hall, 2004.

4. **Sharma N, Aggarwal LM.** Automated medical image segmentation techniques. *J Med Phys* 2010;35:3-14.

5. **Elnakib A, Gimel'farb G, Suri J, El-Baz A.** *Medical image segmentation: a brief survey in multi modality state-of-the-art medical image segmentation and registration methodologies*. New York: Springer, 2011.

6. **Hu YC, Grossberg MD, Mageras GS.** Survey of recent volumetric medical image segmentation techniques. In: Barros de Mello CA, ed. *Biomedical engineering*. Vienna: Intech, 2009:321-46.

7. **No authors listed.** Itk-SNAP. http://www.itksnap.org (date last accessed 11 February 2016).

8. **No authors listed.** NiftySeg. http://cmictig.cs.ucl.ac.uk/wiki/index.php/NiftySeg (date last accessed 11 February 2016).

9. **No authors listed.** SPM: by members & collaborators of the Wellcome Trust Centre for Neuroimaging. http://www.fil.ion.ucl.ac.uk/spm/software/ (date last accessed 11 February 2016).

10. **No authors listed.** 3D slicer: a multi-platform, free and open source software package for visualization and medical image computing. http://www.slicer.org (date last accessed 11 February 2016).

11. **Wollny G, Kellman P, Ledesma-Carbayo MJ, et al.** MIA - a free and open source software for gray scale medical image analysis. *Source Code for Biology and Medicine*, 2013;8-20:1-20.

12. **Yushkevich PA, Piven J, Cody Hazlett H, et al.** User-guided 3D active contour segmentation of anatomical structures: Significantly improved efficiency and reliability. *Neuroimage* 2006; 31:1116-28.

13. Gibson I, Rosen D, Stucker B. *Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing*. Second ed. New York: Springer, 2010.

14. Scott J, Gupta N, Weber C, et al. *Additive manufacturing: status and opportunities*. Washington, DC: Science and Technology Policy Institute, 2012. https://cgsr.llnl.gov/content/assets/docs/IDA_AdditiveM3D_33012_Final.pdf (date last accessed 11 February 2016).

15. No authors listed. Committee F42 on additive manufacturing technologies.http://www.astm.org/COMMITTEE/F42.htm (date last accessed 11 February 2016).

16. No authors listed. 3D printing healthcare. http://www.osteo3d.com (date last accessed 11 February 2016).

17. No authors listed. Medical modeling. http://www.medicalmodeling.com (date last accessed 11 February 2016).

18. Sanghera B, Naique S, Papaharilaou Y, Amis A. Preliminary study of rapid prototype medical models. *Rapid Prototyping Journal* 2001;7:275-84.

19. Potamianos P, Amiss AA, Forestes AJ, McGurk M, Bircher M. Rapid prototyping for orthopaedic surgery. *Proc Inst Mech Eng H* 1998;212:383-93.

20. Frame M, Huntley JS. Rapid prototyping in orthopaedic surgery: a user's guide. *ScientificWorldJournal* 2012:838575. PMID:22666160.

21. Mahaisavariya B, Sitthiseripratip K, Oris P, Tongdee T. Rapid prototyping model for surgical planning of corrective osteotomy for cubitus varus: report of two cases. *Inj Extra* 2006; 37:176-80.

22. Sheth U, Theodoropoulos J, Abouali J. Use of 3-dimensional printing for preoperative planning in the treatment of recurrent anterior shoulder instability. *Arthrosc Tech* 2015;4:e311-e316. PMID:26759768.

23. Wu ZX, Huang LY, Sang HX, et al. Accuracy and safety assessment of pedicle screw placement using the rapid prototyping technique in severe congenital scoliosis. *J Spinal Disord Tech* 2011;24:444-50.

24. Sugawara T, Higashiyama N, Watanabe N, Uchida F, Kamishina H, Inoue N. 3D computer technology for future spinal surgery *J-STAGE* 2015;24:318-26.

25. Ogden K, Ordway N, Diallo D, Tillapaugh-Fay G, Aslan C. Dimensional accuracy of 3D printed vertebra progress in biomedical optics and imaging. *Proceedings of SPIE* 2014; 9036:903629.

26. King R. (2008, October 6). Printing in 3-D gets practical. *BusinessWeek Online*. http://www.businessweek.com/technology/content/oct2008/tc2008103_077223.htm (date last accessed 21 September 2015).

27. Berman B. 3-D printing: The new industrial revolution. *Bus Horiz* 2012;55:155-62.

28. D'Urso PS, Redmonda MJ. A method for the resection of cranial tumours and skull reconstruction. *Br J Neurosurg* 2000;14-16.

29. Tam MD, Laycock SD, Bell D, Chojnowski A. 3-D printout of a DICOM file to aid surgical planning in a 6 year old patient with a large scapular osteochondroma complicating congenital diaphyseal aclasia. *J Radiol Case Rep* 2012;6:31-7. PMID:22690278.

30. No authors listed. LayerWise. http://www.layerwise.com (date last accessed 11 February 2016).

31. No authors listed. Lima corporate orthopaedic motion. http://www.lima.it/homepage.html (date last accessed 11 February 2016).

32. Zhanga Y, Zhuc J, Wanga Z, Zhoua Y, Zhanga X. Constructing a 3D-printable, bioceramic sheathed articular spacer assembly for infected hip arthroplasty. *Journal of Medical Hypotheses and Ideas* 2015;9:13-9.

33. Imanishi J, Choong PF. Three-dimensional printed calcaneal prosthesis following total calcanectomy. *Int J Surg Case Rep* 2015;10:83-7.

34. Singare S, Yaxiong L Dichen L, et al. Fabrication of customised maxillo-facial prosthesis using computer-aided design and rapid prototyping techniques. *Rapid Prototyping J* 2006;12:206-13.

35. Singare S, Dichen L, Bingheng L, Yanpu L, Zhenyu G, Yaxiong L. Design and fabrication of custom mandible titanium tray based on rapid prototyping. *Med Eng Phys* 2004;26:671-6.

36. Stoora P, Suomalainenb A, Lindqvista C, et al. Rapid prototyped patient specific implants for reconstruction of orbital wall defects. *Journal of Cranio-Maxillofacial Surgery* 2012;42:1644-9.

37. El Halabi F, Rodriguez JF, Rebolledo L, Hurtós E, Doblaré M. Mechanical characterization and numerical simulation of polyether–ether–ketone (PEEK) cranial implants. *J Mech Behav Biomed Mater* 2011;4:1819-32. PMID:22098881.

38. Mazzarese B, Nicotera N, Theriault H. Modeling bone fixation implants with absorbable polymers using 3-D printing Biomedical Engineering Conference (NEBEC), 2015 41st Annual Northeast 2015; 7117129.

39. Rengier F, Mehndiratta A, von Tengg-Kobligk H, et al. 3D printing based on imaging data: review of medical applications. *Int J Comput Assist Radiol Surg* 2010;5:335-41. PMID:20467825.

40. Stevens B, Yang Y, Mohandas A, Stucker B, Nguyen KT. A review of materials, fabrication methods, and strategies used to enhance bone regeneration in engineered bone tissues. *J Biomed Mater Res B Appl Biomater* 2008;85:573-82. PMID:17937408.

41. No authors listed. 3D printed spine implant. https://www.rmit.edu.au/news/all-news/2015/august/australias-first-3d-printed-spine-implant/ (date last accessed 10 April 2016).

42. Pati F, Song TH, Rijal G, Jang J, Kim SW, Cho DW. Ornamenting 3D printed scaffolds with cell-laid extracellular matrix for bone tissue regeneration. *Biomaterials* 2015;37:230-41. PMID:25453953.

43. Arafat MT, Lam CX, Ekaputra AK, Wong SY, Li X, Gibson I. Biomimetic composite coating on rapid prototyped scaffolds for bone tissue engineering. *Acta Biomater* 2011;7:809-20. PMID:20849985.

44. Mavroidis C, Ranky RG, Sivak ML, et al. Patient specific ankle-foot orthoses using rapid prototyping. *J Neuroeng Rehabil* 2011;12;8:1. 8-12.

45. No authors listed. Cortex: exoskeleton protecting the internal skeleton. http://www.evilldesign.com/cortex (date last accessed 11 February 2016).

46. Zhang YZ, Lu S, Chen B, Zhao JM, Liu R, Pei GX. Application of computer-aided design osteotomy template for treatment of cubitus varus deformity in teenagers: a pilot study. *J Shoulder Elbow Surg* 2011;20:51-6.

47. Cartiaux O, Paul L, Francq BG, Banse X, Docquier PL. Improved accuracy with 3D planning and patient-specific instruments during simulated pelvic bone tumor surgery. *Ann Biomed Eng* 2014;42:205-13. PMID:23963884.

48. Landi A, Mancarella C, Gregori F, Delfini R. Spinal neuronavigation and 3D-printed tubular guide for pedicle screw placement: a really new tool to improve safety and accuracy of the surgical technique? *J Spine* 2015;4: e118. doi:10.4172/21657939.1000e118.

49. Brown GA, Firoozbakhsh K, DeCoster TA, Reyna JR., Moneim M. Rapid prototyping: the future of trauma surgery? *J Bone Joint Surg Am* 2003;85-A(suppl 4):49-55. PMID:14652393.

50. Pietrabissa A, Marconi S, Peri A, et al. From CT scanning to 3-D printing technology for the preoperative planning in laparoscopic splenectomy. *Surg Endosc* 2016;30:366-71.doi: 10.1007/s00464-015-4185-y. Epub 2015 Jul 3.

51. Frisoli A, Solazzi M, Reiner M, Bergamasco M. The contribution of cutaneous and kinesthetic sensory modalities in haptic perception of orientation. *Brain Res Bull* 2011;85:260-6.