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The Use of 3D Printing Technology in the Ilizarov Method Treatment: Pilot Study

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A – research concept and design; B – collection and/or assembly of data; C – data analysis and interpretation; D – writing the article; E – critical revision of the article; F – final approval of article

Abstract

Background. Significant developments in additive manufacturing technology have occurred in recent years. 3D printing techniques can also be helpful in the Ilizarov method treatment.

Objectives. The aim of this study was to evaluate the usefulness of 3D printing technology in the Ilizarov method treatment.

Material and Methods. Physical models of bones used to plan the spatial design of Ilizarov external fixator were manufactured by FDM (Fused Deposition Modeling) spatial printing technology. Bone models were made of poly(L-lactide) (PLA).

Results. Printed 3D models of both lower leg bones allow doctors to prepare in advance for the Ilizarov method treatment: detailed consideration of the spatial configuration of the external fixation, experimental assembly of the Ilizarov external fixator onto the physical models of bones prior to surgery, planning individual osteotomy level and Kirschner wires introduction sites.

Conclusions. Printed 3D bone models allow for accurate preparation of the Ilizarov apparatus spatially matched to the size of the bones and prospective bone distortion. Employment of the printed 3D models of bone will enable a more precise design of the apparatus, which is especially useful in multiplanar distortion and in the treatment of axis distortion and limb length discrepancy in young children. In the course of planning the use of physical models manufactured with additive technology, attention should be paid to certain technical aspects of model printing that have an impact on the accuracy of mapping of the geometry and physical properties of the model. 3D printing technique is very useful in 3D planning of the Ilizarov method treatment (*Adv Clin Exp Med* 2016, 25, 6, 1157–1163).

Key words: 3D printing, medicine, the Ilizarov method.

Significant developments in additive manufacturing technology have occurred in recent years. Currently, there are a number of 3D printers available on the market, enabling the production of objects *via* a variety of printing technologies: SLA (Stereo Lithography Apparatus), FDM (Fused Deposition Modeling), SLS (Selective Laser Sintering), etc. The additive manufacturing process consists of several stages. Three-dimensional digital model forms the basis of 3D printing; its preparation is the first step in the process.

Next, using printer-specific software, a model-based file with printing procedure is prepared. At this stage, the person managing model production

selects printing parameters such as layer height, wall thickness, the manner and degree of filling, the type of additional supporting system of the object to be printed; these will translate directly into the quality and speed of print.

The last stage of production is additive printing of the model. Depending on the employed technology, the finished artifact does not require additional processing and usually is the final product.

A wide range of materials, from metal powders and alloys through plastics (thermoplastic, thermoset), ending with materials such as paper, chocolate or concrete, are currently used in 3D printing. Three-dimensional printing technology

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gy quickly finds application in many fields due to the considerable variability of employed materials. One such area of application of 3D printing technology is medical engineering.

Some areas of medicine have benefited from the introduction of 3D printing technology [1–4]. The use of additive manufacturing in medicine may include the production of the model of the organ or structures such as tools to assist treatment during the planning stage [1–4]. 3D printing technology makes it possible to print any drafted model; therefore, adapting medical products to fit the anatomical shape does not pose constraints to production.

3D printing techniques can also be helpful in the Ilizarov method of treatment. Worldwide, the employment of the Ilizarov method is increasing [5–8]. Among its many applications is the treatment of complex multiplanar deformities in children and adults; unfortunately, this is associated with many complications [6–10]. Complex multi-dimensional deformations, aplasia and hypoplasia of bones, especially in children, are diagnosed more often, but rarely treated, particularly in children at a younger age. This is due to the structural complexity of the Ilizarov apparatus following the addition of hinges which enable corrections of a multiplanar deformity, the small size of the Ilizarov apparatus for the youngest children, the necessity of precisely mounting and installing the stabilizer onto the patient, and the increased possibility of complications following treatment [5–8, 11].

The aim of this study was to evaluate the usefulness of 3D printing technology in the Ilizarov method treatment. To the best of the authors' knowledge, there have been no studies published in international literature analyzing the use of 3D printing in the Ilizarov method of treatment.

According to the authors, the use of 3D printing in the planning stage of the treatment process and the configuration of the spatial structure of the stabilizer may significantly contribute to increasing the effectiveness of treating limb deformations. Bone models printed in 3D technology, based on a 3D reconstruction of computer tomography, can facilitate individual planning of the structure of the Ilizarov apparatus, which is particularly important for the correction of complex multilayered deformations and treatment of small children. 3D printing technique may determine whether it is technically possible to perform the complex Ilizarov method operation, construct a model of the apparatus which will be unerringly congruent with impaired limb anatomy, plan the different stages of treatment and correction as well as consequential structural changes, and designate appropriate safe

zones for the introduction of Kirschner wires and the Schanz screw.

These benefits resulting from the use of 3D printing in the planning stage of the Ilizarov method treatment can shorten the course of therapy and reduce the risk of complications.

Material and Methods

The employment of bone models printed by additive manufacturing in the course of planning treatment was submitted for consideration. Physical models of bones used to plan the spatial design of the Ilizarov external fixator were manufactured by FDM (Fused Deposition Modeling) spatial printing technology. During the preparation of the model for printing, attention should be paid to impaired geometry caused by artifacts, distortion of geometry and to the selection of filtering parameters.

In the first stage, a CT (computed tomography) scan with 3D reconstruction was performed in a 3-year-old patient with a planned lengthening and axis correction of the lower leg using the Ilizarov method. A CT image reconstruction was carried out by selecting appropriate tissues (skeletal structures), which then allowed us to create a three-dimensional object in a .stl format (Fig. 1).

Fig. 1. Tibia and fibula extracted from computed tomography data

The next step consisted of removing artifacts from the model and customizing it to the printing requirements by smoothing out surface irregularities *via* the use of appropriate filters. Model transformation is a complex process. Errors caused by the recording method of computed tomography or magnetic resonance imaging have a direct impact on the geometry of the selected digital model. Model surfaces were thoroughly checked to detect discontinuities and impaired geometry deviating from the physiological structure of the bones. Fig. 2 illustrates this issue. Applying filters to a structure with visible errors in geometry may lead to a complete transformation and deformity of the model (Fig. 3). An important parameter of the model is the size of the mesh from which the model is built. Excessively large size of the mesh leads to loss of fine details of geometry.

Image filters were applied to an artifact-free model. The manner of selecting the filter and its qualities directly affect the geometry, dimensions

and quality of the model. Various filter variants are discussed in Fig. 4. The described methodology is important to the accuracy of the printed object, because it ensures the continuity of the model and uniform transition between the planes.

Using dedicated 3D printer software, physical parameters of the three-dimension digital model, including layer thickness, wall thickness of the model, and type and degree of the filling, were defined; additionally, the scaffolding system intended to support bone printing was designed. Due to the geometry of the long bones, it was necessary to provide scaffolding which would support the print-out. The supporting elements were removed after the printing was completed. The drawings (Fig. 5 and Fig. 6) show the parameters that directly affect the physical parameters of the print, object production accuracy, as well as weight. Optimization of model printing strives to achieve the best physical parameters of the printed model with minimum material usage, and shortest duration of printing.

Fig. 2. Analysis of the model surface in order to verify the accuracy of geometry. Generated artifacts are marked

Fig. 3. Distortion of geometry caused by leftover artifacts. The size of the mesh also has an essential influence on the accuracy of the model. Bigger size elements cause a loss of model detail

Fig. 4. An example of filter application where the model not subjected to the process is indicated as A, while B and C show the unfavorable effect of geometry deformation. Optimally prepared model that maintains the correct geometry is shown in Fig. D

Fig. 5. Distribution of internal model fill density for successive fill density percentage of 10%, 20%, 30%, 50%, 70%, and 90% with a constant outer wall thickness parameter of 0.8 mm

Fig. 6. The effect of changes in the thickness of the model shell (0.3 mm – 2 mm) at a constant fill density equal to 30%

3D Builder device, printing via the FDM additive manufacturing, was used to produce the physical models of bones. Bone models were made of poly(L-lactide) (PLA). The model was printed with

the following parameters: layer height of 0.3 mm, shell thickness of 0.8 mm and 30% fill density. The printed object required the removal of supporting scaffolding (Fig. 7).

Fig. 7. Model of the bones printed with FDM additive manufacturing

Results

A model of the tibia and fibula, acquired from computed tomography imaging, was developed and printed using FDM technology. Printed 3D models of both lower leg bones allow doctors to prepare in advance for the Ilizarov method treatment: detailed consideration of the spatial configuration of the external fixation, experimental assembly of the Ilizarov external fixator onto the physical models of bones prior to surgery and plan individual osteotomy level and Kirschner wires introduction sites (Fig. 8). It is noteworthy that the length of the bone did not exceed 100 mm, and the diameter of the diaphysis was approximately 7 mm; therefore, the adjustment of the apparatus on the printed object supported preoperative preparation. The Ilizarov apparatus consisted of 3 rings: proximal ring fastened with three Kirschner wires (diameter = 1.2 mm), middle ring mounted with two Kirschner wires, and distal ring secured with two Kirschner wires.

Discussion

Additive methods are increasingly used in many fields, its main asset being the ability to print complex shapes, which are exceptionally troublesome to achieve using traditional technologies. Similarly, 3D printing technology is used increasingly in medicine. Most often this involves the production of implants with geometry individually tailored to a specific patient (custom made) and with gradient qualities ensuring better biomechanical compatibility of the implant with tissue, e.g. bone [12]. Additive manufacturing is also used in tissue engineering. Another flourishing field of application for 3D printing is the provision of support for surgery planning using physical models of the body or fragment of the osteoarticular system in order to practice the most advantageous variant of approach during the operation. This is especially important in complex and unusual cases [2–4]. This paper presents the possibility of using physical models of bones obtained using 3D printing

Fig. 8. The Ilizarov apparatus mounted onto bone models printed using FDM additive manufacturing technique

to plan lower limb lengthening and axis correction surgery in a small child using the Ilizarov method.

The spatial structure of the apparatus adjusted to the limb and the distortion, as well as the accurate assembly of the apparatus, are very important in the healing process of the Ilizarov method treatment [6–8, 11, 13, 14]. Printed 3D bone model allows for the accurate preparation of the Ilizarov apparatus spatially matched to the size of the bones and prospective bone distortion.

3D printing also makes it possible to plan and test the experimental insertion of Kirschner wires and the Schanz screw in the optimal spatial arrangement on the 3D model. Proper spatial geometry of the introduced implants affects the stability of the Ilizarov apparatus and the results of treatment [6–8, 11, 13, 14]. It also permits trial correction of the deformity with the possibility of assessing the precision and the degree of accuracy of correction and exactness of the spatial location of hinges and distractors of the Ilizarov apparatus.

Employment of the printed 3D models of bone will allow more precise design of the apparatus, which is especially useful in multiplanar distortion and in the treatment of axis distortion and limb length discrepancy in young children. This will allow for the optimization of the spatial structure of the apparatus and the planning of potential alterations in the construction of the stabilizer. It can, therefore, be concluded that the printed physical models of bones constitute an important part of treatment strategy preparation. 3D bone printing will allow practice mounting of the Ilizarov apparatus on physical models which will improve the process of training doctors in the use of the Ilizarov method. This will permit simpler and more precise treatment. The aforementioned benefits of employing 3D bone printing in the planning stage of the Ilizarov method treatment will shorten the duration of surgery and treatment and reduce the risk of complications, which will result in better outcomes and lower treatment costs.

In the course of planning the use of physical models manufactured with additive technology, attention should be paid to certain technical

aspects of model printing that have an impact on the accuracy of mapping the geometry and physical properties of the model.

One such aspect requiring special attention is the process of applying filters to the image in the course of preparing the model for 3D printing. Cooperation between the doctor and the engineer is essential, so that the initial model properly replicates the geometry of the patient's bone, while being, at the same time, adapted to additive manufacturing technology or calculations using the finite element method (FEM).

Problems with detailed reconstruction of disturbed anatomy of the deformed limb are encountered in traditional radiographs and even in 3D reconstructions of CT scans. 3D printing technique allows for a very accurate reconstruction of the bone, while keeping its actual size and spatial geometry [8–11], which facilitates the planning of treatment.

Optimization of model printing strives to achieve the best physical parameters of the printed model with minimum material usage and the shortest duration of printing. Given the fact that the model was used to mount the Ilizarov apparatus, it was essential to reinforce the endurance parameters of the object. We have an impact on the physical parameters of the model, which allows us to achieve model rigidity analogous to the rigidity of bone. Printing parameters were selected based on the abovementioned aspects.

As denoted by the authors, 3D printing technique is very useful in 3D planning of the Ilizarov method treatment, especially when treating small children, where the dimensions of the bones require high-precision planning of the stabilizer configuration. Further research on the employment of 3D printing to assist in the Ilizarov method treatment, especially when dealing with correction of the arm, forearm or thigh deformity, is needed. In the next stage of the study, the authors intend to combine the construction of the Ilizarov apparatus using 3D bone models with a surgical procedure performed on patients.

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