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Visualization of Biomedical Products based on Paper-based Color 3D Printing

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Abstract

To explore the accurate physical visualization of customized biomedical parts using the paper-based color 3D printing, taking specific surgical training tools as tested samples, a visualization workflow was proposed and discussed with relative parameters. Three keynote elements of visualization workflow were analyzed by using model transformation, printing parameters controlling and entity evaluation from given digital congenital heart disease model, digital kidney model and digital pulmonary model. On the basis of Cutting-Bonding Framework (3D-CBF) strategy, kidney model was divided into two subblocks and layout during printing controlling phase, to develop specific principles for practical and economic physical visualization in modern surgical training applications. Since tested specimens were all captured from real pathological models accompanied with remarkable microscopic features, all these were processed with transformation adjustment to enhance practical feasibility of paper-based color 3D printer. Considering the experiencing service of surgical training parts, the physical qualities of printed biomedical parts were focused on tensile strength and surface color authenticity. According to final results of printed surgical models, the proposed paper-based 3D printing process workflow can implement vivid visualization of tested digital models, and further shared optimization suggestions for consistent physical visualization in biomedical field.

1. Introduction

3D printing was a rapid digital fabricating technology, which leaded customized manufacturing industries by accurate physical visualizations [1]. In recent years, 3D printing technology had shown many progresses into printing speed and printing materials for various printing processes [2]. All these changes had expanded the scale of 3D printing industrialization, particularly into neoteric color 3D printing processes which achieved from the functional manufacturing to precise manufacturing. In the view of printed substrates, color 3D printing processes can be summarized into six categories including paper-based color 3D printing process, plastic -based color 3D printing process, powder-based color 3D printing, metal-based color 3D printing process, organism-based color 3D printing process and glass-based color 3D printing process. The paper-based color 3D printing process provided more lifelike, low-cost and environment-friendly than other printing processes, even if the principle of accurate color reproduction for different printing materials was an unsolved puzzle [3]. In the paper-based color 3D printing field, new researches are gradually focusing on printing quality evaluation of customized entities produced by paper-based 3D printers such as MCOR IRIS 3D printer or ARKE 3D printer [4]. In the early stage, the paper-based color 3D printing mostly applied into the cultural-creative industry, terrain map industry and architecture industry, because of attractive colorful visualization [5, 6]. Later, this process was gradually developed and optimized by new printing workflows from specific customized applications [7]. For example, the vivid physical visualization of customized wine packaging model was an interesting experimental research case in 2017 [8].

Personalized fabrication of biomedical products was also a topic of general interest for 3D printing applications from printed models to produced living organ tissues [9]. Color characteristics were worth exploring by medical educators or surgeons to produce more and more customized surgical training tools formed from real surgical cases for young doctors or informed patients [10]. Currently, so few color biomedical parts printed by 3D printing techniques had been granted a product registration certificate by the FDA or other national agencies, mostly limited to the printing quality and corresponding evaluation standard for evidence-based personalized features. In addition, traditional customized medical instruments did play an important role in daily life for sick or disabled person, while also required much time and labour based on conventional manual methods. Feasible 3D printing processes were developed from FDM, SLS, SLM and DLP, which mainly provided physical structure products among most biomedical applications, while surgical training tools required vivid color reproduction to distinguish and determine diseased tissue and surgical details [11]. Recently, Wyss Institute for Biologically Inspired Engineering in Harvard University and MIT Media Lab's Mediated Matter group proposed a voxel-printing method which converted discontinuous data sets into dithered material deposition marks for physical visualizations with high-resolution details [12]. Their major goal was to prevent data alteration and arbitrary boundary details loss from digital information expression to physical material compositions by the Poly-Jet 3D printer. Subsequently, the MIT CSAIL Computational Manufacturing team showed a new spectral vector error diffusion algorithm to solve completely the layout discretization and color quantization issues of customized medical parts implemented by resin-based 3D printing process [13]. However, above-mentioned advanced methods weren't available for implementing paper-based 3D printed color surgical training tools.

Considering usage eco-cycle and cost problems, surgical scientists are increasingly interested into using paper-based 3D printed specific surgical training models in China. Meanwhile, the paper-based 3D printed color models can be arbitrarily segmented and reconstructed to understand internal multi-layered structures at a very affordable way. So, reliable vivid physical visualization of biomedical parts is still a big challenge for private surgery departments [14]. Even if color 3D printing technology is good at creative visualization of color 3D models, feasible principle and practical framwork based on color 3D printing processes with paper-based substrate were rarely developed [15]. However, useful integral workflow of 3D printing applications in biomedical customization field was still eager for practical guides of process optimization and design principles of digital 3D models. In this article, an integrated framework for paper-based 3D printing applied into customized surgical training models were gradually demonstrated by given cases including specific congenital heart disease model, pulmonary model and kidney model. The following sections were presented the qualitative analysis of digital 3D model design, process workflow and quality evaluation based on paper-based 3D printing process, wherein providing applicable strategy for further industrialization of more complexed surgical training models using paper substrate.

2. Methodology

The market of customized biomedical parts is increasing in biomedical field, and eager for a comprehensive workflow about paper-based 3D printing process. At the same time, original digital models were often transferred from MRI images or PET images by 3D data processing algorithms. Existing paper-based 3D printers also have some inherent limitations about original digital models, which required special examples and visualization principles to understand the potential integral workflow which can simplify the printing optimization of surgical workers and reduce patient fees with an improved printing efficiency. Relative apparatus, materials and experimental settings are shown in the following sections.

2.1. Apparatus & materials

In this paper, all physical visualization of biomedical parts such as surgical training models were implemented by paper-based color 3D printing process based on IRIS 3D printer. This machine was widely applied into the cultural and creative industries with above-mentioned advantages, focused on vivid color reproduction quality. All experimental apparatus and materials were detailed in Table1and Table2. For IRIS 3D printer, its maximum build size is 256×169×150 mm, which illustrated a limited factor influenced on further industrialization in customized biomedical applications. The maximum pull range of digital spring dynamometer is up to 500N, which can meet tensile test of biomedical parts based on aqueous adhesive and relative parameters.

Table1. Apparatus and its relative information

Equipment	Types	Manufacturers
IRIS Paper-based 3D printer	Matrix 300	Mcor-Tech
Digital spring dynamometer	NLB-500	ALIYIQI
Color-IT software	V10	Mcor-Tech
Blender software	V2.7	Blender Institute

Table2. Materials and their relative information

Raw Material	Uses	Manufacturers
Aqueous adhesive	Adhesive	Mcor-Tech
Office A4 paper	Substrate	Nine Dragons
CMYK jetting ink	Colorant	Mcor-Tech
Water-based ink	Posttreatment	HERO Brand

In addition, the grammage of office A4 paper usually used 80 g/m2, and provided two-sided consistency for each piece. The CMYK jetting inks were similar with jetting inks using Epson jetting printer in graphic printing field, while the permeability is different from each other. Aqueous varnish was as the additional reprocessing agent to improve surface quality of printed entities, which wasn't from the Mcor-Tech official source. This aqueous varnish is impregnated by a specific dilution ratio, just slightly increased the extra cost.

2.2. Integrated framework of vivid visualization

To be exact, paper-based 3D printing process was adhered to the laminated object manufacturing principle using paper sheet substrate rather than film sheet. Meanwhile, the contour cutting method had also been changed from laser cutting to knife head cutting by Mcor-Tech company. Combined Epson jetting printer and configured color inks, the new coloring system and forming system can be connected smoothly in the paper-based 3D printer. Currently, the IRIS paper-based color 3D printer was the first 3D printer provided ICC profiling system adjusting color management capability to achieve lifelike gradient color reproduction, while the color gamut of paper-based 3D printer was also smaller than that of digital profile of original 3D models in RGB color space. The achievable color range was still a concerned issue for high-value antiquities reproductions in traditional process workflow showed in Figure1, while a new level of accuracy can be improved by the proposed integrated process framework illustrated in Figure2.

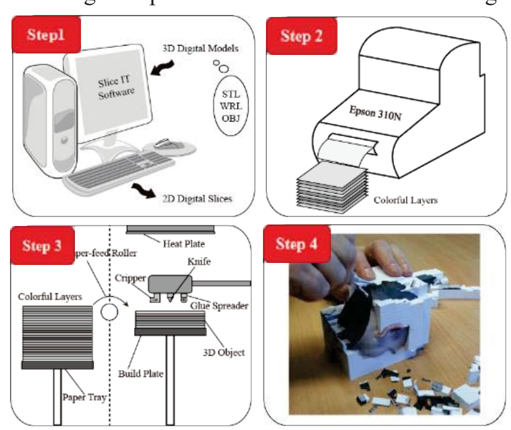

Figure 1. Traditional paper-based 3D printing process workflow (Four steps)

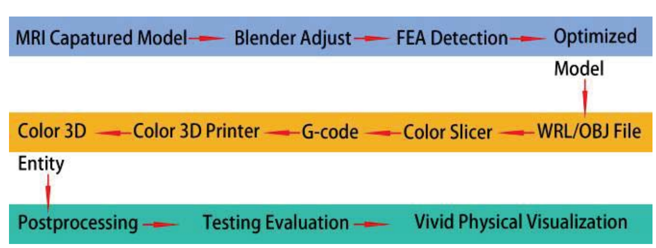

Figure2. Proposed integrated paper-based 3D printing process workflow

In the traditional paper-based 3D printing process, the whole workflow was defined as four steps such as slicing step, colorizing step, forming step and repairing step. Above four-steps workflow was the basic training for general consumers, also easy for young surgical doctors, while difficult to implement designed 3D models.

Slicing step is a key step that transformed digital STL format into a set of continuous sliced layers with topological triangular facets. In paper-based 3D printing technique, the thickness of each sliced layer is theoretically set to a fixed value, while this attribute value is easily changed in other color 3D printing processes. Coloring step is to print distributed colorization contour with central cutting maker of each sliced layer, which is a relatively independent step that can be done with conventional inkjet printers. Forming step is the step that best reflects the nature of the additive manufacturing technology, which mainly consisted of configured path cutting and bonding operations. Repairing step is to remove cutting scrap of all bonding layers and fix surface quality by relative postprocess. Sawtooth effect of finished entity had become a troublesome issue for customized paper-based 3D printed object based on traditional printing workflow. Specifically, the IRIS Color-IT software can compute and show the overall forming time of sliced digital 3D models before colorized by Epson jetting printer.

In Figure2, an integrated paper-based 3D process workflow was illustrated with more detailed steps for physical visualization of biomedical parts, compared to traditional workflow. The finite element analysis (FEA) detection was to inspect mechanical weak areas of the digital model to be printed, and check redesign results by Blender software to match the structural accuracy requirements of current color 3D printers. Another obvious improvement was the change that conversion principle of the input format file of the printed object from STL file to WRL file or OBJ file. Similarly, a set of color sliced layers of desired 3D color models was directly generated from the updated Color Slicer tool. Due to the large size of the biomedical model, it is hard to directly implement relative physical visualization, and required special strategies such as the 3D-CBF strategy early proposed in the industrialization of large-size 3D printed color models. Hence, the testing evaluation step is even more important for the printed surgical training model.

2.3. Customized digital surgical training models Transformation

Surgical training models, as one of the most feasible paper-based 3D printing industrializations, it also needs to meet a lot of personalized performance requirements which originated from daily different tissues and various patients. Generally speaking, the most basic properties are surface roughness, tensile strength, brittleness strength and color fastness. Surface roughness is used for quick judgement of Sawtooth effect on printed color entities, which further determined whether more post-processing is needed. Since printed objects were implemented by paper substrate bonded layer by layer, the first principle that the inner wall of the cavity model should not be too thin, such as a preferred thickness of at least 300 ums during Blender STL format transformation. In Figure 3(a) and 3(c), it can be seen that pulmonary model and heart model with many hollow tubular structures such as small vessels and bronchi. For the non-lesion area of sampled tubular structures, relative digital adjustment was optimized to fill the whole structure by default. In addition, the physical visualization of customized surgical training models often deals with irregular structural connectors with multi-scale and cross-scale strength features, such as specific kidney model illustrated in Figure 3(b). For this case, digital conversion should be focused on providing enhanced design for fragile structures based on FEA analysis.

2.4. Specific 3D printing parameters setting

For the integrated process workflow, the configuration of printing parameters is similar with that of traditional paper-based 3D printing process. The most important setting is to compute a set of sliced layers of the surgical training model, and generate the efficient G-code that current color 3D printer can recognize by Color-IT software. The overall forming time is mainly affected by the total number of sliced layers and the total length of cutting path in each sliced layer. From the point of view of settings, it is the difference between the placement strategy and the placement angle of tested surgical training models in a WRL or OBJ format displayed into the slicing software. For this case, only the kidney model should be layout and sliced together based on previous proposed 3D-CBF strategy including cutting angle, layout angle and dipping method. Considering geometric dimensions of tested kidney model, the cutting angle selected 0° angle (perpendicular to the horizontal plane) with only one area located between the left kidney and left ureter. For the pulmonary model and congenital heart disease model, they were both layout on the horizontal plane providing the maximum visible surface without any segmentations.

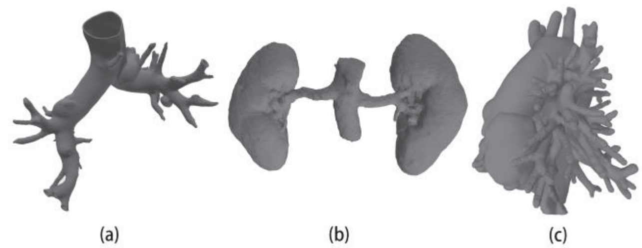

Figure3. *Displayable digital surgical training modes including digital pulmonary model, digital kidney model, digital congenital heart disease model, respectively.*

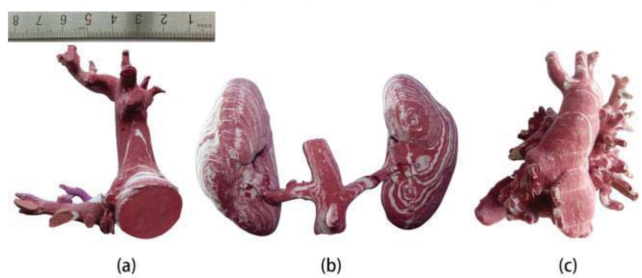

Figure4. *Photographs of 3D printed surgical training entities including printed pulmonary model, kidney model, congenital heart disease model, respectively.*

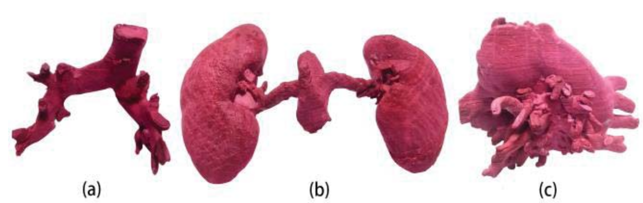

Figure5. *Photographs of post-processed 3D surgical training entities including vivid pulmonary model, kidney model, congenital heart disease model, respectively.*

2.5. Quality evaluation of printed 3D models

For 3D printed surgical training models, quality evaluation methods were still relying on the detection methods of traditional biomedical instruments, such as mechanical properties, chemical properties and surface properties. For paper-based 3D printed entities, specific evaluation indicators can choose tensile strength, surface sawtooth effect, color reproduction accuracy, and color stability. The tensile strength is to measure bonding strength of printed subblocks based on 3D-CBF strategy, since the bonding strength between paper-based layers is tested to be strong enough. The surface sawtooth effect is to check the surface appearance optimized by the postprocessing step in the proposed integrated printing workflow. The color reproduction accuracy is to test the color difference between original models and printed entities with dipping treatment. The color stability is to observe surface color change threshold of 3D printed models under normal conditions.

3. Results analysis

Based on above-mentioned experimental settings and new proposed paper-based 3D printing process workflow, customized digital surgical training models were presented in Figure3, such as digital pulmonary model, digital kidney model, digital congenital heart disease model, respectively. All these digital specific models were adjusted by Blender software and checked by FEA analysis. The direct outputs of color 3D printer in the proposed workflow were illustrated for three surgical training entities in Figure4. For the tensile strength test, the tensile strength value of cutting joint in printed kidney model can be up to 160 N based on the digital spring dynamometer, and slightly increased after post-processing.

Compared to raw results in Figure4, the Figure5 showed final vivid physical visualization of post-processed 3D surgical training entities including pulmonary model, kidney model, congenital heart disease model. It was obvious that the surface sawtooth effect of post-processed samples become more invisible from given specific parameters setting. This improvement was also seen for color reproduction accuracy, especially for kidney model. The color stability of printed models remained essentially constant after specific dipping treatment. What needs to be explained here is that all test evaluations don’t discuss the influence of irregular layout strategies, but need further study.

4. Summary and *future directions*

Paper-based color 3D printing process had been verified as a useful accurate replication of digital surgical training models for medical students and patients to improve understanding of the surgical plan, based on vivid communication medium. Moreover, in the proposed integrated workflow, presented printing quality evaluation indicators can provide a quantitative optimization reference for improving process parameter settings throughout any visualization steps, given the absence of official standards. New researches should go beyond the feasible investigation of printed biomedical parts to develop a general integrated analysis system consisted of quality monitoring strategies and performance enhancement algorithms, and make it more practical for most complex clinical surgical applications based on this workflow.

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