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Design in Paediatric Healthcare: Rethinking 3D models of paediatric orthopaedic data using Design approaches

Abstract

This paper discusses the application of design approaches and methodologies to address an urgent need for appropriate and effective visualisation and modelling tools in the Sydney Children's Hospital Network (SCHN). This project investigates how codesigned 3D printing systems, workflows and 3D print material composites and can improve understanding of bone tissue formations and deformations in children and infants. Data visualisations are crucial for scientific discovery, data analysis and knowledge exchange between experts and general audiences. Until recently, visualisations of bone tissue formations had been constrained to screen-based imagery or laboriously handmade 3D models. (Ploch, 2016.) Significant visualisation advances have come through the application of new technologies from other fields such as the gaming industry and the military, including virtual and augmented reality, while 3D printing first developed for manufacturing, offers physical and material understandings of data. Despite these advances they do not meet the complex needs of paediatric orthopaedic researchers.

The design team addressing this project have focused on a co-designed approach to meeting the needs of the hospital and computational design and 3D printing fabrication methodologies for system-inherent capabilities for accurate and repeated transfer of numeric data to 3D form and shape. The team also builds on the extensive uptake of 3D printing as a prototyping technology within a design context where researchers have developed innovative workflows and materials. These design skills are being deployed in this project to customise the systems and materials to suit the needs of clinicians.

The Problem

Orthopaedic surgeons and biomedical engineers at Sydney's Children's Hospital Network need accurate models of patient anatomy in order to analyse complex health issues through pre-surgical visualisation and rehearsal, facilitate training of registrars in surgical techniques and patient education. Currently, bone tissue data is visualised and shared between scientific researchers using imaging modalities such as CT, MRI, or X-ray, and on special occasions plastic 3D printed models or expensive handmade models. These modes of visualisation inadequately represent the material structure, texture and density of actual paediatric bone formations; Even in combination, these modes of visualisation under theorise the importance of haptic feedback, spatial relationships between bones, materiality and customisation in understanding and communicating complex anatomical data (Baskaran et al. 2016).

The tactile and material experience of drilling into or cutting through bones is an important cue in surgery, letting surgeons know when bony landmarks have been reached when vision is not possible. Trainee surgeons currently practice on foam bone models, animal bones and plastic 3D prints. Foam bone models demonstrate consistent anatomy but lack the correct haptic feedback of actual bones. Animal bones are a different shape, and scale, particularly to infant bone formations and the plastic 3D prints melt from the friction of the drill or saw.

To address their visualisation and 3D model needs, the Centre for Children's Bone and Musculoskeletal Health has established the Engineering Prototypes & Implants for Children (EPIC Lab), to do basic 3D printing and develop and test implants. The EPIC lab can accurately 3D print plastic models of bones, however there are no commercially available 3D printed materials that accurately simulate the complex texture and structural variations of bone tissue. The EPIC lab needs the advanced computational design knowledge to create simulations of specific conditions and a 3D print material and system to accurately simulate the complex textural and structural qualities of bone tissue.

While this research has a particular focus, it also aims to explore the broader implications of materiality and haptic interaction within scientific data visualisation. In this way, this research investigates how an innovative 3D printing material might contribute to user's comprehension of biological data. The resulting processes, methods and outputs of the research and its case studies are thus situated at the nexus of models for tangible interaction, embodied experiences, design and science communication. This is based on the concept that three-dimensional visualisations have the potential to reflect data and facilitate communication through haptic, material and visual experiences. Tactile engagement in this form creates new ways of experiencing data that engage the user's sensory experience, has multiple viewing angles and allows for collaboration and discussion between diverse disciplinary audiences (Dunn, 2017). The models fabricated as part of the research project are not intended to replace current visualization methods. Instead, they supplement and enhance knowledge transfer and give new insights into data sets.

The Approach

The role of codesign is an integral focus of this research. In projects such as this, collaboration across different disciplines can alter the research methods and formal boundaries of traditional knowledge areas. When experts from different fields collaborate, their distinctive research and thinking practices can produce alternate ways of exchanging, transforming, and disseminating information. Through a collaborative design (co-design) approach, this project provides a design-led approach to data visualisation and applies a design research method in the context of SCHN. While SCHN has expertise in bone tissue research and visualisation, there is significant potential for design knowledge to collaboratively address the partner's needs.

Previous SCHN attempts to address these deficiencies, executed within a scientific/ medical research framework, have failed, demonstrating the need for a co-design approach. According to Vicente (2004), there are many examples of socio-technological systems which have been designed while insufficiently taking human factors into account, regularly leading to serious problems in actual use in the complexity of the real world. Co-design involves placing continuous user and participant engagement and testing at the core of the research approach. It is an important part of the approach because it enables a wide range of stakeholders to contribute to both identifying the exact nature of the problem, as well as developing appropriate and viable solutions (Sanders and Stappers, 2008). Co-design, first described by C. K. Prahalad and Venkat Ramaswamy in 2004, has gained critical attention for its utility in addressing context-specific scenarios, as well as signaling a more empathic and less hierarchical design research method. Many co-designed projects coincide with a broader understanding of Design Thinking and follow similar innovation processes (P. G. Rowe 1987).

By codesigning a visualisation workflow, custom material and 3D printing process, this research creates physical models or visualisations that mimic values such as material structure, texture and density accurately. The project generates new knowledge in the areas of design innovation, visualisation and 3D printing, using a co-design approach that involves designers, computational designers, material scientists and biomechanical researchers.
The co-design process used in this project encourages lateral approaches to identifying the precise focus of the challenge and iteratively, collaborating to arrive at innovative solutions. Using co-design and the broad combined expertise of the research team, the project addresses SCHN's needs by building on international precedents to develop a customised approach combining user surveys and user testing, 3D printed prototyping, material development and fabrication that generate innovation and builds collaboration between researchers and stakeholders. To date there have been two codesign workshops, the first was

held at the EPIC lab at Westmead Children's Hospital with staff to identify the existing systems in use, clarify the correct stakeholders and using different scenarios and stimulus, identify the exact nature of the problems.

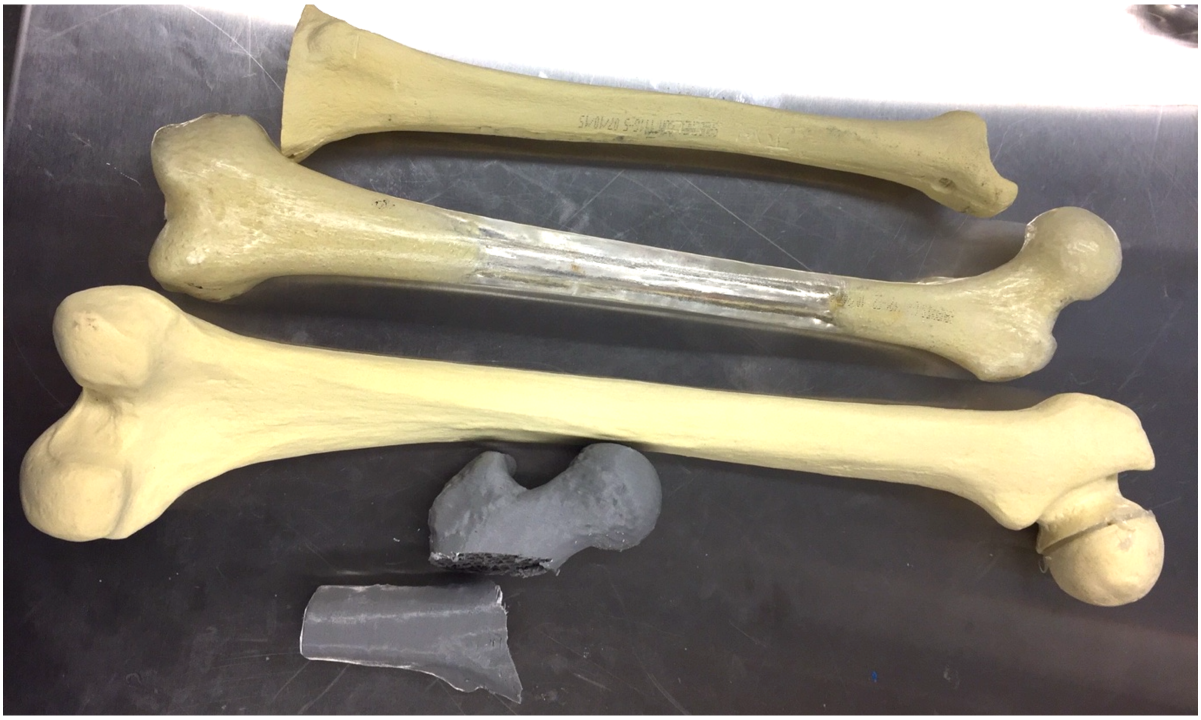

Figure 1. Models currently used by clinicians at the SCHN, Image by Kate Dunn.

Computational Design

Computational Design has been defined by Menges and Ahlquist (2011) as a "process [that] starts with elemental properties and generative rules to end with information which derives form as a dynamic system". Menges and Ahlquist also introduce multi-agent approach, a topic that has, according to Zavoleas and Haeusler (2017), been employed in architecture in order to explore the influences of different contextual factors yet can also offer a methodology to tackle the issues addressed in this paper. Referring to Cybernetics (Pask, 1969) as an initial source, Zavoleas and Haeusler further argue that "a design problem may be described by a set of influences interacting with each other as part of a dynamic system. This thinking can be adopted for the purpose of scientific data visualisation and through its architecture context and background, affords a better connection to fabrication. This is particularly relevant to the aims of this project and enables outcomes to move beyond visualisation to advanced fabrication and realistic customised 3D models.

3D Print Processes

There are numerous types of 3D printing, including fused deposition modelling (FDM), laser sintered powdered printing, direct metal laser sintering, electron beam 3D printing, binder jet powder printing, selective deposition laminating (SDL) and material jet printing. Each of these processes uses different materials and has multiple possible applications. This project focuses on FDM and binder jet printing for the fabrication process as they are the 3D print systems that best tolerate different material experiments while maintaining optimum functionality.

FDM (Fused Deposition Modelling) FFF/ (Free Form Fabrication) and Extrusion 3D printing are similar processes with different names attributed by different printer developers. It is the most common type of 3D printing and can be at an industrial scale or a domestic desktop scale. The process relies on extruding a material through a hose and nozzle in a pattern determined by an STL file. The material is extruded onto a bed or plate of some kind depending on the characteristics of the material being extruded. Many of the cheaper FDM 3D printers use a plastic filament that is heated in the extruder head and then extruded onto a slightly warm platform. The material builds up in fine layers supported in places by a scaffold made of either the same material or another that can be washed away or chemically dissolved after the printing is complete. This printing process relies on the material bonding with the layer beneath as it is printed to ensure the structural integrity of the final printed object. This process requires temperature or other environmental controls such as moisture or air movement to ensure layers' bond at the correct rate. FDM is relatively easy to adjust for different purposes as some printers are designed for use with different types of filaments and many of the mechanisms can be easily hacked or altered. It is also a process that can be scaled up by introducing large gantry frames and robotic arms for delivering materials.

Binder Jet Powder Printing was designed to work with powdered gypsum, however the machines can be adapted to work with other powdered materials. 3D Powder printing machines are divided into two platforms or beds; one is a feed bed or platform and the other, a build bed or platform. The powdered building material is swept in incremental layers by a roller from the feed bed to the build bed by a gantry-style arm. The liquid binder is then projected in the pattern determined by the STL file input into the machine across the X-Y axis. After each layer is bonded, the build bed drops incrementally to allow for the next layer of build material to be swept over from the feed bed in preparation for the next layer of the form being built. The process of printing the material while it is encased in the powder around it means that the object is fully supported as it is formed. Fine details that are either suspended or would be undercuts in another process are held in place as they fuse and then cool.

Once printing is complete, the object can be removed - the build bed can be raised to the surface of the machine and the unfused powder removed by vacuum. This process can be used with multiple types of powder such as gypsum and powdered clay. Colour can be added to the binder.

Material Development -building on precedents

Initial material investigations include gypsum base products, poly lactic acid (PLA) and recently calcium carbonate ($CaCO_3$). STL files of bone models were printed to test for the haptic experience of cutting through and drilling into the models as well as the capacity for detailed customised forms. Models were printed in ABS plastic, PLA, resin and ZCorp powder to compare the material qualities of each 3D print.

Figure 2. 3D printed models testing different 3D materials and 3D print processes. Image by Dr Kate Dunn.

Using a ZCorp 510 printer with ZCorp powder, initial tests demonstrated that the process could replicate small detail very accurately and produce models with enough structural integrity to be handled and shared between researchers. These tests also proved that gypsum could mimic bone to some extent in its materiality and importantly would respond to surgical procedures like cutting and sawing in a similar way to bone tissue.

Figure 2. Example of powder printed gypsum bone. Image by Dr Kate Dunn

The research also investigated the creation of a poly lactic acid (PLA) based material for use in FDM printers to develop more realistic bone models for use in quality control and system development in the context of CT X-ray imaging as a starting point. The aim was to create a filament that could be easily printed by inexperienced persons using a simple, cheap consumer level 3D printer. PLA has a higher density and similar mass attenuation coefficient to water, which is significantly lower than bone. In order to increase the mass attenuation coefficient of the produced material, filament containing PLA and ~33% (w/w) calcium carbonate ($CaCO_3$) was produced by hot mixing and dual extrusion. The resulting material was uniform in diameter, was similar in appearance to commercially available PLA (Figure 3A), although was significantly more brittle. Printing of the bone mimicking PLA based material was successful and shows potential for multiple applications including this project. Further testing using the bone micking PLA and consumer level 3D printers demonstrated that complex and anatomically correct models could be printed. A full-sized adult skull was printed successfully (Figure 3C) and is currently in development for use as a CT and MR phantom by medical imaging researchers. In contrast to regular PLA, the printed bone mimicking material has a granular finish which adds to the haptic experience of the user. In a further demonstration of the utility of this material, we printed a third metacarpal (finger bone) (Figure 3D).

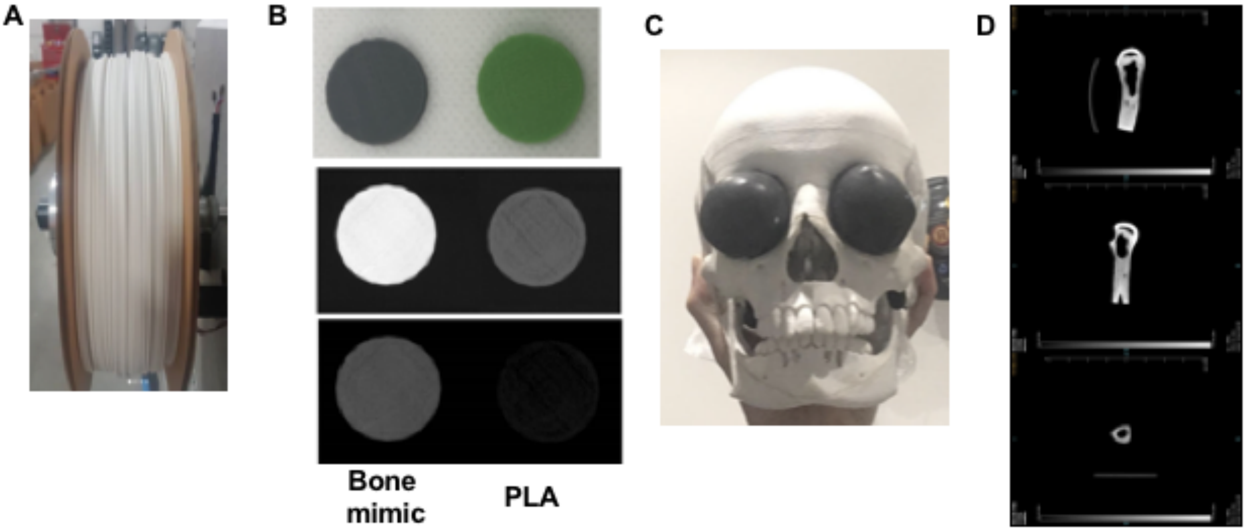

Figure 3. (A) Spooled PLA/$CaCO_3$ filament. (B) Pictures and dual X-ray absorption images at 40 (middle) and 80 (bottom) keV showing radio-opaqueness of PLA/CaCO3 bone mimicking material. (C) Full sized adult human skull 3D printed using FFF and bone mimicking PLA/CaCO3 material. (D) CT scan of third metacarpal bone printed in PLA/CaCO3 bone mimicking material. Images by Dr. Blake Cochran

Next steps

The next steps in the project are to conduct further co-design workshops to determine the strategy for the next iteration and the means of implementation.

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