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Applications of 3D topography scanning and multi-material additive manufacturing for facial prosthesis development and production

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Abstract

Prosthetic based rehabilitation offers several advantages over surgical intervention, however, devices are generally handmade using labour intensive and subjective manufacturing techniques. We investigate the use of optical scanning to capture the surface topography from a volunteer’s facial anatomy, reconstruct this into a 3D CAD model, and from that design a patient specific prosthesis. This approach offers many advantages over existing techniques as data collection is non-intrusive, rapid and provides anatomically precise information. A CAD approach affords greater flexibility when evaluating design iterations and allows for the creation of ‘parts libraries’ for use with patients with no initial reference anatomy. The final prosthesis is realised through high resolution, multi-material 3D printing for precise model reproduction and to add functionalities such as mimicry of soft and hard tissues. Ultimately, we believe our approach provides an optimised, low-cost approach for streamlining the complete methodology for prosthesis production.

1 Introduction

In a human population facial defects can arise as a result of congenital deformities, disease infiltration, and trauma. Given the prominence of the face and how it influences human interactions, such disfigurements can have a profoundly negative impact on the quality of life of a patient. With respect to rehabilitation, there are primarily two treatment option, which comprise surgical intervention or the use of a prosthesis. The decision making process as to which option is the most suitable is not so clearly defined and is dependent on a number of factors, including the size/severity of the condition, age, etiology, and critically, the patient's own personal preference [1, 2]. Examining prosthesis based rehabilitation, there are several immediate advantages when compared to surgical intervention such as the immediate aesthetic improvement, its simplicity over surgery, the ability to explore several design iterations without impact on the patient and its low cost. More recently there has been a surge of interest in a tissue engineering approach to replace missing or compromised organs [3, 4], however despite the promise of this technology there are still many issues to resolve before this is likely to become a reality. Therefore prosthetic treatment provides a more robust, tried and tested approach which has a quick turnaround time for part production and does not have complications associated with surgical intervention, such as tissue rejection.

Traditional prosthesis production is a long, labour intensive process, requiring the use of several invasive and subjective techniques over the entire fabrication process. A summary of the fabrication stages can be found in Figure 1. Typically the process begins with some form of casting approach, generally using plaster, to ascertain the topography of the defective area, or uncompromised anatomy that could be used as a template for the prosthesis [5, 6]. In some instances the plaster is placed over the entirety of a patients face, requiring breathing to be performed through a straw until the plaster sets. Consequently, due to the discomfort of this process the patients can often move during the casting process, resulting in an inaccurate topography map. Following the formation of plaster cast, a wax model is formed and manipulated to realise the finished prosthesis model. At this stage fixation device alignment is also performed, embedding either mechanical or magnetic abutments into the wax model. The process of alignment and finishing of the wax model are all performed manually, with the end result being wholly dependent on the artistic skill of the clinician, which is arguably subjective in nature [7]. Once the wax model is finalised, it is formed into a plaster negative, which in turn is used to form the final silicone prosthesis. Any additional touches to the model, such as the addition of colours and hair, are again performed manually. This makes the whole process of prosthesis production a very arduous and labour intensive process.

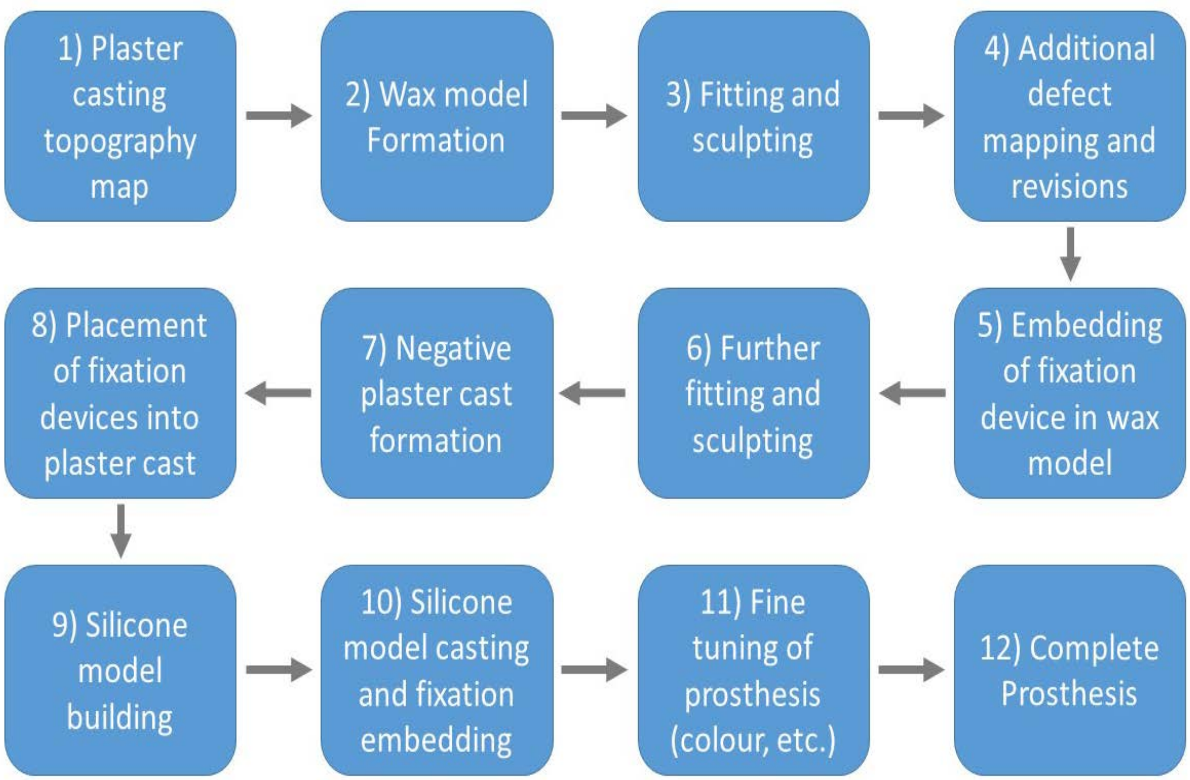

Figure 1: Traditional process chain for prosthesis fabrication

Traditional prosthesis development is on a turning point, where several disruptive 3D technologies are likely to transform traditional prosthesis production. Modern optical scanning techniques readily allow for the rapid, high resolution reproduction of surface topographies, to a precision of <100μm while capturing useful data such as texture maps of a patients skin [8-10]. Additionally, data is obtained non-invasively and can performed using laser free methodologies, greatly improving the potential uptake of this technology in a clinical capacity. Modern Computer Aided Design (CAD) software readily allows for the conditioning of 3D scan data to create a complete model, with the added advantage of allowing for the digital storage of design iterations and the final model. Such digital data conditioning and storage, when applied to prosthesis production, compares very favourably to traditional hand crafting techniques. Finally modern 3D printing technologies offer the ability to easily and rapidly reproduce a high resolution digital model into a physical part [10-16]. Fabrication can also be achieved using a vast array of flexible and biocompatible materials, allowing for augmentation of existing practises, and potentially, direct prosthesis fabrication.

In this study we have investigated the use of optical scanning, CAD and 3D printing in the direct production of various facial prosthesis (ear and nose). Previous studies have primarily focused on the use of such technologies for the production of a cast to augment traditional techniques, or models which are made in rigid plastics. By contrast, the novelty in this work is to use high resolution 3D printing of flexible materials for the direct production of a prosthesis which not only is of a higher quality surface finish as compared to previous studies but also mimics the tactile feel and pigmentation of human soft tissues. We also investigate the production of advanced prosthesis models, comprising multi-model and multi materials designs, which more closely reproduces human tissue through mimicry of both skin and cartilage. Our technique offers several advantages over traditional techniques as the use of optical scanning for topography mapping is non-invasive, can acquire data within minutes and realises anatomically precise, high resolution data, ideal for prosthesis production. A digital CAD approach for prosthesis design is superior when compared to traditional casting and hand crafting approaches as design iterations can be easily digitally stored, do not require any fabrication/material consumption and allows for operations such as mirroring of a model with relative ease. Finally, the use of high precision 3D printing allows for rapid digital part realisation, can produce sophisticated prosthesis comprising complex multi-material/models and can readily allow for precise reproduction of a given model should duplicates be required. Ultimately, we believe the techniques presented in this work realise a patient specific, low-cost and high resolution approach to streamlining prosthesis optimisation and production.

2 Experimental

In this study we have investigated the use of several 3D digitising, rendering and printing technologies to directly create prosthesis replica from a person's anatomy. The complete process chain can be seen in Figure 2, where surface topography maps are made using an optical scanner, designs are post processed using CAD and the final model is realised using high resolution, multi-material 3D printing.

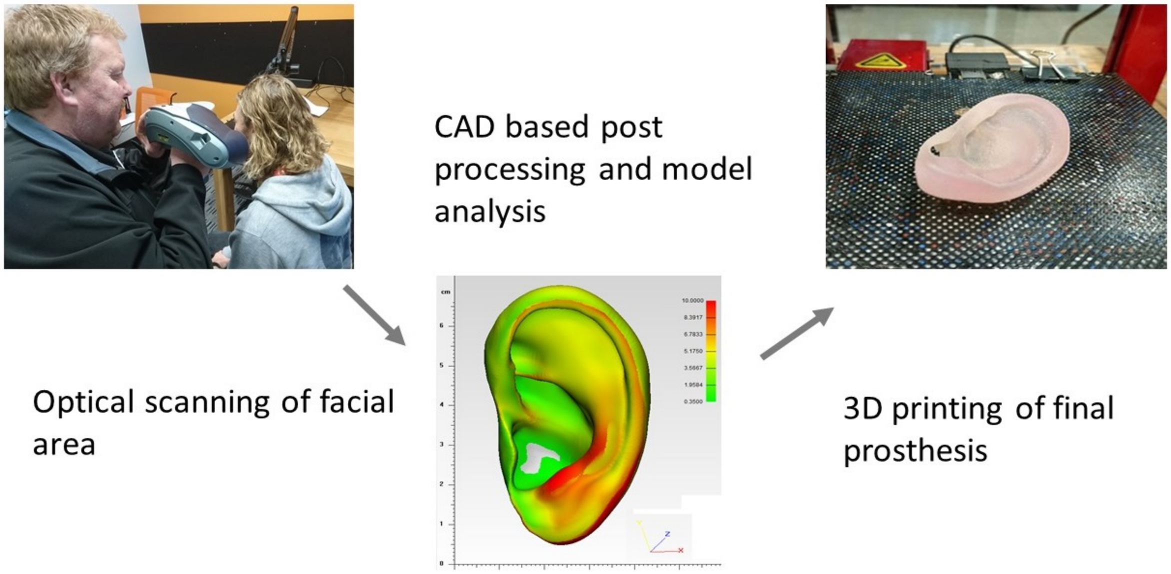

Figure 2: Diagram illustrating the proposed process chain for prosthesis production

2.1 Topography mapping and model construction

In this study a laser free, optical scanning system (Spider, Artec, Luxembourg) was employed to obtain the surface topography of a nose and ear of a volunteer. Laser-free scanning technology alleviated any health concerns resulting from laser exposure to the eyes. The scanner used had image scan resolution of approximately 50-100µm, which is more than adequate to resolve all the major and minor details of the anatomical part rendered. The scanner operates alongside a proprietary software (Artec studio 10, Artec, Luxembourg), which allow for the real-time visualisation of the scan data during acquisition. It was found that several translations of the scanner were required to obtain the full surface map, comprising translations at approximately 10cm/s in a lateral and vertical arcing motion. The scanner allowed for a part to be rendered rapidly within approximately 3-5 minutes.

The scanner software processes the input data as a point cloud, which is converted into a full contour map. Rudimentary operations can also be performed to condition the data, removing spurious noise, cropping of unrequired data, filling of holes/gaps in the model and smoothing of contours. The resulting output is as an enclosed model, and so further post processing is required to hollow a part and realise features such as nasal cavities and ear canals.

2.2 Model construction and Post processing

Data from the scanner was conditioned using more sophisticated CAD software to process the surface topography data and to construct more advanced design for composite model printing. In this study all additional post processing was performed using the 3-Matic software package (Materialise, Belgium), which can allow for direct STL manipulation, error checking and part thickness analysis. Data conditioning comprised smoothing of rough surfaces, removal of features that could lead to print failure, and to perform procedures such as part hollowing.

In this study we aimed to realise an advanced prosthesis that more closely mimics human physiology in terms of tactile feel and pigmentation. As a demonstrator we took a constructed model of the ear and reconstructed it to build separate models of the cartilage and a composite of the softer tissues. Facets of the cartilage model were constructed by a purely design based approach and so to obtain anatomical accuracy the model was constructed by cross referencing anatomical drawings of the ear cartilage and by direct feel of the test subjects actual ear. Approximations were then used to determine the layer thickness of the skin relative to the cartilage in the model.

2.3 3D Printing

Once rendering and post processing had been completed, the final models were directly 3D printed to produce the final prosthesis. To obtain a high accuracy in digital reproduction a high resolution 3D printer was used (Connex 3 500, Stratasys, USA) which can print models in up to three individual materials or blends thereof to an accuracy of 16-30µm. This level of accuracy was more than adequate to reproduce all major and minor surface contours, whilst also realising a high quality surface finish to the prosthesis, similar to that obtained by traditional techniques. The printer operates exclusively using a set of materials which are developed by Statysys for use in this printer, with no option to use non-proprietary materials. These system is generally designed for product prototyping and design evaluation purposes and so facets relating to exact composition and biocompatibility of the materials used are not known. Exploration of the material properties will be the subject of our future work.

Initially, a model is loaded into the printer’s software as an STL file and is allocated a specific material combination before being sliced into the individual printing layers. Simultaneously a water soluble support material is allocated as required to ensure the build integrity. The printer operates using a Polyjet technology, whereby a proprietary liquid photo curable polymer is delivered by the print head and subsequently flattened and cured by a UV lamp. Once a model is complete, a final cleaning phase is required to remove the support material before the part is ready for use. The printing process can take on average 2-3 hours for a part to be printed, depending on its size and orientation.

The printer used in this study was capable of printing in several different materials, which have a variety of different colour and mechanical properties. For instance the Tango plus material range is a flexible material, while the Vero materials are rigid coloured materials. For the final prosthesis parts we examined a combination of both Tango plus and Vero materials such that we could obtain a final model with a flexible tactile feel but also with adjustable colours. It was our hope in this study to realise combinations that mimic the feel and pigmentation of a person’s actual tissue. Further, the advanced multi model approach allows for further control of the tactile feel of a given anatomical part.

3 Results

3.1 Scanning and model creation

Various scans were performed on a test subject in an attempt to reproduce the surface topography of their nose and left ear. In this instance the subject was a health individual who suffered no facial defects, allowing for comparison of the printed prosthesis with the original anatomy. When performing scans, the fast fusion mode of the scanner was utilised, which allowed for rapid, real-time visualisation of the scans as they were being performed. Scans were performed translating the scanner through the various orientations previously described. Following completion of the data acquisition several additional data conditioning phases were performed using Artec studio to remove spurious nose and to reconstruct gaps in the data. Following completion of the scans, the software allowed for several automated procedures to crop the part of interest from the wider facial data and to convert the scan from a surface to an enclosed mesh.

It was found that there were limitations to the scanning process and areas of the skin which were shiny/reflective were difficult to render during scanning. This limitation could be overcome using a mat finish power to dampen optical reflections, however, that was not required in this study. Additionally, regions that had low levels of light exposure were equally difficult to render, such as the nasal cavities and ear canal. As such features are critical to the final prosthesis, they had to be rendered independently using 3-matic.

3.2 Model post processing

3.2.1 Single model

Following initial rendering, the models were checked to remove errors such as inverted normals, multiple shells, noisy shells, etc. This procedure ensure the best quality of digital data to be used for the subsequent design phases. In general the rendered models from the scanner looked reasonably close to the final prosthesis models and so only relatively simple post processing was required. With respect to the nose data, the nasal cavities were completely enclosed and so the first procedure was to remove excess digital material to open these areas and to provide access to the reverse side of the model. The necessity for this is that generally a recipient of such a prosthesis will have use of their nasal ducts and so open access here would allow for a potential patient to retain the ability to smell, breathe, etc. With respect to the ear data, by cross referencing the major contours against the original test subject, it was found that several of the contours formed by the cartilage had been lost during the post processing within the Artec Software. Therefore these areas were manually reconstructed using the ‘push pull’ and extrude functions within 3-matic. Figure 3a) illustrates the final model of the ear prosthesis

With respect to the ear, when a thickness analysis was performed, it was found that there were regions which were <350µm thick. While this is not an issue to the aesthetics of the digital mode, should this be printed, this region would be extremely fragile. From initial test prints at this thickness in the rubber like Tango plus material, it was found that the parts ruptured during the support material removal phases. Several design iterations were examined increasing the minimum thickness in steps of approximately 200µm, where it was found that for thicknesses greater than 1mm the models could be cleaned without rupturing. Therefore the thickness analysis of the part is critical to the integrity of the final prosthesis using the Tango plus material, and the parts were thoroughly inspected to ensure no regions were of a thickness less than 1mm. Figure 3b) shows a model of the ear before and after the thickness analysis and subsequent model region growing.

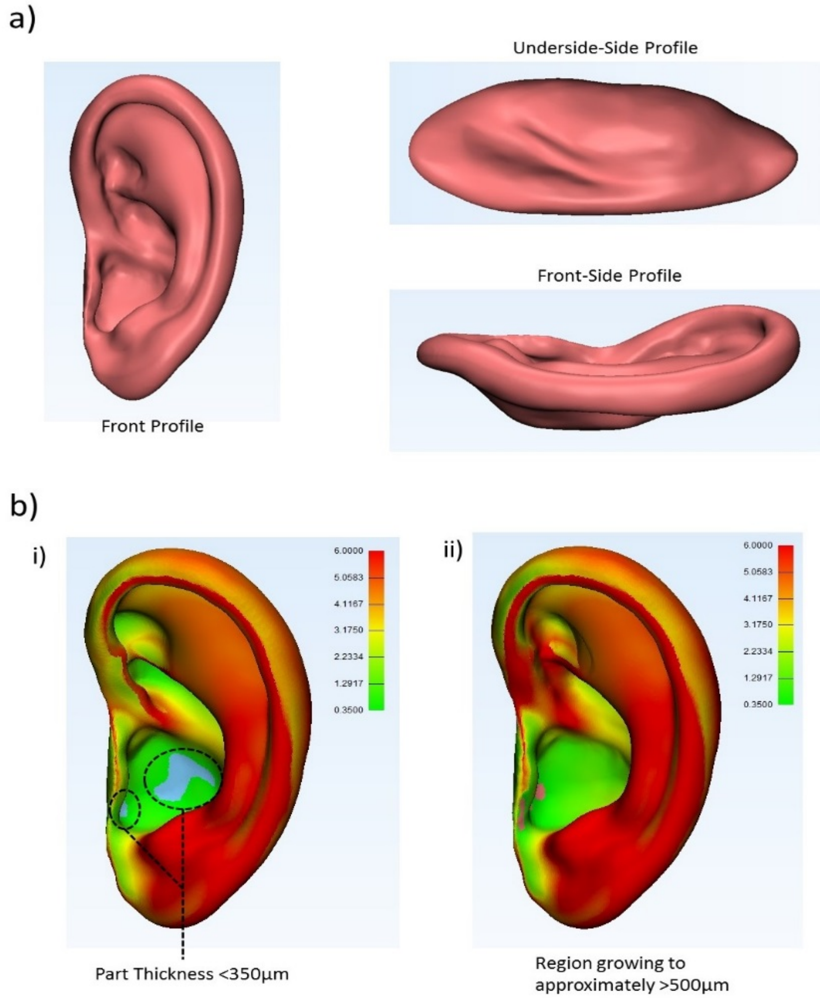

Figure 3: a) Various orientations of the ear prosthesis model. b) Colour map thickness analysis of the ear model for i) the raw data model input from the 3D scanner software, ii) post processed model to grow the thickness of the inner ear section to approximately ≥1mm.

3.2.2 Multi-component ear modelling

The anatomy of the human ear comprises a single piece of cartilage tissue in the ear which makes the design process relatively simple in comparison to more complex cartilage structures such as the nose. Initially attempts were made to render the cartilage of the ear as a stand-alone model. To achieve this the original ear model was duplicated and reduced in size by 96% to create a replica structure that was positioned approximately 1.5mm into the original ear model. This new model was then reformed by referencing anatomical drawings of a generic human ear cartilage, the contours captured within the scanned ear model and by direct feel of the human subject. The cartilage reconstruction process can be performed to a high degree of precision using digital thickness analysis to augment the design process, however arguably the use of feel to determine model topography is a subjective metric. It is noted that this part of the process is merely for qualitative assessment of the model and forms a very minor part in the design process and does not compromise the precision of the final rendering. The final model that was achieved can be seen in figure 4, which closely matched the medical diagrams.

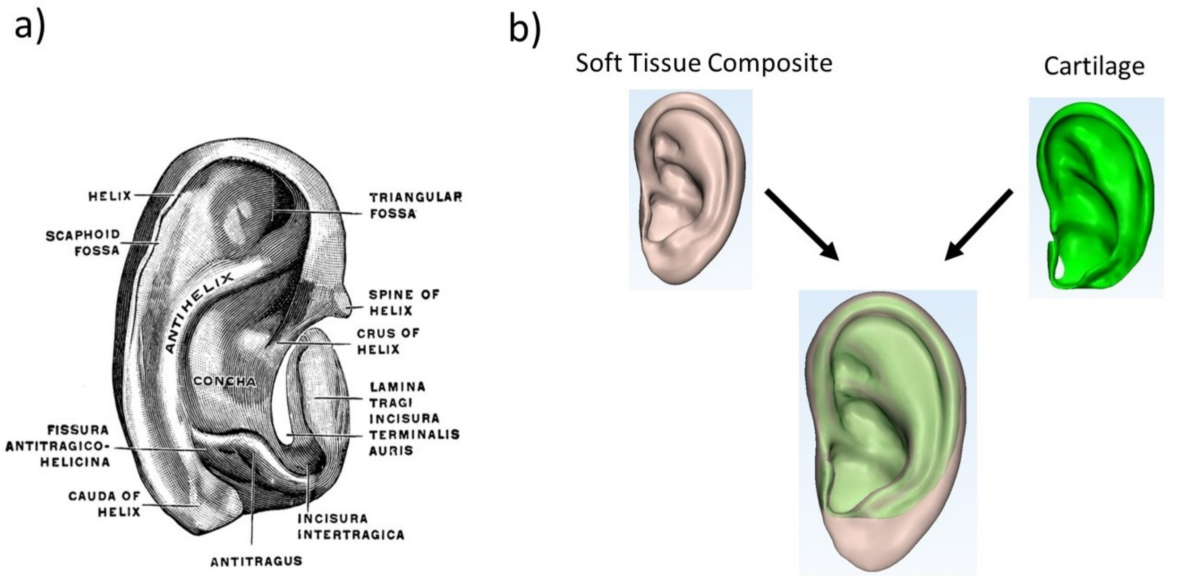

Figure 4: a) A classical medical diagram of the cartilage within the ear [17], adapted from https://lookfordiagnosis.com/mesh_info.php?term=ear+cartilage&lang=1. b) The multi-model design of the ear prosthesis comprising the soft tissue composite and the cartilage. For visualisation purposes both segments are also represented individually.

3.3 Prosthesis 3D printing

3.3.1 Single model printing

Following completion of the models, initial tests were performed to ascertain the printing precision, model integrity, mechanical conformity and pigmentations that could be achieved using a multi-material combinatory approach. The Connex printer is capable of printing with 3 materials simultaneously. However as flexibility is achieved through the use of the transparent Tango plus material, only two additional materials (colours) could be used. Given the availability of colours by the manufacturers, it was decided that blends of magenta and yellow would provide the best options for skin pigmentation mimicry. An effective colour map was produced of the different material combinations when using Tango plus and Vero materials as can be seen in figure 5a). Another issue that arose was the percentage blend of the rigid Vero with the flexible Tango plus material, where a threshold of >50-60% Vero material compromised the tactile feel beyond the desired flexibility found in a typical prosthesis. The tango plus material used in this study was a translucent variant, which on its own provided the softest tactile feel but was not a suitable colour for a prosthesis. It was found that a minimum of 10% Vero material was required to provide any visually noticeable pigmentation into a given prosthesis. Various combinations of Tango and Vero material were explored to print the final prosthesis, and the various material combinations examined are illustrated in Figure 5a).

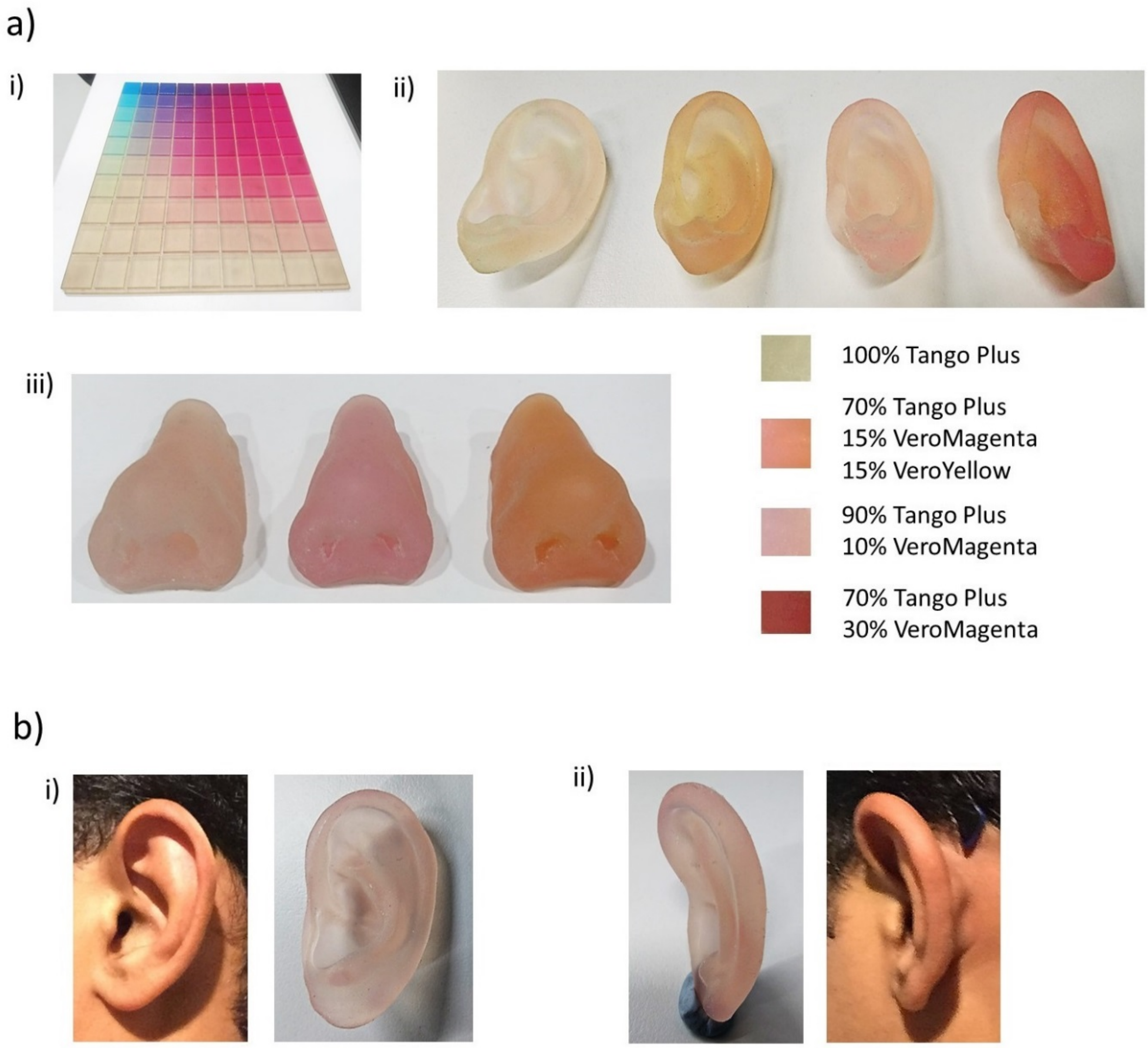

Figure 5: a) i) An image of the material map which show the various colour combinations possible with the 3D printer using two Vero colours and the flexible Tango plus material, and images of various printed prosthesis of ii) an ear and iii) a nose model. Material combinations are also highlighted in the legend. b) Comparative images of the subject's ear and the 3D printed model from i) side and ii) reverse profiles.

The high resolution of the connex printer and it effective use of dissolvable support material allows for the reproduction of both the ear and nose models and with a smooth surface finish. The reproduced models were found to be a very good match to the original anatomy, both in terms of major surface contours and overall size. Various nose and ear models can be seen in figure 5aiii), where is can be clearly seen how the multi-material printing allowed for a diverse array of prosthesis pigmentations from lighter to darker skin tones. Also show in figure 5b) is a comparison of the printed ear prosthesis relative to the volunteer subject's original ear. It can be seen that the final prosthesis very closely matches the original contours of the ear, validating the efficacy of this technique. All 3D printed models were realised using a single material combination across the entirety of the model. When examining the ear models more closely, it was found that the richness of the visible colour changed depending upon the thickness of the material. By comparison the nose models did not exhibit such features. This is perhaps due to the thickness tolerances of these models, which were generally between 1 and 6mm allowing for varying degrees of translucency. In contrast the minimum thickness of the nose was approximately 15mm therefore at these thicknesses all translucency properties are negligible. This facet is similar to human physiology, where the thickness of the soft tissues overlaying the cartilage of the ear has a variety of different pigmentations owing to its relative thickness. We hope to examine such facets more closely in future work.

The printed models were qualitatively assessed for their tactile feel and mechanical compliance to that or the original human subject. Tests comprised the ability to flex the lobe area, a vertical compression test from the lobe to the upper portion of the ear and a lateral compression test pinching across the centre of the ear. It was found that the printed models all exhibited similar characteristic to the original anatomy, such that upon relaxation of the compressive force that the ears would return to the neutral position of the model, as can be seen in figure 6a). It was noted that the printed material was more rigid, despite its elasticity, than real human anatomy. This resulted in a greater force having to be applied to achieve the various modes of compression, highlighting limitations of current printable, flexible materials. The purpose of this work was to present our methodology regarding the scanning, design and printing capabilities and we hope to more quantitatively measure mechanical properties of the prosthesis in future studies. It is also noted that as the percentage combination of the Vero material was increased in the model, the necessary applied force became larger. At a percentage of 60% Vero, the elasticity of the model was compromised beyond an acceptable level and became noticeably rigid. This therefore limits the wider colour combinations possible while still retaining acceptable levels of elasticity to mimic human mechanical properties. We hope in future work to quantify such forces both for real anatomy and printed prosthesis.

3.3.2 Multi-model printing

Beyond a single material model, we attempted to realise multiple models, rendered using independent material combinations, thereby mimicking the softer and harder tissues of the ear. The connex printer allows for the overlay of multiple models and for independent material allocation to each when printing. We therefore processed the advanced ear model such that the soft tissue composite was printed with 100% Tango plus and the Cartilage model was printed with 50% Tango plus and 50% VeroMagenta. These material combinations were used primarily for visualisation purposes such that each element could be visually differentiated, and the final printed model can be seen in figure 6b). The connex printer was found to provide excellent multi-material printability, with the two materials seamlessly blending into a single structure without any impact on the final surface finish of the model. Therefore the polyjet printing process of the connex is considered ideal for rendering of blended materials as well as multiple models for direct prosthesis printing.

Once again the mechanical properties of the model were assessed by qualitative compression tests. On this occasion it was found that there was much greater rigidity to the ear model, as expected, however the ability to be compressed vertically and laterally were not compromised and the model would also return to the neutral position upon relaxation of the compressive force. It was noted that the movement of the ear lobe was identical to the single material/model prints. Outcomes of the multi-model printing illustrate that the mechanical properties of the printed models can be further modified to reach increasing levels of complexity, as found in actual human anatomy. We hope in the future to more quantitatively assess the mechanical properties and to explore the ability to more seamlessly blend the colour combinations into a more realistic final model

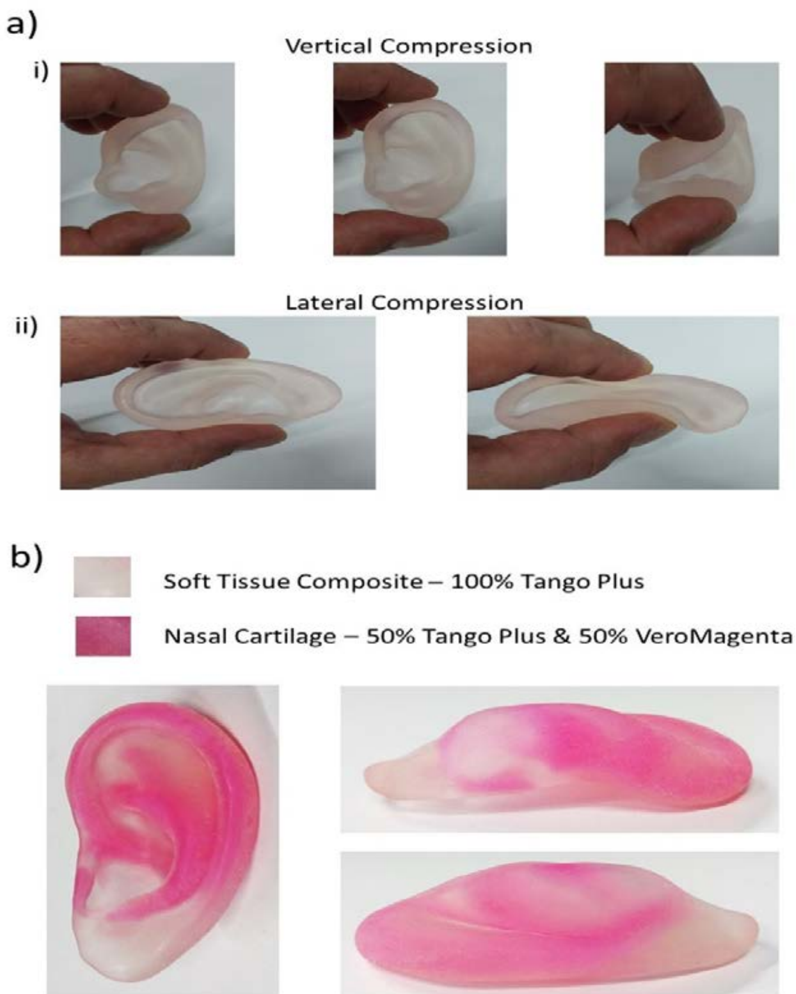

Figure 6: a) Qualitative compression of the model to demonstrate the realism in the tactile feel for both i) vertical and ii) lateral compression. b) Multi-model printing of the ear, with independent material combinations for the cartilage and residual soft tissue composite.

4 Conclusions

This study has demonstrated the potential of the 3D design and multi model/material printing, augmented with the use of optical surface scanning, to produce realistic prosthetic models of both the ear and nose. The fabricated prosthesis were realised to a high degree of accuracy and surface finish, and we believe the technique suitable to render additional prosthetic parts, such as orbital prosthesis. We realised advanced prosthesis models beyond the traditional single model variants using novel design techniques to render components such as cartilage alongside other soft tissues (skin, etc). Using the multi-material printing approach we could tailor the skin pigmentation of the prosthesis to a variety of skin tones, whilst also mimicking the mechanical properties of the original anatomy. The mechanical properties can be further tailored using a multi-model approach. Currently there are limitations in the complexity of the skin tones that can be mimicked without compromising the mechanical properties, due to the percentage material combinations. Additionally, the overall printed prosthesis tactile feel is more rigid than actual anatomy. These limitations are primarily due to the materials used in the 3D printer, but we believe as the technology matures over the coming years, these limitations will be resolved. Ultimately, the findings in the work validate our approach for direct prosthesis production which overcome limitations relating to the subjective nature of current prosthesis fabrication, and allow for production within a single day. This compares favourably to traditional techniques where typically a prosthesis if fabricated over several weeks/months. Ultimately, this technique holds considerable potential for implementation within a clinical setting, streamlining to overall process for prosthesis production and could see applications in other niche areas such as soft robotics or anatomical modelling.

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