DEVELOPMENT AND VIRTUAL VALIDATION OF A NOVEL DIGITAL WORKFLOW UTILISING OPEN-SOURCE SMARTPHONE BASED STEREOPHOTOGRAMMETRY IN PROSTHETIC REHABILITATION OF PALATAL DEFECTS

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by

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LIST OF ABBREVIATIONS

3D	Three dimensional
SPINS	Smartphone intelligence-based stereophotogrammetry
OS/F	Open source and free software combination
IDE	Integrated Development Environment
MSA	Mesh Surface Area
VV	Virtual Volume
HD	Hausdorff's distance
DSC	Dice similarity coefficient
CAD	Computer aided design
CUDA	Computer unified device architecture
SFM	Solid from motion

LIST OF APPENDICES

PEMBANGUNAN DAN PENGESAHAN MAYA ALIRAN KERJA DIGITAL BARU MENGGUNAKAN STEREOFOTOGRAMETRI BERASASKAN TELEFON PINTAR DAN KECERDASAN DALAM PEMULIHAN PROSTETIK KECACATAN PALATAL

ABSTRAK

Kecacatan palatal boleh dipulihkan dengan menghasilkan prostesis maksilofasial yang dipanggil “obturator” setelah impresi diambil untuk meniru kecacatan palatal. Model-model tersebut kemudian disimpan secara digital menggunakan perkakasan yang mahal serta tidak mudah didapati untuk mengelakkan kerosakan fizikal atau kehilangan data. Apabila diperlukan, “obturator” di masa hadapan dirancang secara digital menggunakan perisian proprietari yang mahal dan dibuat menggunakan pencetak 3D. Objektif penyelidikan ini adalah untuk membina dan mengesahkan pengimbas 3D stereofotogrametri berasaskan telefon pintar ekonomi (SPINS) dan untuk menilai ketepatannya dalam merancang prostetik menggunakan perisian sumber terbuka oleh kajian perbandingan. Model kecacatan palatal diimbas menggunakan SPINS dan dibandingkan dengan pengimbas laser standard. Parameter perbandingannya adalah luas permukaan jejaring, isipadu maya, jarak Hausdorff (HD) dan pekali kesamaan Dice (DSC). Ambang had penerimaan untuk HD ditetapkan kepada <0.5 mm dan DSC > 0.70. Model 3D yang dihasilkan SPINS kemudian digunakan untuk merancang obturator digital menggunakan aliran kerja sumber terbuka. Perbandingan obturator digital dibuat dengan menggunakan parameter yang sama dan dibandingkan di antara ‘model laser yang diimbas dengan perisian proprietari’ dan ‘model laser yang diimbas dengan perisian sumber terbuka’. Tidak ada perbezaan yang signifikan ($P > .05$) pada luas permukaan dan isipadu ketika

membandingkan pengimbas SPINS vs Laser, dengan SPINS memenuhi kedua-dua ambang penerimaan. Luas permukaan permukaan jejaring dan isipadu masing-masing 2.12% dan 1.79% lebih tinggi daripada pengimbas laser. Penilaian aliran kerja sumber terbuka terhadap perisian proprietari juga menunjukkan tidak ada perbezaan yang signifikan (P> .05) di luas permukaan dan isipadu alat prostetik dengan semua kumpulan memenuhi ambang penerimaan HD dan DSC. Jika dibandingkan dengan prosedur proprietari standard, aliran kerja sumber terbuka menunjukkan luas permukaan kurang 5.80% manakala isipadu lebih 21.40% pada alat obturator yang direka dari model laser yang diimbas. Sebagai alternatif, apabila menggunakan SPINS, sumber terbuka menunjukkan luas permukaan kurang 6.53% manakala isipadu lebih 15.08% pada alat obturator. Dari simulasi ini, SPINS dan aliran kerja sumber terbuka perlu digunakan di klinik untuk penilaian lebih lanjut berkaitan penyimpanan rekod kecacatan maksilofasial.

DEVELOPMENT AND VIRTUAL VALIDATION OF A NOVEL DIGITAL WORKFLOW UTILISING OPEN-SOURCE SMARTPHONE BASED STEREOPHOTOGRAMMETRY IN PROSTHETIC REHABILITATION OF PALATAL DEFECTS

ABSTRACT

Palatal defects are rehabilitated by fabricating maxillofacial prostheses called obturators upon plaster models obtained by taking impressions of the defect site. The models are then digitally stored using expensive and not-readily-available hardware to prevent physical damage or data loss. When required, future obturators are digitally designed using expensive proprietary software and 3D printed. The objective of this research was to utilise and validate an economic in-house smartphone based stereophotogrammetry 3D scanner (SPINS) and to evaluate its accuracy in designing prostheses using open source pipeline by a comparative study. Palatal defect models were scanned using SPINS and compared against the standard laser scanner. The parameters of comparison were mesh surface area, virtual volume, Hausdorff's distance (HD) and Dice similarity coefficient (DSC). The acceptability threshold for HD was set to <0.5mm and DSC > 0.70. SPINS derived 3D models were then used to design digital obturators using an open source workflow. Comparison of digital obturators were made using the same parameters and compared against 'laser scanned models with proprietary software' and 'laser scanned models with open source software'. There were no significant differences (P>.05) in surface area and volume when comparing SPINS vs Laser scanner, with SPINS meeting both acceptability thresholds. Mesh surface area and volume were 2.12% and 1.79% more than the laser scanner respectively. Evaluation of open source workflow against proprietary

counterparts also suggested no significant differences ($P>.05$) in surface area and volume of the prosthetic bulbs with all groups meeting both HD and DSC acceptability thresholds. When compared against the standard proprietary procedures, open source workflow demonstrated 5.80% less area and 21.40% more volume in obturator bulbs when designed from laser scanned models. Alternatively, when developed from SPINS, open source demonstrated 6.53% less area and 15.08% more volume in obturator bulbs. From the current simulation, SPINS and open source workflow should be applied to the clinical setting for further evaluation of maxillofacial defect record keeping.

CHAPTER 1

INTRODUCTION

1.1 Background

A maxillary obturator is a prosthesis that rehabilitates the defect in the palate/maxilla following one of multiple situations; they can be fabricated to rehabilitate and improve the quality of life after surgical resection following partial or total maxillectomy or applied to patients with surgically untreated clefts. (Tolhurst and Huygen 1985; Rogers et al. 2003; Chigurupati et al. 2013; Breeze et al. 2016; Dholam et al. 2019)

However, the conventional fabrication of the obturator prosthesis is a technique sensitive procedure and is a particular challenge when taking an impression of the defect. The patient's heightened expectations following the complex procedures also lead to overall diminished levels of post-treatment satisfaction. (Kumar et al. 2016; Dos Santos et al. 2018). Furthermore, there is a persistent risk of impression material clinging at the complex defect cavities after maxillectomy. Often times these residues go unnoticed until later when there is a foreign body reaction and the patient returns with complications like congestion, sinusitis, respiratory obstruction among others which might require referral to specialists and subsequent hospitalisation (Chate 1995; Ravikumar et al. 2015; Datta et al. 2017)

Although unfathomable, successfully recording the palatal impression is casted into dental models, upon which a temporary prosthesis is fabricated and periodically readjusted to facilitate proper healing. Clinicians have to refer to the defect models during readjustment phase. After provision of temporary obturators, the models are preserved and retrieved upon future reference especially during the fabrication of definitive prosthetics after completion of healing.(Singh et al. 2013) However, the dental models are subjected to wear and tear, breakage, or misplacement, which warrant a fresh process of obtaining impressions prior to definitive prostheses fabrication. This ordeal creates inconveniences for both the patient and the clinician, increase treatment durations and may compromise clinical success. In recent years, CAD-CAM and rapid prototyping in prosthetic dentistry have introduced methods of averting these issues.

Advanced healthcare facilities have gradually assimilated the transition of digital record preservation. Although, it is difficult to record the entire defect by 3D scan, initially the clinicians create a physical model using conventional impression techniques which is subsequently scanned using high accuracy laser scanners and secured digitally with multiple copies of the same. Whenever necessary, the prosthetic moulds/templates are then digitally designed, and 3D printed; averting impression-related risks to the patient while saving valuable time for the clinicians. (Farook et al. 2020a). This allows the models to be stored long after treatment completion in virtual space without the risk of weathering or accidental damage. However, such proprietary Scanning & CAD technology is expensive to purchase and upkeep. For such technologies to improve prosthetic care in developing regions, some economic modifications to the overall procedure can be made to improve feasibility.

Increasing smartphone usage and a plethora of associated advanced dental technologies have created substantial inclusivity worldwide.(Oncescu et al. 2013). Fortunately, constant improvizing portable technology is gradually bridging the gap between developing and developed countries marking the next digital revolution.. Furthermore, the online accessibility to open-source (free to use and modify) CAD software have proven to be consistently reliable in dental designing.(Talmazov et al. 2020). Thus, it becomes imperative to evaluate whether smartphones and open-source

CAD can be incorporated into designing of maxillary obturators to create an economic and readily accessible digital workflow for the practicing clinician.

1.2 Problem Statement

Hardware limitation: The method to scan and digitize dental casts (data acquisition) require procurement of very expensive hardware, such as 3D intraoral scanners and laser scanners. Such technology cannot be readily accessed by clinicians working in developing nations.

Software limitation: The proprietary software used to process (modify, preserve, and design) the scanned models are expensive to purchase and maintain the subscription. Such commercial software also have a very steep learning curve owing to their wide arsenal of in-built feature-rich functionalities.

1.3 Justification

Hardware justification: Consumer cameras have been shown to be beneficial in capturing other aspects of dentistry like endodontics, oral surgery, and orthodontic profiling. However, limited data is available on the usefulness of smartphones in scanning 3D dental casts for prosthetic rehabilitation. Furthermore, to our knowledge, no device has been fabricated to utilise smartphone's camera for the purpose of maxillary defect cast scanning by stereophotogrammetry.

Software justification: The smartphone scans can only be justified if the resultant outcomes can be processed and used for digital prosthetic design. The workflow needs to be economic, and therefore can be done by open-source CAD software suite. However, to our knowledge, a workflow is not available which utilises open-source and/or free software for processing smartphone scanned maxillary defect casts and subsequently utilising them to develop digital obturators.

1.4 Clinical Implications

This study will aim to create a system which will utilise smartphones to capture dental defect models and process them using open source. This will enable a cost-effective method of digitising the dental models with defect as data for record keeping purpose and allow for production of subsequent obturator bulbs from the digital data as per clinical demand.

1.5 General Objective

To create a **S**mart**P**hone-based **IN**tuitive **S**tereophotogrammetry (SPINS) device to capture maxillary defect casts (data acquisition) and then use open source workflow to design digital obturator bulbs using said casts (data processing). The workflow can then be compared against their standard laser scanner and proprietary software counterparts.

1.6 Specific Objectives

1. To compare the Mesh Surface Area and Virtual Volume of digital defect cast models produced by SPINS versus the standard laser scanned counterparts
2. To observe the Hausdorff's distance (HD) and Dice similarity coefficients (DSC) in the comparison of digital defect models produced by SPINS versus their standard laser scanned counterparts
3. To compare the mesh surface area and virtual volume of obturators developed from Open source SPINS workflow, open source Laser scan workflow and proprietary laser scan workflow
4. To observe the HD and DSC in the comparison of obturators developed from open source SPINS workflow versus proprietary workflow

1.7 Research Questions

1. Are there any differences in the virtual parameters (mesh surface area, virtual volume, Hausdorff's distance and Dice similarity coefficient) of scanned defect casts when comparing between SPINS and standard laser scanner?
2. Are there any differences in the virtual parameters of obturator bulbs when comparing among SPINS – open source workflow, Laser scan – open source workflow and Laser scan – proprietary workflow?

1.8 Null Hypotheses

1. There will be no significant differences in the virtual parameters (mesh surface area and virtual volume) of scanned defect casts when comparing between SPINS and standard laser scanner
2. There will be no significant differences in virtual parameters (mesh surface area and virtual volume) when comparing among SPINS – open source workflow, Laser scan – open source workflow and Laser scan – proprietary workflow.

CHAPTER 2

LITERATURE REVIEW

2.1 A Brief introduction

Maxillofacial prosthodontics deal with the prosthetic rehabilitation of acquired, congenital or developmental disfigurements where surgical intervention is not enough (Hatamleh et al. 2010). Said prostheses range from intraoral obturators to extraoral auricular, nasal, orbital, ocular prostheses.

As accounted in history (Peng et al., 2015), in 1967, Herbert Voelcker first proposed the use of computers for solid modelling (later on called 3D printing). Charles Hull later, in 1986, improved on the previous work and invented 3D models and stereo-lithography. Stereo-lithography file format: standard tessellation language (STL) is still commonly used for 3D printing. 3D printing, over the years had many names, starting from the obvious "3 dimensional printing", "additive manufacturing" and "solid free-form technology", "rapid prototyping" and "computer aided design – computer aided manufacture" etc.(Aldaadaa et al. 2018) Regardless of the name being given, the principles almost invariably remain the same; there has to be a means of data acquisition, data processing and data output.

Data acquisition can be by means of CT scans, Cone beam CT scans, laser scans or 3D photographs/photogrammetry. Data processing usually refers to the software at play to work on and edit the data acquired. In this case, data processing is aimed to fabricate the prosthesis or its associated components. Data output refers to 3D printing of the processed image and can be carried out using one of many industrial or desktop 3D printing technologies.

2.2 How are conventional prostheses made?

In order to understand the digital workflow, one needs to understand how the conventional prosthesis has been made throughout the decades. The conventional method of fabricating all the mentioned prostheses has a similar workflow. A conventional impression is taken using hydrocolloids, elastomeric or thermoplastic materials. These materials record the negative imprint of the defect site, also known as a mould. These moulds are filled with investment materials to create a cast of the defect site. The clinician or technician would then design the prosthesis onto the defect site using wax, try it onto the patient to match colour and marginal integrity. Once satisfactory adaptation and colour matching is done, the final wax product is converted into silicone or acrylic using their respective processing armamentarium. Silicone is the material of choice for said rehabilitation for its robust physical properties.(Barman et al. 2020) The final prosthesis may need to have their margins recontoured according to aesthetic or functional needs. This is done at chairside by using soft setting materials known as tissue conditioners and relining material. The entire process is called relining and is more important in obturator and ocular prostheses than the other prostheses.(Jain et al. 2011; Jamayet et al. 2017; Farook et al. 2019; Al Rawas et al. 2020)

Obturator prostheses over the years have been classified by various authors according to various set criteria. Authors have used Aramany's (Aramany 1978) and Brown's (Brown and Shaw 2010) classifications in various instances to find that Aramany's Classification 1 and Brown's classification 2a & 2b were the most common defects being rehabilitated across large patient sample sizes(Kreeft et al., 2012; Huang et al., 2015; Chen et al., 2016; Dos Santos et al., 2018). This was kept in consideration when simulating the samples for the current study.

2.3 The digitisation of obturators

With the advancement in digitization in the other fields of maxillofacial prosthetic dentistry(Farook et al. 2020a), one can easily assume that the management of post-surgical head and neck cancer patients would see significant digital progress. Yet only 12 papers (as of late 2019) have been recorded with some form of digital workflow to design the obturator prosthesis. Furthermore, all 12 papers were published in the last 6 years. Of the 12 articles reviewed, 4 articles (Jiao et al. 2014; Rodney and Chicchon 2017; Tasopoulos et al. 2017; Tasopoulos et al. 2019) mentioned only CT scans as means of data acquisition while 2 articles (Michelinakis 2017; Palin et al. 2019) reported only CBCT. While 2 groups of authors(Michelinakis et al. 2018; Kim et al. 2019) mentioned using only intraoral scans, 3 authors(Huang et al. 2015; Elbashti et al. 2016; Ye et al. 2017) mentioned the combination of intraoral scanners with CT/CBCT. Kortes et al.(Kortes et al. 2018) also mentioned the use of CT with MRI and physical model of dentition for optimal data acquisition. Digital cameras and smartphone cameras have recently been used in dental model scanning (Elbashti et al. 2019; Stuani et al. 2019) however has not yet been applied to maxillary defect data acquisition. It is important to note that although several authors recorded digitally designing the implants or framework of dentures that house the obturator bulb (Kim et al. 2014; Mertens et al. 2016; Park et al. 2017; Soltanzadeh et al. 2019), limited number of recorded articles mention digital workflow to design the bulb itself.

8 out of 12 articles (Jiao et al. 2014; Huang et al. 2015; Elbashti et al. 2016; Rodney and Chicchon 2017; Tasopoulos et al. 2017; Ye et al. 2017; Kortes et al. 2018; Palin et al. 2019) relied on one of the ‘Materialise’ software tools (MIMICS, 3-matics, Magics or Simplant/Proplan) for either digital image processing or CAD based design. They were used either as standalone support or in combination with other CAD

software. Therefore, this was considered a undeclared standard for the rehabilitation process. Meshmixer (AutoDesk)(Kim et al. 2019; Tasopoulos et al. 2019) and Geomagic studio (Jiao et al. 2014; Huang et al. 2015; Ye et al. 2017) were also used in the computer aided designing.

Regarding the 3D printing, 10 out of 12 articles (Jiao et al. 2014; Michelinakis 2017; Rodney and Chicchon 2017; Tasopoulos et al. 2017; Kortes et al. 2018; Michelinakis et al. 2018; Kim et al. 2019; Palin et al. 2019; Tasopoulos et al. 2019) reported using stereolithography (SLA) or Multi-Jet modelling (MJM) photocuring resin technology and only 1 author (Elbashti et al. 2016) used fused deposition modeling (FDM) desktop printing.

2.4 Data acquisition and processing for digital obturators

As explained within a recent systematic review (Farook et al. 2020a), concerned with digital maxillofacial prosthetic design, the process of digital design start with data acquisition. In the case of CT and CBCT scans, the DICOM data needs to be segmented and converted into 3D models using image processing software such as MIMICS. As CT & CBCT scans are prone to artefacts (Schulze et al. 2011), the details need to be corrected and smoothened before conversion. Huang (Huang et al. 2015) and Jiao (Jiao et al. 2014) also suggested the use of cotton rolls or gauze to separate the buccal soft tissue contact with the defect site to ensure more precise CT data. Additionally, Farook (Farook et al. 2020c) also proposed of ways to control tongue position during CBCT data capture. In the case of presurgical designing of obturators, Kortes (Kortes et al. 2018) mentioned the combined use of MRI to demarcate the tumor margins and CT scans to design the prosthesis. This could allow minimal effort of relining during the surgical excision procedure and thus simplify the overall process.

Once the processed images are exported as STL file, it is processed using a CAD software like Geomagics, 3-matics or Meshmixer. Then depending on the preference of the clinician, the anatomical model of the defect site can be printed which would serve as a mould for conventional fabrication of the obturator bulb. However, Palin(Palin et al. 2019) and Jiao(Jiao et al. 2014) suggested to block out unfavourable undercuts in CAD before printing the anatomical model. Otherwise removal of the resin bulb template from the printed cast can prove to be a challenge if there are unblocked undercuts and may result in fractures. Should the bulb be printed directly, Farook (Farook et al. 2020b) discussed ways in which the prostheses can be designed using both Materialise and Autodesk Meshmixer software.

Both 1-piece obturator design (Ye et al. 2017) and 2-piece obturator designs (Tasopoulos et al. 2019) were recorded by authors which were successfully fabricated based on printed anatomical models. Ye (Ye et al. 2017) compared digitally designed casts with similar conventional casts using linear inter landmark distances between certain points and found insignificant differences ($P>0.05$) with high ICC values (0.977 to 0.998) when comparing between the digital and conventional casts. The final construct of the prosthesis was also accurate to 1mm contact discrepancy.

2.5 Past methods of digital obturator synthesis

Of the articles that incorporated digital workflow to obturator design, 7 authors (Michelinakis 2017; Tasopoulos et al. 2017; Ye et al. 2017; Michelinakis et al. 2018; Kim et al. 2019; Palin et al. 2019; Tasopoulos et al. 2019) used computerized assistance to print anatomical models of the defect site which would serve as a mould for conventional fabrication of the prosthesis. Digitally printed anatomical models carry the advantage of negating tissue compression during data acquisition, as opposed to the conventional impression technique which displaces soft tissue around the defect during the process. Another added advantage of printing the model instead of conventional investment cast would be the elimination of thermal expansion and contraction the investment materials experience around the defect site (Park et al. 2017; Ye et al. 2017). The said advantages weigh in greater merits if the initial data is acquired by intraoral scanning. This results in a quick reliable workflow of obtaining the model of the defect at dental chairside, albeit at the expense of some loss in volume details otherwise obtained from CT scans (Kulczyk et al. 2019). This is probably one of the reasons some clinicians recorded the defect using both intraoral scanning and CT or CBCT scans. A possible disadvantage to printing the entire model as opposed to just the prosthesis would be the 10-24 hours of manufacture time and associated cost implications of the printing filaments (Tasopoulos et al. 2017).

Huang (Huang et al. 2015) and Jiao (Jiao et al. 2014) used the digital defect data to fabricate custom special trays to record a final impression of the defect site. For digital custom trays, apart from the better fit; Huang (Huang et al. 2015) discussed that CAD trays show better distribution of impression material but with no statistical significance ($P>0.05$) and decided that the quality of the final impression can be affected by a magnitude of issues other than tray design. The manufacture of digital trays does not add significant improvement to the conventional workflow rather incur the additional costs of 3D printing a tray.

Only Kortez (Kortes et al. 2018) and Rodney (Rodney and Chicchon 2017) mentioned printing the CAD prosthesis/bulb for the defect. However, Rodney (Rodney and Chicchon 2017) suggested under-sizing the bulb by 2-5mm for further chairside relining. The bulbs can also be made hollow by CAD by reducing fill density or removing an inner segment during design. However, various authors (Rodney and Chicchon 2017; Tasopoulos et al. 2017; Kortes et al. 2018; Farook et al. 2020b) mentioned that regardless of the accuracy of design, the digitally fabricated prosthesis would also need to be relined to ensure proper seal of the defect. Digital workflow cannot eliminate this step for obturator-based rehabilitation especially in the case of soft palate defects. Jiao (Jiao et al. 2014) stated the importance of border moulding following bulb insertion for soft palate defects as the palate is relaxed in CT scans but tend to expand posteriorly during speech and deglutition.

2.6 The need for digital record keeping

The dental casts are subject of weathering, physical damage and time dependent deterioration, and require more storage space. Furthermore, silicone prostheses are subjected to time dependent degradation and the moulds must be used from time to time to create new prostheses for the same patient (Barman et al. 2020) thus creating an imperative to store the models in a conservative way. While printing the anatomical mould was preferred by many clinicians, Kim (Kim et al. 2019) suggested that scanning the intraoral anatomy during follow-up visits and fabricating a new bulb accordingly could simplify the necessary periodic relining. Thus, outlining the need for digital record keeping. Indeed, digitising the data could potentially eliminate storage space requirements and negate most hazards posed to the models themselves. The data can be easily and conveniently retrieved and processed accordingly.

As a necessary response, authors (Fantini et al. 2013; Reitemeier et al. 2013; Elbashti et al. 2016) proposed digital record keeping for other maxillofacial defects by creating a digital library from these scanned data and hold the various types of maxillary defects to use for future references. However, all proposed methods outlined the use of desktop laser scanners or commercial intraoral scanners. The use of smartphones to scan defect data, although recently discussed for auricular models

(Elbashti et al. 2019), was not used for digital record keeping of maxillary defects as the results obtained were not comparable with the highly accurate laser scanning (Elbashti et al. 2017).

2.7 The comparison parameters used within this study

The current research focused on analysing the workflows from a digital in-vitro environment. The parameters however should be clinically relevant. For obturators, fit and accuracy are two of the most important aspects and are often dictated by the surface area and volume that the bulbs occupy. Since the defects and their respective bulbs are of irregular nature, the best way to compare the two objects would be to calculate a computer generated interpoint discrepancy of approximately 50,000 points. The discrepancy output (Hausdorff's distance), displayed in millimetres can estimate the amount of point cloud accuracy between two objects. Generally, a discrepancy of 0.5 – 5mm is considered acceptable within maxillofacial prosthetics (Farook et al. 2020b; Sharma et al. 2020). The volumetric spatial overlap of the two similar bulbs can be analysed using Dice similarity coefficient which can evaluate how volumetrically similar or dissimilar two objects are. The use of Hausdorff's distance (HD) and Dice Similarity coefficient (DSC) was recently used in 2013 by Egger (Egger et al. 2013) in the measurements of glioblastoma, then more recently in 2019 to analyse craniofacial anatomy (Abdullah et al. 2019) and in 2020 to compare between digital maxillofacial prosthetic workflows (Farook et al. 2020b). Generally DSC of above 0.7 is considered acceptable (Guindon and Zhang 2017). The calculation used to obtain DSC is mentioned below:

$$\frac{2 * (A \cap B)}{A + B}$$

Where A is the volume of the standard reference and B is the volume of the comparative.

CHAPTER 3

MATERIALS AND METHODS

3.1 Study Design

Comparative study

3.2 Study Location

School of Dental Sciences, Universiti Sains Malaysia – Health Campus, Kubang Kerian, 16150 Kota Bharu, Kelantan, Malaysia

3.3 The sample source

Cast model fabricated from ideal dental moulds **(Figure 3.1)** were manually drilled to simulate maxillary palatal defects based on past literature **(Figure 3.2)**. Therefore, no human samples or interactions were required for this study

Figure 3.1 Preformed moulds from which the dental models were made

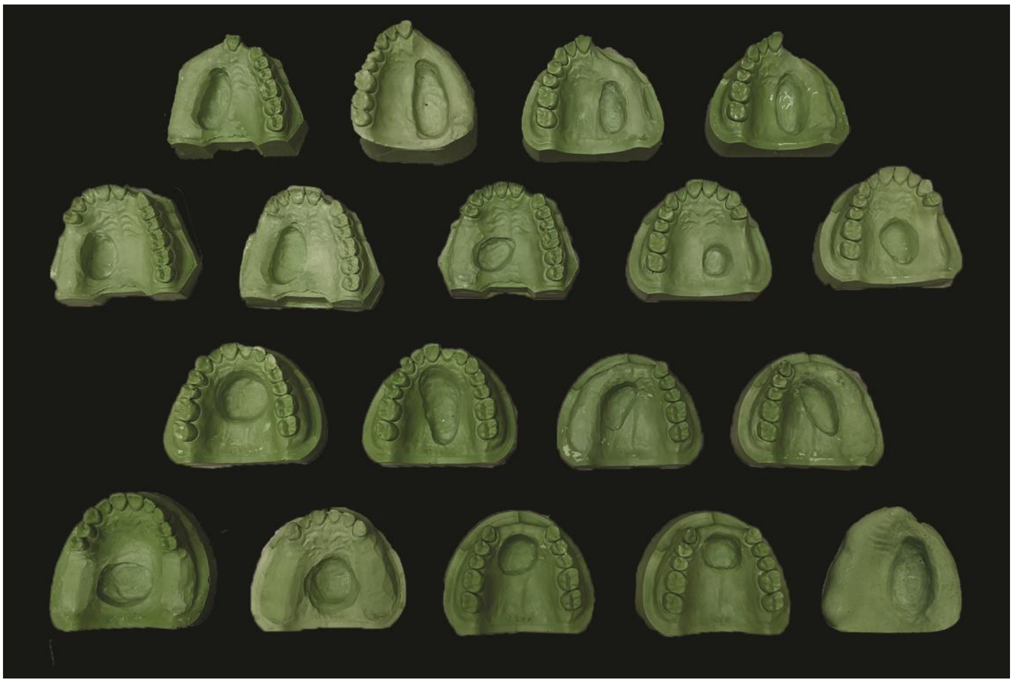


Figure 3.2 Defects simulated onto the models extracted from the ideal moulds. (models arranged in chronological order according to their number)

3.4 Ethical approval for sample acquisition

Not Applicable. The current study was exempted from ethical review by the Human Research Ethics Committee of USM (**USM/JEPeM/20070393**)

3.5 Sample size calculation

- **For Specific objectives 1 and 2:** An effect size of 0.8 (Cohen's d) with α=0.10 and power of 0.80 suggested a total of 30 samples. A similar study (Elbashti et al. 2019) determined an effect of 6.18 using G-power (Faul et al. 2009)) and therefore a large effect size was deemed appropriate to observe significant changes. Considering the possibility of human/computer generated errors, an additional 20% samples were placed in each group to create a total sample size of 36 with an actual power of 0.86. Therefore, 18 physical models of palatal defects were simulated.

- **For Specific objectives 3 and 4:** An effect size of 0.505 derived from a previous study (Elbashti et al. 2017) with $\alpha=0.05$ and power of 0.80 suggested that a total sample size of 42 across 3 groups {G-power tool(Faul et al. 2009)} would be adequate. Considering the possibility of human/computer generated errors, an additional 30% samples were considered, resulting in a total sample size of 54 and actual power of 0.91.

3.6 Research equipment

1. NextEngine Laser Desktop Scanner
2. Arduino UNO R3 (ATmega328) board with stepper motor & driver (ULN2003)
3. Bluetooth shutter printed circuit board with Bluetooth 4.0 receiver
4. 12V white LED light strips
5. Custom metallic arc, plywood base and corrugated diffuser sheets attachment
6. AMD Ryzen 5 2500u 15W TDP laptop (2018). 8GB DDR4 SODIMM 2400Hz RAM, 240GB m.2 NVMe SSD
7. Smartphones: Smartphone 1 (2015); 12MP, f/2.2, single camera sensor. Smartphone 2 (2016); 13MP, f/1.9, single camera sensor. Smartphone 3 (2018); 16MP, f/2.0, dual camera sensors. Smartphone 4 (2017); 16MP, f/1.7, dual camera sensors. Smartphone 5 (2019); 12MP, f/1.5-2.4, dual camera sensors. Smartphone 6 (2019): 12MP, f/1.5-2.4, triple camera sensors
8. Software: 3-matics (Materialise Innovation suite), NextEngine Scan Studio (NextEngine Santa Monica), Autodesk Recap Photo (Autodesk Inc), Autodesk Meshmixer (Autodesk Inc.), Blender (Blender Foundation), Cloudcompare (DanielGM), Cura 4.6 (Ultimaker Cura), Meshlab (Opensource project)

3.7 Method of data collection

The research was conducted in 4 phases (A-D)

3.7.1 Phase A: Development of SPINS

SPINS is composed of a turntable driven by a stepper motor **(Figure 3.3)**, and a custom arc-shaped **(Figure 3.4)** smartphone mount designed in CAD. A custom ball bearing roller **(Figure 3.5)** was designed to the shape of the arc to facilitate attachment and movement of the smartphone. The stepper motor was controlled by an Arduino UNO microcontroller board and a stepper motor driver. The Arduino board was programmed using an Arduino integrated Development Environment (IDE) software.

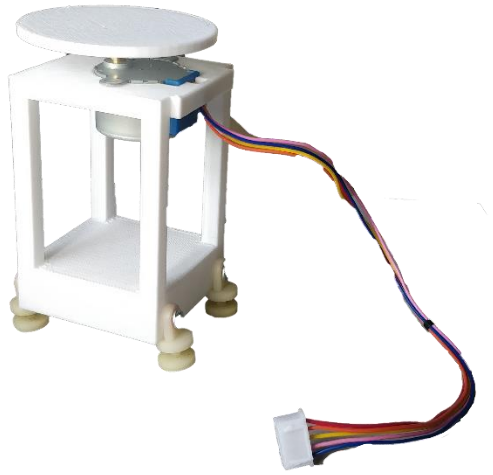


Figure 3.3 The Arduino driven stepper motor with turntable

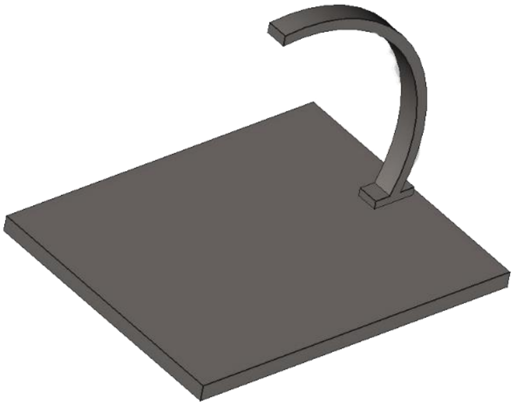


Figure 3.4 CAD design of custom arc

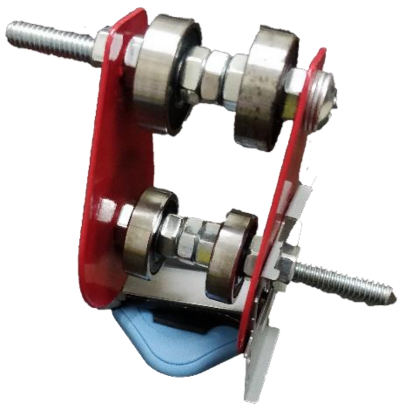


Figure 3.5: custom metallic ball bearing roller

The turntable was programmed to make a 360° turn in 24 steps, where each step was equivalent to 15° of rotation (Stuani et al. 2019). The stepper motor used in this project had a revolution of 2048 steps per revolution in full-stepping mode. So, to make an exact 15° angle of turn, the stepper motor needed to make 85.33 steps of rotation. Since a stepper motor can only turn in an exact number of steps, the closest it could get to 15° angle of rotation was to make 85 steps of rotation, which produced 14.94°. The motor was programmed to stop for 500ms after each 85 steps (~15°), during which, the smartphone camera was wirelessly triggered by a Bluetooth shutter module to capture an image of the sample on the turntable. To trigger the image capture, the Arduino board was programmed to send a high signal for 100ms to the Bluetooth remote shutter. The cycle of 15° rotation and the image capture was repeated until the turntable made a full 360° turn, which resulted in a total of 24 images captured. Details of the associated Arduino codes are mentioned in **Appendix A**.

The images were projected in real-time on to the user's laptop using a screen mirror tool (Airdroid, Sand Studio). Each cycle of 24 images was controlled by an Arduino switch. Twenty-four images of the model were taken at each of the three sleeve stops (25°, 55° and 345° on the arc) **(Figure 3.6)** while the arc position was manually switched after each 24-image capture cycle. This resulted in a total of 72 images per model after moving across all three sleeve stops.

Figure 3.6 The angles on the arc where magnetic sleeve stops were placed

Corrugated plastic white sheets with white 15-diode 12V LED strips acted as primary diffused light source **(Figure 3.7).** A diffused ring light facing perpendicularly downward onto the model was also fixed on the crest of the arc to serve as secondary light source. The luminosity at the centre of the turntable was recorded at 1252 Lux

(Lux Light Meter, Doggo Apps, Russia) **(Figure 3.8).** A black sheet was placed in the background to prevent loss of camera focus in between shots.

Figure 3.7 Corrugated white diffuser sheets with white LEDs and black focusing sheet

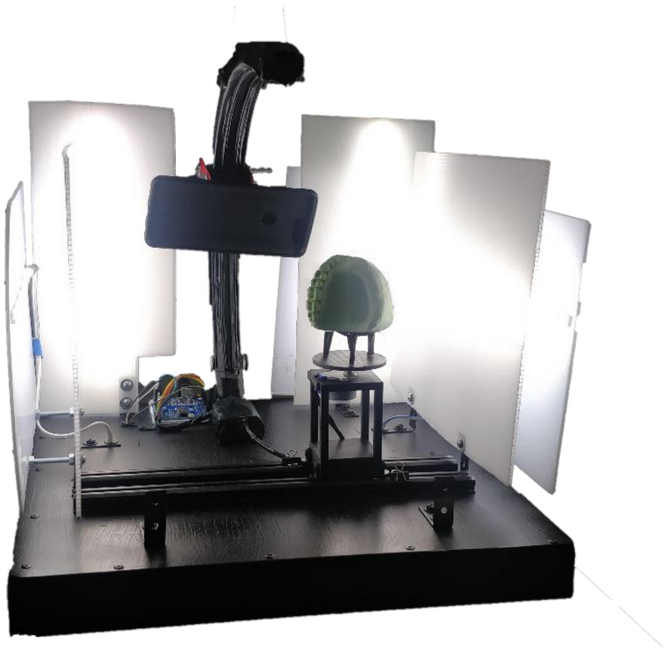
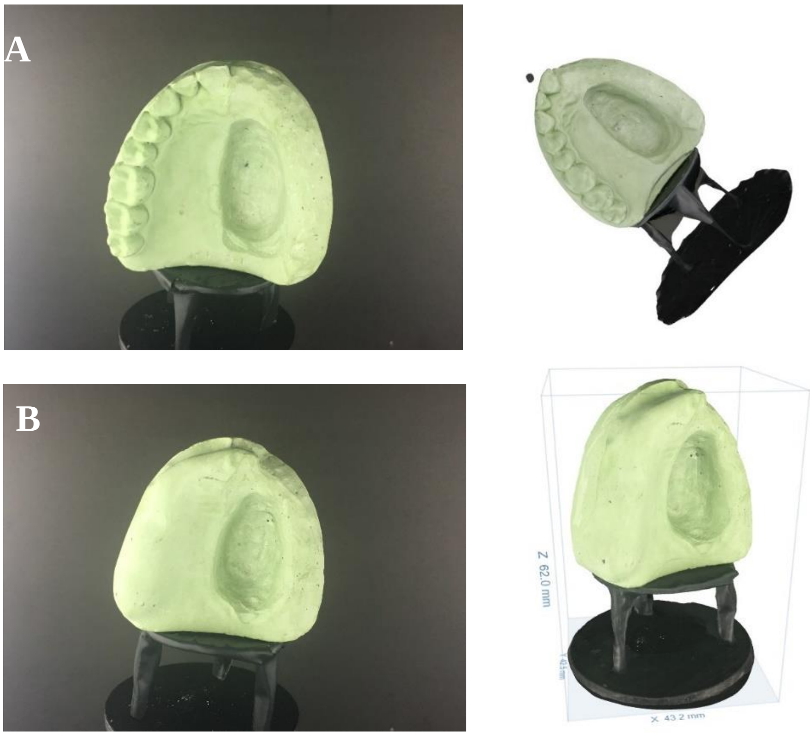
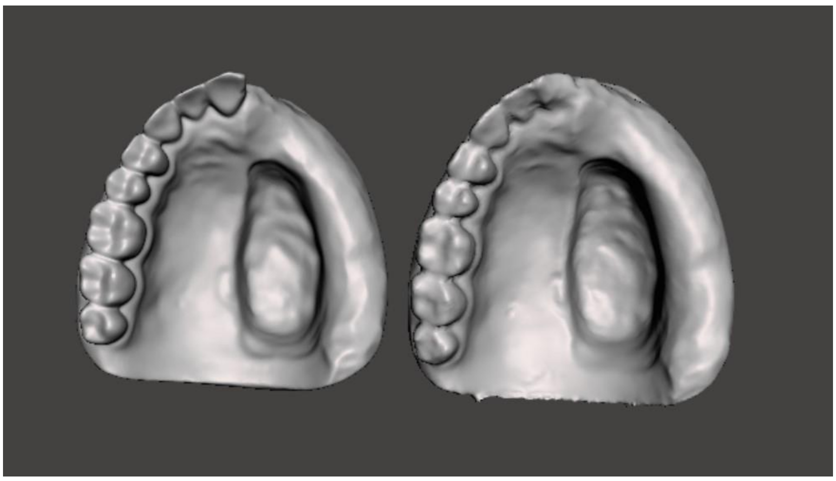


Figure 3.8 Device set up to illuminate and capture data from defect casts

Smartphones took focused images using their default smart camera systems. The images were transferred via cloud to Recap Photo (Autodesk Inc., USA); a software which automatically matched common points in each image and stitched the points to form a 3D model. **(Figure 3.9)**



A: Example of an ideal image with resultant 3D model (Sample 2). **B:** Example of an ideal image with resultant 3D model (Sample 18)



C: Comparison of laser scanned model (left) vs an ideally taken SPINS model (right)

Figure 3.9 Photogrammetry results from Recap Photo

The 3D models were scaled to actual size by measuring three successive linear reference distances on the physical model and entering the values for the stitched 3D model using dedicated software commands (Elbashti et al. 2019; Stuani et al. 2019). The 3D model was then exported as STL with a maximum triangle budget of 200,000 ±10,000 triangles. The software commands have been detailed in **Appendix B**. Models derived from both laser scanner (NextEngine, Santa Monica, USA) and SPINS were decimated to maintain this budget and prevent an unfair mismatch during comparison.

3.7.2 Phase B: Pilot test of SPINS using different smartphones

Two physical models of simulated palatal defects (Model no. 2 & 18) were randomly selected by a randomisation software (Random number generator, RandomApps Inc.) and laser scanned (NextEngine, Santa Monica) **(Figure 3.10)** for pilot testing in phase B. All physical models in this study were fabricated from pre-existing silicone moulds and hence no human samples were required. The model designs were supervised by maxillofacial surgeons to ensure realistic recreation of palatal defects.

Figure 3.10 Laser scanning the models

Six smartphones (specifications detailed in **section 3.6**) released from 2015-2019 were chosen to pilot test SPINS. Models 2 and 18 were scanned by the smartphones and later processed by ReCap to produce 3D models.

Mesh surface area (MSA), virtual volume (VV), HD, and DSC were analysed for all 6 smartphone results. Normality of the pilot data was tested by Kolmogorov-Smirnov test and Kruskal-Wallis one-way test was used to analyse MSA and VV within the groups. Laser scanned models 2 & 18 were selected as standard reference when comparing HD and DSC. The software commands used to obtain the data have been detailed in **Appendix B** and findings of the pilot trial have been documented in **section 4.1**. A final calibration was carried out for both the device and digital workflows implemented using randomly selected models from the simulated defects to inspect any unforeseen design errors, which were simultaneously troubleshoot and rectified prior to data collection. The errors troubleshot have been mentioned in **Appendix C**.