THE FABRICATION OF TMJ 3D MODEL FOR ARTHROCENTESIS AND ARTHROSCOPY SIMULATION

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ABSTRACT

Background: Arthrocentesis and arthroscopy are relatively safe procedures for treatment of arthrogenic Temporomandibular Disorders (TMD). This study aims to fabricate a Temporomandibular joint (TMJ) 3D model for arthrocentesis and arthroscopy simulation.

Material and Methods: Based on data collected from cadaveric dissection, a TMJ prototype was designed with 3D design software. Prototype was 3D printed and arthrocentesis and arthroscopy simulation trial were conducted on the model.

Results: The prototype satisfied key parameters of having a palpable zygoma, watertight TMJ capsule, mouth opening of >35mm and detachable parts for replacement after simulation. In terms of surgical simulation, we were able to identify key anatomical structures such as the canthus and tragus for surgical marking, and successfully insufflate and irrigate the upper joint space of the TMJ to simulate arthrocentesis and arthroscopy lysis and lavage. The total printing cost for this prototype was RM 628 (USD 151.36) with the cost of replacement parts after simulation at RM 103 (USD 24.82).

Conclusion: This TMJ prototype can be used for teaching and training of arthrocentesis and arthroscopy.

Keywords: temporomandibular joint, athrocentesis, arthroscopy, simulation.

ABSTRAK

Latar Belakang Penyelidikan: *Arthrocentesis* dan *arthroscopy* adalah kaedah rawatan sendi rahang yang selamat. Matlamat kajian ini adalah pembinaan model 3 dimensi rahang dan sendi untuk simulasi rawatan *arthrocentesis* dan *arthroscopy*.

Bahan dan Kaedah Penyelidikan: Berdasarkan maklumat serta pemerhatian daripada pembedahan mayat, prototaip sendi rahang direka bentuk dengan perisian komputer reka bentuk 3D. Mesin pencetak 3D digunakan untuk mencetak prototaip dan simulasi *arthrocentesis* dan *arthroscopy* dijalankan pada model tersebut.

Keputusan: Prototaip ini memenuhi syarat reka bentuk utama seperti zygoma yang boleh dirasai, sendi kedap air, bukaan mulut melebihi 35mm serta bahagian yang boleh diganti selepas simulasi. Dari segi simulasi prosedur, struktur anatomi utama seperti telinga dan sudut mata boleh dikenal pasti untuk penandaan pembedahan. Sendi rahang boleh dipamkan air untuk simulasi prosedur *arthrocentesis* dan *arthroscopy*. Kos cetakan 3D untuk prototaip ini adalah RM 628 (USD 151.36) manakala kos alat gantian setiap simulasi adalah RM 103 (USD 24.82).

Kesimpulan: Prototaip sendi rahang ini sesuai untuk pelajaran dan latihan dalam prosedur *arthrocentes*is dan *arthroscopy.*

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LIST OF SYMBOLS AND ABBREVIATIONS

3D	:	3 Dimension
ABS	:	Acrylonitrile Butadiene Styrene
AVF	:	Arteriovenous Fistula
CT	:	Computed Tomography
DC/TMD	:	Diagnostic Criteria for Temporomandibular Disorders
DICOM	:	Digital Imaging and Communications in Medicine
FDM	:	Fused Deposition Modelling
MJ	:	Material Jetting
MRI	:	Magnetic Resonance Imaging
OMFS	:	Oral and Maxillofacial Surgery
RDC/TMD	:	Research Diagnostic Criteria for Temporomandibular Disorders
RTV	:	Room Temperature Vulcanizing
STL	:	Stereolithography
TMD	:	Temporomandibular Disorders
TMJ	:	Temporomandibular Joint

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CHAPTER 1: INTRODUCTION

1.1 Backgrounds

Temporomandibular joint (TMJ) is a ginglymoarthrodial joint that produces both hinge (gingly) and gliding (arthrodial) movement. It connects the mandible to the skull and moves in function during mastication and speech. Normal movements of the mandible include protrusion, retrusion and lateral excursions.

TMJ arthrogenic problems has now been included under Temporomandibular disorder (TMD) which covers a much wider group of conditions such as musculoskeletal problems, neuromuscular and the joint complex itself. It is estimated that TMD affects up to 15% of the adult population with peak incidence of 20-40 years old (Gauer & Semidey, 2015). Common joint problems of the TMD include internal derangement, disc adhesion, joint dislocation and subluxation, arthritis and disc inflammation. Signs and symptoms of intra-articular TMD are joint pain and clicking, and limitation of mouth opening. The prevalence of disc displacement with reduction in the general population is 11.4% (Manfredini et al., 2011).

Arthrocentesis and arthroscopy lysis and lavage are 2 procedures that can successfully reduce the pain in patients with TMD. Arthrocentesis is a blind procedure whereby a pair of needles are inserted into to TMJ upper joint space to allow irrigation with normal saline or Ringer's lactate solution. It is normally performed under local anaesthesia and works by flushing out inflammatory mediators and breaking adhesion thus reducing pain and increase joint mobility.

Meanwhile, arthroscopy provides visualisation and inspection of TMJ upper joint space. On top of lysis and lavage, and removal of disc adhesion, procedures such as repositioning of the articular disc and open reduction internal fixation of condylar fracture can also be performed with arthroscopy.

Arthroscopy lysis and lavage was first conducted by Ohnishi as early as 1975 (Onishi, 1975). It was determined much later that visualisation of the upper joint space is not necessary to achieve the treatment objectives of irrigation that arthrocentesis was introduced.

Systemic review and meta-analysis by Al-Moraissi shows better outcome in maximum incisal opening and pain reduction in arthroscopy (Al-Moraissi, 2015). This was attributed to larger diameter portal in arthroscopic lavage leading to more extensive removal of inflammatory mediators. Nevertheless, the rate and extend of complications are lesser in arthrocentesis (Nitzan, Dolwick, & Martinez, 1991). Other disadvantages of arthroscopy are its high cost and the need for general anaesthesia.

Arthroscopy complications ranges from 1.8 to 10.3% (Carls, Engelke, Locher, & Sailer, 1996; Gonzalez-Garcia et al., 2006; McCain et al., 1992; Tsuyama, Kondoh, Seto, & Fukuda, 2000). Severe complications such as facial, trigeminal and auditory nerve injury, glenoid fossa perforation, tympanic membrane and middle ear perforation resulting in deafness, extradural haematoma, and arterio-venous fistula has been reported (Al-Moraissi, 2015). Arthrocentesis on the other hand is safer with the only major complication being reported was extradural haematoma (Carroll, Smith, & Jakubowski, 2000).

There is no doubt that training in arthrocentesis and arthroscopy will improve surgeon's skill and reduce complication rate. Currently available training model include live surgery, computer simulation, cadaver and training model (Monje Gil et al., 2016; Wang, Liu, Hsiao, & Kumar, 2019).

It was reported that in United Kingdom, with larger population and having established training facilities, there are still inadequate TMJ surgical training opportunities for surgeons and trainees to gain exposure and build up skills (Elledge, Green, & Attard, 2017). Furthermore, performing surgery on a live patient without prior practical training carries risks to the patient.

Cadaver can best simulate real patient experience but carries some drawbacks. Cadaver dissection has limited availability, high cost and possess ethical considerations for surgical training.

There is study to investigate the use of animal for arthroscopy training (Kaduk & Koppe, 2007) but differences in anatomy have to be taken into consideration. Computer simulation on the other hand does not provide the tactile sensation and real life simulation of an actual surgery.

Hence the aim of this study is to fabricate a reliable TMJ 3D model for arthrocentesis and arthroscopy simulation.

1.2 Aim and Objectives

1.2.1 Aim

To fabricate a TMJ 3D model for arthrocentesis and arthroscopy simulation.

1.2.2 Objectives

1. To develop a reliable and reusable TMJ 3D model with surgical anatomy for arthrocentesis and arthroscopy simulation
2. To develop a watertight TMJ capsule capable of withstanding TMJ lysis and lavage

CHAPTER 2: LITERATURE REVIEW

2.1 Temporomandibular joint anatomy

TMJ consists of condyle of the mandible encapsulated by a dense fibrous membrane of joint capsule. It sits in the glenoid fossa of the temporal bone.

Within the joint capsule lie the articular disk that divides the capsule into superior and inferior synovial cavity. Articular disk is composed of dense fibrous connective tissue, thinnest at the centre and thickest anterior and posteriorly. Synovial cavity contains synovial fluid that acts as a lubricant. In the adult population, superior cavity has volume of about 1.2ml while the inferior cavity is 0.9ml (Norton, 2012).

TMJ is held in place and supported by collateral ligaments and temporomandibular ligament. Stylomandibular and sphenomandibular ligaments located on the medial ramus help to stabilize the joint by limiting the anterior protrusion and pivoting the mandible.

Collateral ligaments consist of collagenous connective tissue that does not stretch. There are 2 collateral ligaments; medial collateral and lateral collateral ligaments. Medial and lateral collateral ligaments support the articular disc and attached anteriorly to the capsule and superior head of lateral pterygoid. Temporomandibular ligament also known as lateral ligament lies on the lateral aspect of the TMJ capsule and prevents lateral and posterior displacement of the condyle. It has 2 bands, the outer oblique which is the larger band is attached to the articular tubercle and inferior of condyle while the smaller inner horizontal attaches to the articular tubercle, lateral condyle and disk (Norton, 2012).

Mandible articulate by both rotational and translational movement. The first 20mm of mouth opening is rotational or hinge movement while further movement causes the articular disc and condylar head to slide anteriorly.

Mandible movements are controlled by the temporalis muscle which is attached to the coronoid process of the mandible and the temporal fossa, masseter muscle which attaches to the ramus of the mandible and the zygomatic process, and finally, the pterygoid muscles which are made up of medial and lateral pterygoid. Medial pterygoid attaches to the medial side of lateral pterygoid plate and lingual of ramus while lateral pterygoid muscle attaches to the lateral side of lateral pterygoid bone and anterior of the condylar head.

2.2 Temporomandibular Disorder (TMD)

TMJ arthrogenic problems are subset of TMD with internal derangement with reduction being the commonest disorder. In 1989, Wilkes classifies the internal derangement and osteoarthritis of TMJ as summarised in table 2.1 (Wilkes, 1989). Wilkes classification is limited as other TMJ pathology such as tumour and ankylosis were not mentioned.

Stages	Derangement
Early	Early reducing
Early/intermediate	Late reducing disk displacement
Intermediate	Acute/subacute non-reducing disk displacement
Intermediate/late	Chronic non-reducing disk displacement
Late	Chronic non-reducing disk displacement with osteoarthrosis. Gross degeneration of disk

Table 2.1: Wilkes Classification 1989

Diagnostic Criteria for Temporomandibular Disorders (DC/TMD) on the other hand is a diagnostic aid that covers a wider range of TMD which includes the muscle disorders. There is an axis 2 component that covers psychosocial elements of TMD. DC/TMD (2013) is an updated version of Research Diagnostic Criteria for Temporomandibular Joint Disorders RDC/TMD developed in 1992. DC/TMD axis I diagnosis has 3 groups. Group I is muscle disorders while Group II and III are for arthrogenic problems. Group II is disc displacements and group III is for arthralgia, osteoarthritis and osteoarthrosis (Schiffman et al., 2014).

Dimitroulis in 2013 published a new surgical classification for TMD based on 5 categories of increasing severity. His paper provides evidence to justify surgical interventions hence include proposed treatment for different categories of TMD severity (Dimitroulis, 2013). This is an improvement over Dolwick and Dimitroulis 1994 publication which classifies TMJ surgery into relative and absolute indication but did not indicate which kind of surgery for which disorders.

Category	Disorders	Treatment
1	Normal TMJ	No surgery needed
2	TMJ minor changes	TMJ arthrocentesis/arthroscopic lavage
3	TMJ moderate changes	TMJ operative arthroscopy/TMJ arthroplasty
4	TMJ severe changes	TMJ discectomy with or without condylar surgery
5	TMJ catastrophic changes	TMJ resection with or without total joint replacement

Table 2.2: Dimitroulis TMJ Surgical Classification 2013

2.3 Role of TMJ arthrocentesis and arthroscopy

Arthroscopy of the TMJ is a minimally invasive keyhole technique to visualise the TMJ. It comes from the word arthro (joint) and scopy (examination). TMJ arthroscopy was initially described by Ohnishi in 1975 and was only proven 10 years later to be a safe and beneficial procedure through cadaveric studies (Hellsing, Holmlund, Nordenram, & Wredmark, 1984; Holmlund & Hellsing, 1985). TMJ arthroscopy is a less invasive and relatively safer procedure compared to open arthrostomy.

Arthroscopic lysis and lavage reduce pain and significantly improve mouth opening on Wilkes Stage V derangement. Its effectiveness is comparable to open arthrostomy in cases of chronic non reducing internal derangement (Gonzalez-Garcia et al., 2006). Arthroscopy combined with lysis and lavage also provides good long term outcome (Pedroletti, Johnson, & McCain, 2010). On top of therapeutic role, arthroscopy is a good diagnostic tool (Sidebottom, 2009; Tozoglu, Al-Belasy, & Dolwick, 2011).

Besides internal disc derangement, other indications for arthroscopy include perforation of articular disc, degenerative joint disease, rheumatic arthritis and trauma. In a paper published by Gonzalez-Garcia et al, they performed lysis and lavage, electrocautery of posterior ligament, injections of steroid, injection of ethanolamine, myotomy of lateral pterygoid muscle attachments, myotomy and electrocautery, motor debridement, injection of sodium hyaluronate and meniscal suture using arthroscopy on 670 joints among 500 patients (Gonzalez-Garcia et al., 2006).

Early arthroscopic intervention provides a better outcome as progressive nature of certain arthrogenic disorders can lead to severe pain, reduction in function and loss of condylar bone (Israel, Behrman, Friedman, & Silberstein, 2010).

It was later discovered that lysis and lavage of the upper joint space can be done without an arthroscope hence the introduction of arthrocentesis. Arthrocentesis was able to reduce pain and significantly improve maximum mouth opening and lateral movement (Nitzan et al., 1991). In patient with disc displacement without reduction, arthrocentesis can alter the articular disc position in 93.88% of the cases and effective in reducing pain and increase mouth opening regardless of age, gender and pain duration (E. Grossmann, Poluha, Iwaki, Santana, & Iwaki Filho, 2019).

In terms of frequency of treatment, a retrospective study by Kutuk et al on 30 patients demonstrated that repeated arthrocentesis has better outcome in terms of pain and maximum mouth opening than single intervention (Kutuk, Bas, Kazan, & Yuceer, 2019). Investigation into factors affecting arthrocentesis outcome concluded that the use of Ringer's lactate solution significantly reduces pain and improves mouth opening while younger patients with greater initial inflammatory components benefited most from the procedure (Andrabi, Malik, & Shah, 2019).

2.4 TMJ arthroscopy complications

Despite being a relatively safer procedure compared to open surgery, TMJ arthroscopy does have its own complications. Carls et al 1996 reported a 1.77% complication rate of 451 arthroscopies performed while Gonzalez-Garcia et al 2006 reported a similar overall complication rate of 1.34%. Minor complications such as bleeding, swelling, instrument breakage and transient facial nerve weakness has been described. Those complications are mild in nature and transient.

Neurological complications are the most common due to the web of motor and sensory nerves around the TMJ (Carls et al., 1996). Extravasation of irrigation fluid into the pterygomandibular space due to perforation of medial TMJ capsule increases the hydrostatic pressure on inferior and lingual nerve resulting in neurapraxia.

Major rare complications previously not associated with open surgery such as middle cranial fossa perforation with cerebrospinal fluid leak (McCain, 1988), extradural haematoma (Murphy, Silvester, & Chan, 1993), parapharyngeal oedema (Kassam, Cheong, & Cascarini, 2015) and middle ear damage with hearing loss (Sanders, 1986; Van Sickels, Nishioka, Hegewald, & Neal, 1987) have been reported as well.

Lateral extravasation of irrigation fluid which result in risk of facial nerve damage can be caused by multiple puncture sites, straight insertion of cannula and repeated attempts (Carls et al., 1996). Paresis of the facial nerve was observed but no total paralysis has been reported (Gonzalez-Garcia et al., 2006).

Bleeding, on the other hand could be avoided by palpation and identification of vessels and by using lateral puncture technique (McCain, 1988). Vessels commonly involved are superficial artery and vein. Severe haemorrhage will require arthrotomy to arrest (McCain et al., 1992). Two cases of acquired Ateriovenous Fistula (AVF) after arthroscopy has been reported (Moses & Topper, 1990; Preisler, Koorbusch, & Olson, 1991). Both occurred 2 weeks post operatively and was treated with embolization in one case and surgical ligation in the other.

Puncture into the external auditory meatus and laceration of the tympanic membrane has been reported due to the TMJ dislocation towards the meatus (Applebaum, Berg, Kumar, & Mafee, 1988; Van Sickels et al., 1987). Gonzalez-Garcia et al in 2006 reported 2 out of 670 cases of external auditory laceration with no cases of perforated tympanic membrane.

The most serious complication is perforation into the glenoid fossa and has been reported by Murphy et al in 1993 and McCain in 1988. This could be avoided by using canthal-tragal line as a guide (Carls et al., 1996).

Infection from arthroscopy ranges from 0-1% (Carls et al., 1996; McCain, Goldberg, & de la Rua, 1989). Infection is a general complication as with any other surgical procedure. It is multifactorial and is not attributed to surgeons' technical skills.

2.5 TMJ arthrocentesis complications

Arthrocentesis is a procedure with few significant complications. A study by Vaira et al with 433 arthrocentesis on 315 patients reported complications of temporary swelling of periarticular tissue and external auditory canal, transient ipsilateral open bite, periauricular haematoma, and frontalis and orbicularis oculi paresis (Vaira et al., 2018). Vaira et al also reported a 95.1% extravasation rate in their case series. Although extravasation is a minor complication that improves after a few days, it does affect the outcome of the procedure adversely. The causes of extravasation is similar to arthroscopy such as multiple punctures, capsule or discal perforations and anatomical variations (Bas, Yuceer, Kazan, Gurbanov, & Kutuk, 2019).

Major complication of extradural haematoma was reported (Carroll et al., 2000). There is an isolated report of transient facial nerve paralysis with lingual and inferior alveolar nerve anaesthesia (Aliyev, Berdeli, & Sahin, 2019). This complication is due to extravasation of anaesthetic solution into the infratemporal fossa. There were no permanent sequelae from this isolated episode.

2.6 TMJ arthroscopy training

Most of the complications listed above are results of incorrect positioning and placement of the arthroscope. Hence it is undeniable that hands-on surgical training in TMJ arthroscopy will greatly improve a surgeon's skill and reduce complication rate.

A study by Thomas and Matthews shows underutilisation of arthroscopy for TMJ treatment in the United Kingdom due to primarily the lack of perceived need of patients and lack of interest in this area and secondary reason being the lack of training (Thomas & Matthews, 2012).

In the United Kingdom, centralisation and restriction of TMJ surgery to few regions reduced the training opportunities (Elledge et al., 2017). The same study also shows that half of the respondents have no exposure including observation in arthroscopy and only 5 out of 82 respondents did more than 20 arthroscopies per year. Arthroscopy is done by a small number of surgeons in UK and there are insufficient numbers to ensure adequate exposure to trainees (Thomas & Matthews, 2012). Hence other training models such as simulation will be beneficial for trainees.

Based on orthopaedic surgery research, it was concluded that virtual reality training can improve arthroscopic skills and is transferable to operating theatre (Boutefnouchet & Laios, 2016).

Kaduk and Koppe in 2007 analysed the upper joint space of pigs' TMJ to evaluate it as a model for arthroscopic TMJ surgery. He found that the upper joint space thickness to be 1.30 to 1.53mm and concluded that country pigs with body weight of 25-30kg show greatest similarities to human TMJ (Kaduk & Koppe, 2007).

Arealis et al created a cost-effective simulator box utilising web camera as arthroscope for training purposes. The simulator is simple and cheap to build.

However, it is only suitable for basic training and not for practice of advanced technique. The simulator allows arthroscopic training of probing, grasping, tissue resection, shaving, tissue liberation and suture passing. The simulator provides tactile sensation and acquisition of triangulation skills (Arealis et al., 2016).

Monje et al in 2016 validated a TMJ simulator for arthroscopy procedures. They gathered 10 senior maxillofacial surgeons with mean 151 arthroscopies performed to validate the simulator. They concluded the prototype to be very useful for arthroscopy training with disadvantages of low tissue resistance and lack of watertight feature preventing the use of irrigation during practice. The model used in the validation was the first prototype of physical simulator designed for training in TMJ arthroscopy. It has realistic anatomical reproduction. However, the creation process is not part of the study and the cost of the prototype are not mentioned (Monje Gil et al., 2016).

CHAPTER 3: MATERIAL AND METHOD

3.1 Cadaveric TMJ dissection

Structures of TMJ were studied through anatomy textbook. However, textbook is restrictive in the understanding and visualisation of the joint anatomy and function. Hence, cadaveric dissection was done to enhance the understanding of TMJ structures in rest and function. A total of 3 cadavers with intact TMJ from Silent Mentor Program, University Malaya Medical Centre were dissected. Videos of TMJ movements in protrusion and lateral excursion were recorded. Measurements recorded include:

i. Upper joint space volume
ii. Thickness of articular disc
iii. Antero-posterior length and medial lateral width of the articular disc

Upper joint spaces volume was measured by injecting normal saline into the joint. Articular discs were dissected out and its dimension was measured. The data were compiled and shared with our Prototyping Design Engineer for model design.

3.2 Image acquisition

CT data of the head is required for printing of a working model. CT data is chosen over MRI for better hard tissue reproduction. MRI captures better soft tissue data but detailed and fine structures are difficult to reproduce and print. It was decided to separately design the capsule and articular disc of the TMJ. CT data in Digital Imaging and Communications in Medicine (DICOM) was obtained from CT records of Radiology Department, University Malaya Medical Centre. The record is screened with the following inclusion and exclusion criteria:

Inclusion criteria:

i. Age: 25-35 years old
ii. Complete head CT scan with slices from top of skull till lower border of mandible

Exclusion criteria:

i. Edentulous patient
ii. Presence of oral and maxillofacial injury including skull and facial bone fracture as well as facial soft tissue laceration
iii. TMJ pathology such as arthritis
iv. Presence of any soft/hard tissue pathology of the head

The record of a 30 years old gentleman with no head injury and intact condyle were chosen for this study. The CT head scan is in 1mm slices. Informed consent to use the CT data for this research has been obtained from patient.

3.3 Model design

The CT data in DICOM was first converted to Stereolithography (STL) format using 3DSlicer (Surgical Planning Lab, Massachusetts, United States), a free open source modular software. Data in STL format was needed for model design using Meshmixer (Autodesk Research, Toronto, Canada), another free open source software.

The model design aims to incorporate:

i. A base model of head
ii. Zygoma, lateral canthus, tragus and pinna for surgical reference
iii. Watertight TMJ capsule
iv. >35mm mouth opening
v. A detachable skin and TMJ for replacement after multiple puncture practices
vi. Hinge and sliding movement of TMJ
vii. Articular disc movement with TMJ movement

Joint capsule, and articular disc as shown in figure 3.1 was designed and developed with the aid of prototyping design engineer with guidance from data collected from cadaveric dissection.

Meshmixer, with inspector tool and auto repair function was utilised to repair imperfections and prevent manifold.

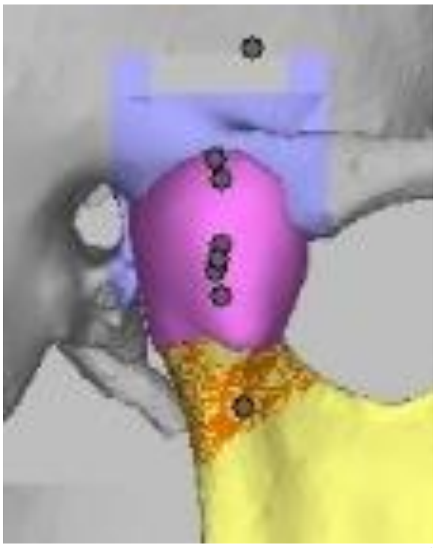


Figure 3.1: Development of TMJ articular disc and capsule

Mandible slot were designed to allow movement of the mandible and facilitate detachment of the condyle from the model. A square slot of 6.5 x 8cm for easy replacement of the flexible skin over TMJ area are demonstrated on figure 3.2 and 3.3.

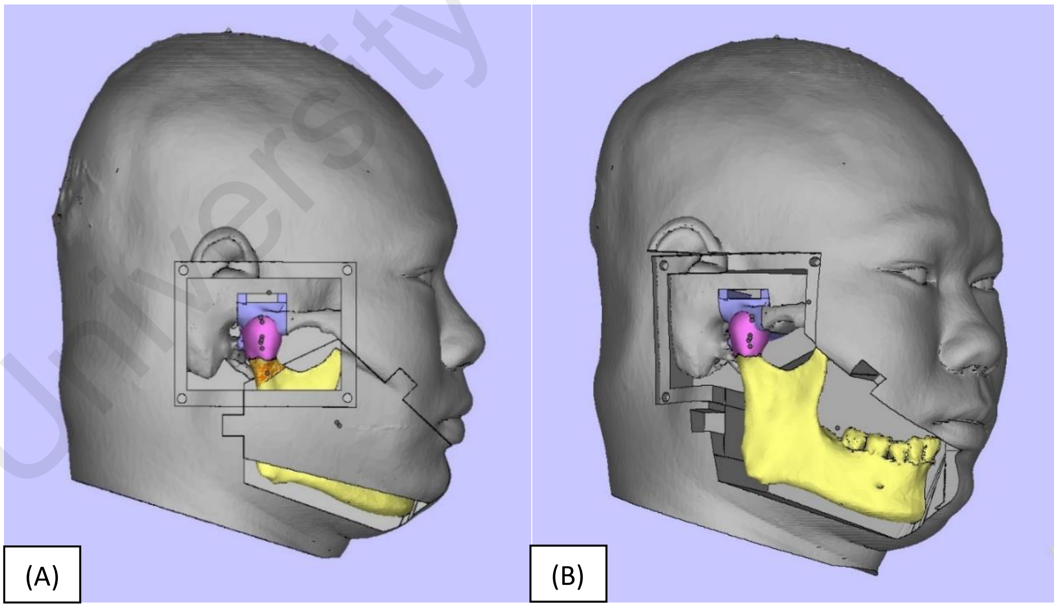


Figure 3.2: Skull with mandible external cover (A) and without external surface (B)

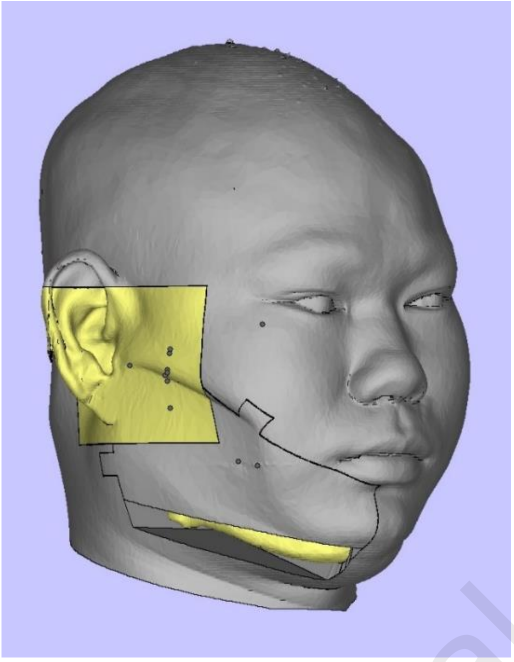


Figure 3.3: Skin layout for needle and arthroscope penetration

Steps taken to reduce the cost of training model include:

1. Creation of mould (Figure 3.4) for commercial injectable silicone.
2. Elimination of ligaments and muscles of mastication.
3. Printing of head scaffold with relatively cheaper Acrylonitrile Butadiene Styrene (ABS) while maintaining smaller 6.5 x 8 cm window of skin layer.

Instead of printing the skin layer (Figure 4.6) which need to be replaced after a few punctures, we opt for moulding with commercial silicone which will reduce the cost significantly. Anatomy such as muscles and ligaments are not essential in arthrocentesis and arthroscopy simulation and thus excluded from the final prototype. The head was printed with ABS material which is considerably cheaper than soft flexible printing material.

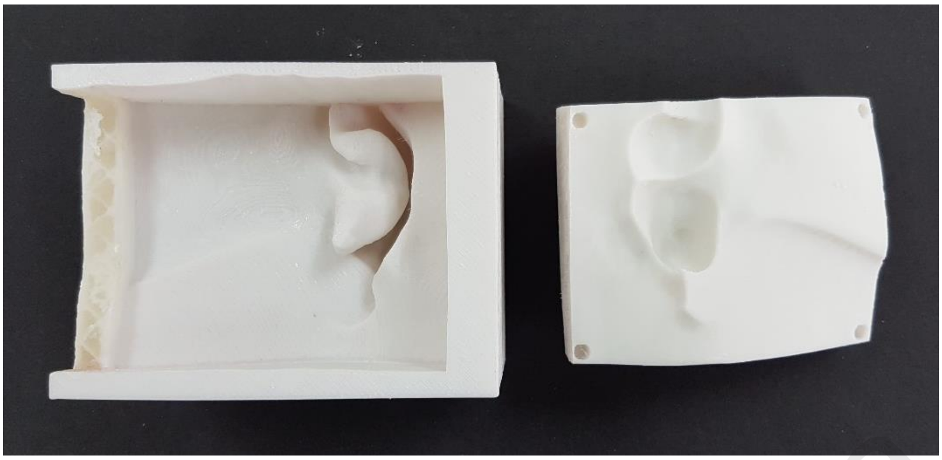


Figure 3.4: Injectable silicone mould for fabrication of elastic skin layer

3.4 Model printing

Model printing was done using 3 materials and 2 printing machines. Four separate components were created separately before being assembled into a working model:

1. Base scaffold which is the head was printed with ABS using UPBOX 3D (Tiertime Teachnology, Beijing, China) printer.
2. Right mandibular ramus, coronoid and body of mandible including the dentition were printed as a single unit with ABS using UPBOX 3D printer.
3. TMJ joint which includes condylar head and neck, joint capsule and articular disc were printed using Flexible Tango Plus FLX930 (Stratasys, Minnesota, United States) and VeroWhite Plus RGD835 (Stratasys, Minnesota, United States) from Connex 500 Multi Material Printer (3D Printers, Toronto, Canada). Support material SUP 705 (Stratasys, Minnesota, United States) was needed to maintain the upper and lower joint space during production.
4. Overlying skin with pinna and tragal anatomy were created with commercial injectable silicone. The mould was printed with ABS material using UPBOX 3D printer.

3D printer can print at a speed of about 50-100mm/s. The model takes about 48 hours in total to print. Tango Plus FLX 930 flexible materials were chosen for its following mechanical properties

Tensile Strength	115-220 MPa
Elongation at break	170-220%
Tensile Tear Resistance	2-4 kg/cm
Polymerized density	1.12-1.13 g/cm^3

Table 3.1: Tango Plus FLX930 mechanical properties

3.5 Arthrocentesis and Arthroscopy simulation

Arthrocentesis and Arthroscopy procedures were simulated on the completed model. The model is tested for the following:

1. Identification of lateral canthus
2. Identification of tragus
3. Marking of canthal-tragal line on the model
4. Contact of lateral rim of glenoid fossa during needle advancement
5. Insufflation and irrigation of joint with normal saline
6. Lavage of >100ml of normal saline
7. Identification of 7 landmarks during arthroscopy diagnostic sweep:
    i. Medial synovial drape
    ii. Pterygoid shadow
    iii. Retrodiscal synovium
    iv. Posterior slope of articular eminence and glenoid fossa
    v. Articular disc
    vi. Intermediate zone
    vii. Anterior recess

3.6 Ethical approval and funding

Ethical approval was obtained from Medical Ethic Committee, Faculty of Dentistry University of Malaya [Reference No: DF OS1717/0042 (P)]. This research was funded by Dental Postgraduate Research Grant (Project No. UM.D/DRMC/628/6/1).

CHAPTER 4: RESULTS

4.1 Cadaveric dissection

Dissection was done on 3 cadavers.

i. 52 years old Chinese male
ii. 59 years old Chinese male
iii. 69 years old Chinese female

All 3 cadavers have intact TMJ and no head injuries. The attachment of TMJ capsule is shown in figure 4.1. The dissection was performed by a postgraduate maxillofacial surgical trainee under the supervision of senior consultant.

4.1.1 Articular disc

All dissected articular discs show no sign of degeneration or perforation. The disc is thinnest at the centre and thickest at the anterior and posterior as shown in figure 4.2. The discs have an average of 2.67mm thickness at its thickest and average dimension of 2.4 x 1.43 cm. Measurements were done using a 1mm precision calliper. The average of 2 readings were taken and shown in figure 4.1.

Sample	Thickness (mm)	Antero-posterior length (cm)	Medial-lateral width (cm)
1	3	1.5	2.5
2	3	1.4	2.3
3	2	1.4	2.4

Table 4.1: Thickness and dimension of articular disc

4.1.2 Upper joint space volume

Upper joint space has an average volume of 1.03 ml. Measurements were taken by injection of normal saline into the upper joint space.

Sample	Volume (ml)
1	1.1
2	1.1
3	0.9

Table 4.2: Upper joint space volume

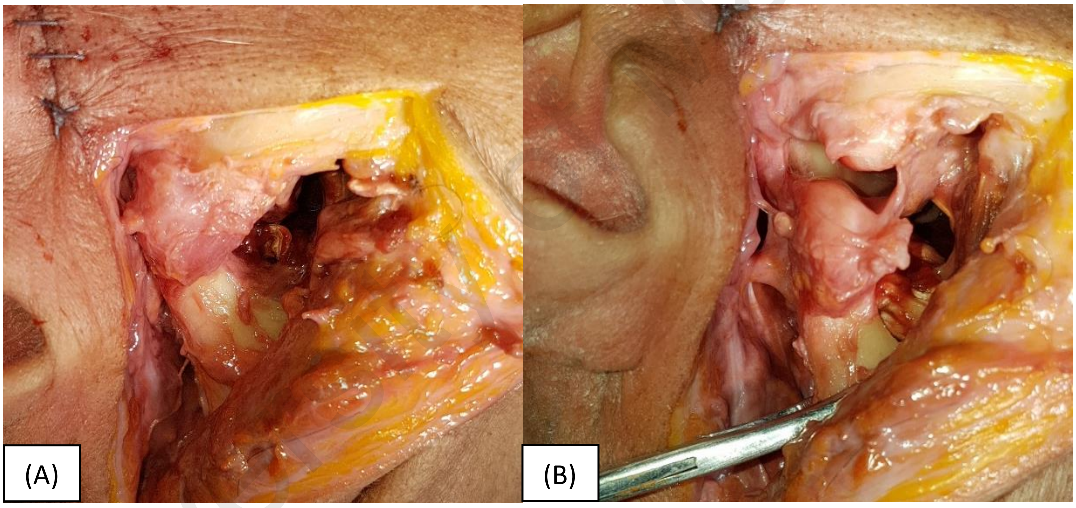


Figure 4.1: TMJ capsule with lateral ligament seen (A) and upper joint space with articular disc attached to condylar head (B)

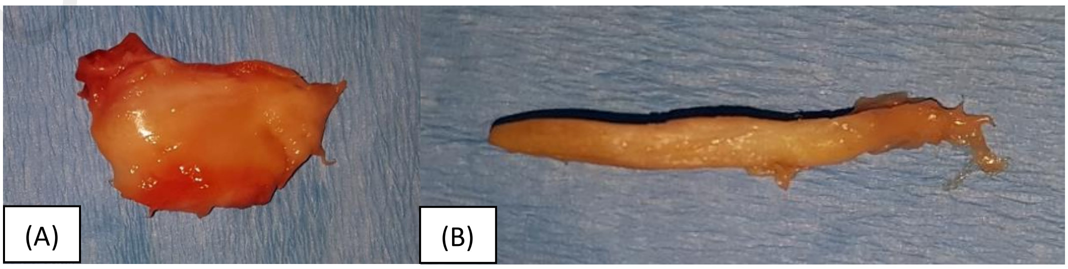


Figure 4.2: Dissected articular disc showing its antero-posterior length and medial-lateral width (A) and thickness (B)

4.2 TMJ training model creation

The first prototype was designed to have a moveable joint, watertight capsule and an articular disc. The main weakness of this prototype is immobile joint and poor structural integrity. It breaks easily after few attempted movements as shown in figure 4.3. Capsular thickness was 1mm.

Figure 4.3: First prototype of TMJ capsule

The TMJ capsule is elongated on the 2nd prototype to allow more joint movement and capsular thickness was increased to 2mm. The joint was able to move freely but the elongated joint is less accurate anatomically as shown in figure 4.4.

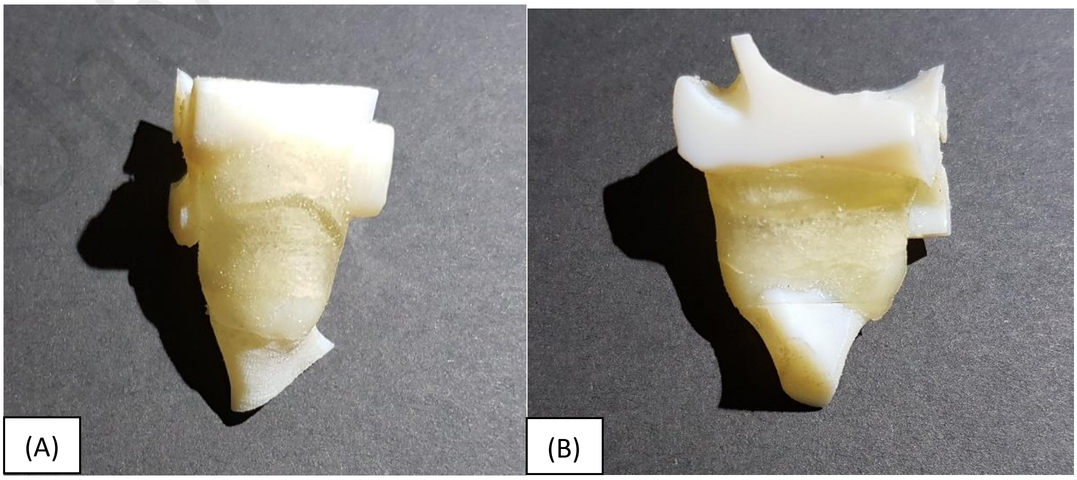


Figure 4.4: Second prototype of TMJ capsule. Front view (A) and side view (B)

The 3rd and final prototype as shown in figure 4.5 has capsular thickness of 2mm. Hinge movement can be replicated but disc movement and translational opening of the condyle remain limited due to the poor elasticity of Tango Plus flexible material. Water retention on upper joint space can be achieved in the final prototype.

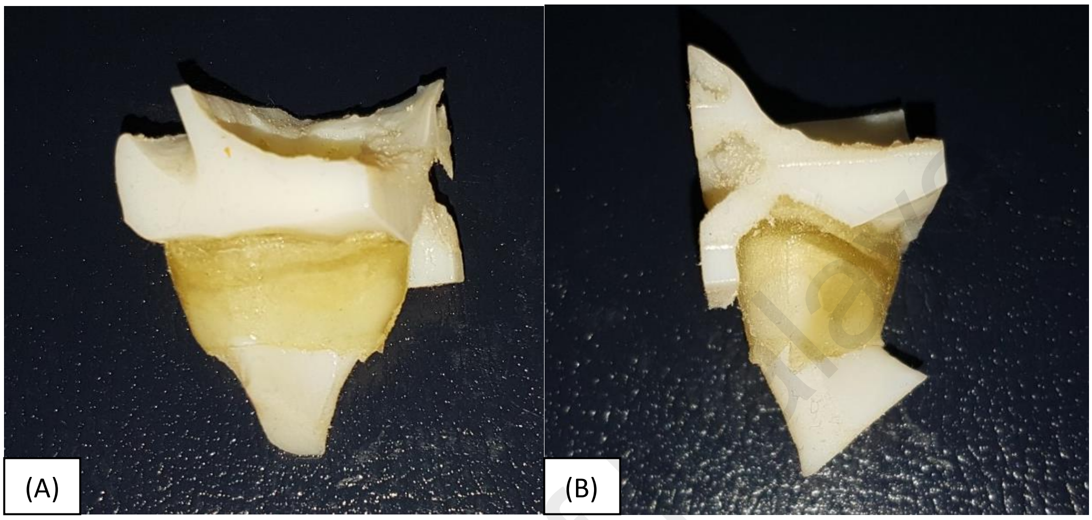


Figure 4.5: Third and final prototype of TMJ capsule. Front view (A) and side view (B)

The overlying skin layer is fabricated from printed mould (Figure 3.4) using commercially available Room Temperature Vulcanizing (RTV) injectable acetic acid silicone. The silicone takes about 24 hours to fully cure. Male slot was designed on the all four skin edges as shown in figure 4.6 for attachment to the female slot base model. It cost about USD 0.72 to produce a skin layer.

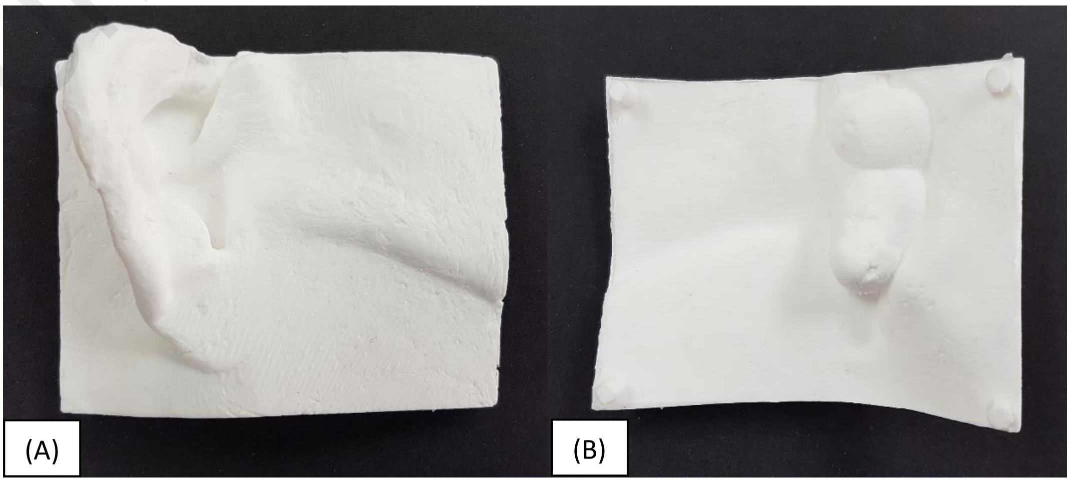


Figure 4.6: Front (A) and back (B) of silicone skin produced from mould

The head base model, mandible and TMJ were printed as separate units. The mandible was adhered to the TMJ with acetone. There is a slot for the mandible on the head base model (Figure 4.7A) where the right hemimandibular unit (Figure 4.7B) sit. They can be assembled without adhesive and the fit is retentive and stable.

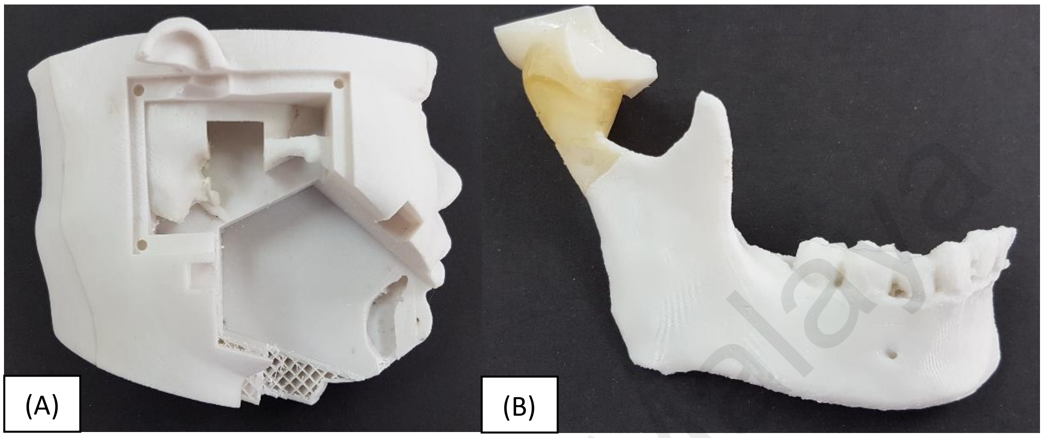


Figure 4.7: Condyle slot on head base model (A) and right hemimandibular unit (B)

The hemimandibular unit can then be replaced easily by sliding it out. The mandible was able to achieve 35mm opening but does not slide forward with opening and the articular disc remained at the same resting position as shown in figure 4.8B.

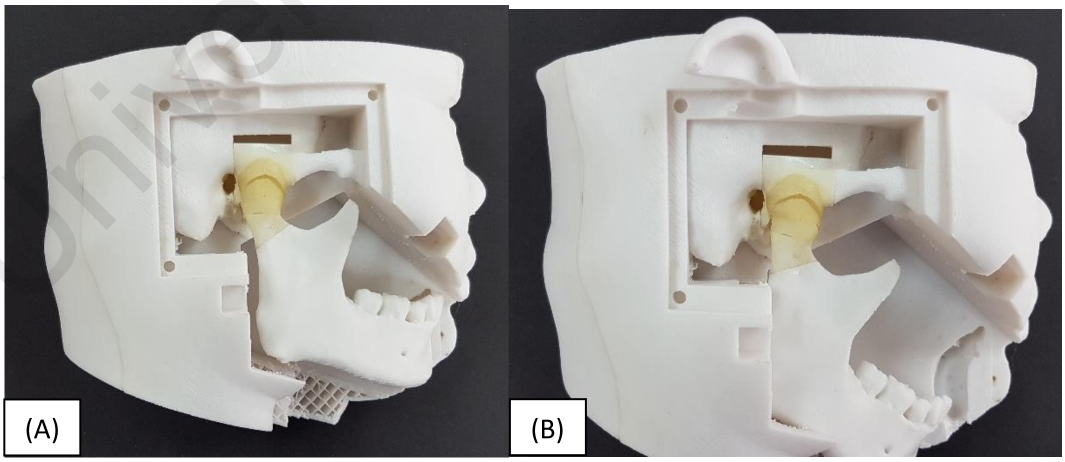


Figure 4.8: Mandible in resting position (A) and mandible in 35cm opening position (B)

Figure 4.9A shows the completed model with TMJ window. This could facilitate anatomical teaching. Completed unit with overlying silicone skin was ready for arthrocentesis and arthroscopy simulation (Figure 4.9B).

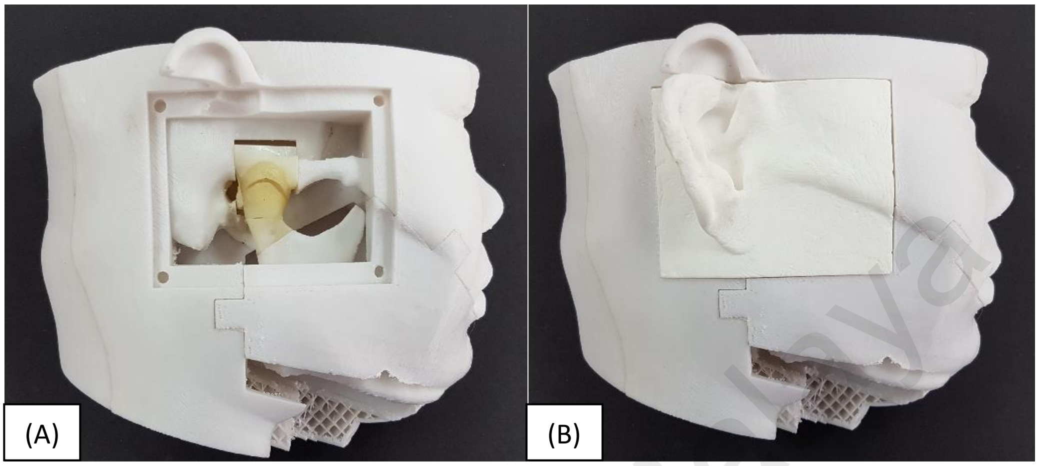


Figure 4.9: Model with an opening to the TMJ and female slot at corners (A) and completed model with silicone skin attachment (B)

The fabricated model satisfied 5 out of 7 of the parameters as shown in table 4.3.

TMJ model parameters	Achieved (✓) / Not achievable (×)
Palpable zygoma	✓
Watertight TMJ capsule	✓
Jaw opening of >35mm	✓
Detachable TMJ joint for replacement	✓
Detachable skin for replacement	✓
TMJ joint replicating hinge and sliding motion of normal TMJ	×
Forward movement of articular disc	×

Table 4.3: TMJ model Parameters

4.3 Arthrocentesis simulation

Canthal-tragal line was drawn on the model. First surgical marking was done at 10mm anterior to the tragus and 2mm inferior while the second marking 20mm anterior and 7mm inferior (Figure 4.10). First needle was punctured on the posterior marking and the second needle on the anterior marking. Depth of penetration was measured at 2.5cm.

10ml of normal saline was successfully irrigated simulating TMJ arthrocentesis as shown in figure 4.11. Skin layer was lifted to confirm the position of both needle on the upper joint space.

Continuous flushing and increased water pressure cause eventual leakage on the TMJ capsule. 18ml of normal saline was successfully flushed before capsule leakage.

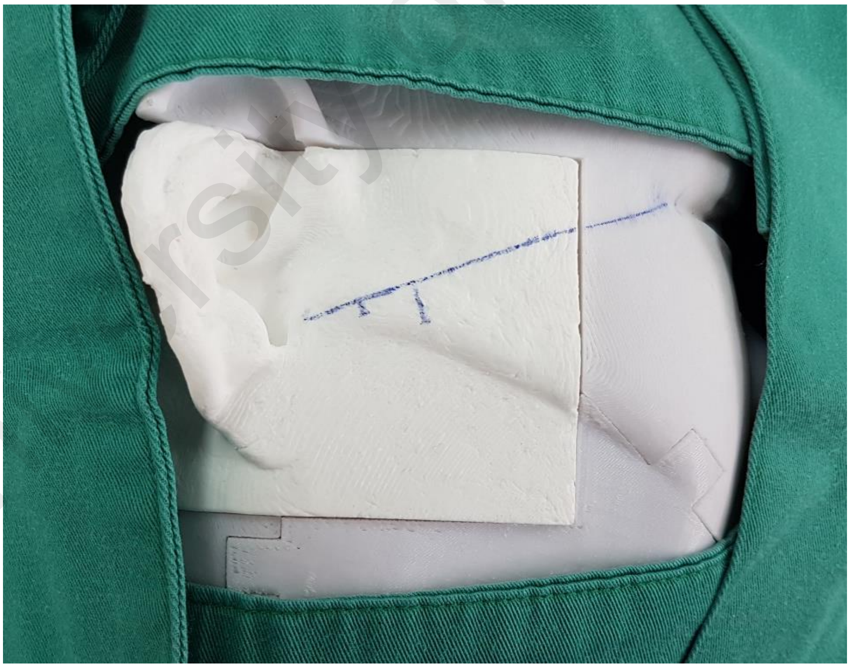


Figure 4.10: Canthal-tragal line and surgical markings on the model

Figure 4.11: Arthrocentesis performed on model

4.4 Arthroscopy

Arthroscopy was done using Tele Pack X LED (Karl Storz, Tuttlingen, Germany) with a straight 0° scope. Trocar penetrates the skin at 10mm anterior of the tragus and 2mm below the Canthal-tragal line. Arthroscope then advanced through lateral recess to reach the upper joint space. Table 4.4 shows structures visible on arthroscopy diagnostic sweep of TMJ model in comparison with human TMJ.

Anatomical Structures	Visibility	
	TMJ Model	Human TMJ
Medial synovial drape	✓	✓
Pterygoid shadow	✗	✓
Retrodiscal synovium	✗	✓
Glenoid fossa and posterior slope of eminence	✓	✓
Articular disc	✓	✓
Intermediate zone	✓	✓
Anterior recess	✓	✓

Table 4.4: Arthroscopy diagnostic sweep of TMJ model and human TMJ

Greyish white translucent lining of the (1) medial synovial can be replicated. Hard structures such as the (2) glenoid fossa and posterior slope of articular eminence can be easily visualised. (3)Articular disc was represented by the smooth surface of Tango Plus flexible material but was limited by the poor mobility of the mandible model to evaluate the position and function of the disc. (4) Intermediate zone too can be seen due to the whitish material that replicates posterior slope and articular disc. Area of the (5) anterior recess can be seen and working cannula can be inserted to this area if necessary. These are shown in figure 4.12. Arthroscopy of human TMJ is shown in figure 4.13

Pterygoid shadow was not seen on the model due to the absence of pterygoid structure and purple hue related to this structure. Retrodiscal synovium is poorly reflected on the model, there was no soft appearance of the synovial membrane, crest and crease of oblique protuberance were not seen vascular network were not replicated.

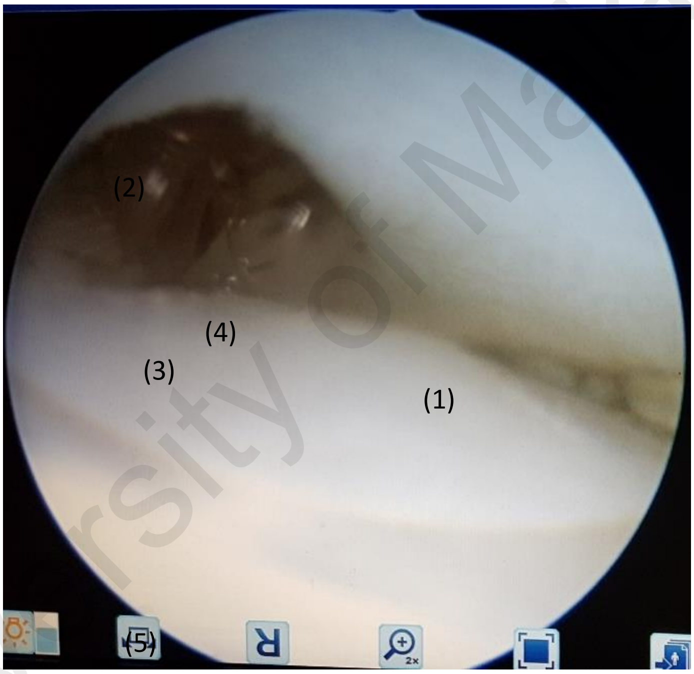


Figure 4.12: Upper joint space of TMJ model visualised on arthroscopy. (1) medial synovial, (2) glenoid fossa and posterior slope of articular eminence, (3) articular disc, (4) intermediate zone, (5) anterior recess.

Figure 4.13: Upper joint space of human TMJ during arthroscopy diagnostic sweep

5 out of 7 parameters were achieved during simulation of arthrocentesis and arthroscopy as shown in table 4.5.

TMJ model parameters	Achieved (✓) / Not achievable (×)
Identification of lateral canthus	✓
Identification of tragus	✓
Surgical markings based on Canthal-tragal line	✓
Contact on lateral rim of glenoid fossa during needle advancement	✓
Insufflation and irrigation of joint with normal saline	✓
Lavage of >100ml of normal saline on upper joint space	×
Identification of 7 structures during arthroscopy diagnostic sweep	×

Table 4.5: Surgical simulation parameter

CHAPTER 5: DISCUSSION

Cadaveric dissection was undertaken to enhance the understanding of the TMJ to better reproduce a training model and is not the main objective of this study. Qualitative data were collected using video and photo recording. In the meantime, physical measurement of the articular disc was carried out. Only dissections of 3 right TMJ were carried out due to the time constraint given by Silent Mentor Program coordinator for this research. Right TMJ was chosen as the model will be developed based on unilateral right TMJ. The dimension of articular disc obtained from this study is 2.4 x 1.43 cm, similar to study by Coombs et al with dimension of 2.21 x 1.4 cm based on 11 male cadavers (Coombs et al., 2019). Coombs et al also reported an average thickness of 3.7mm at the posterior band of the articular disc while the greatest thickness measured in this study was 3mm. With the aid of data from dissection, an anatomically similar TMJ can be reproduced (Figure 5.1).

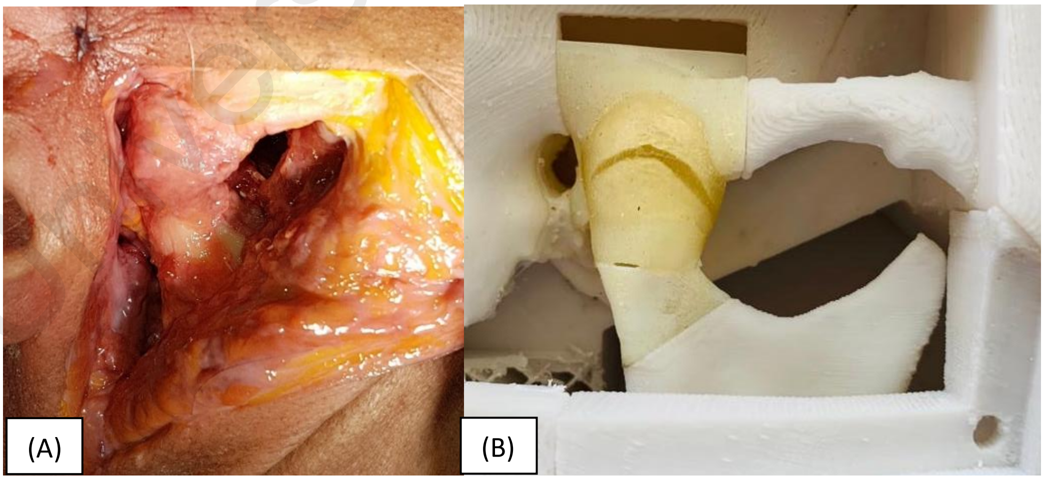


Figure 5.1: Comparison of human TMJ (A) with fabricated TMJ prototype (B)

The CT instead of MRI was used for the construction of this prototype for better bone details and 3D assessment (Bag et al., 2014). Patients with disc pathology and trauma can be visualised and evaluated using CT scan (Roberts, Pettigrew, Ram, & Joseph, 1984). A study on surface osseous changes of TMJ found that CT scan to have good reproduction with the highest accuracy obtained from multi slice axial-associated multiplanar reconstructed images (Zain-Alabdeen & Alsadhan, 2012).

The CT DICOM data belongs to a 30 years old gentleman with a normal TMJ. The age range of 25 to 35 years old for our inclusion criteria were chosen for better outcome of reproducing a fully developed and normal TMJ model. Data from aged patient was avoided as Toure et al shows that more than 50% of his subjects aged more than 75 years old demonstrated articular degeneration (Toure, Duboucher, & Vacher, 2005). Condylar head continues to change as a result of growth and ageing. Meanwhile, condylar cortical plate only fully developed around 20 years old and gradually demonstrate osteoarthritic changes after 3rd decade (Takenoshita, 1982).

It is possible to merge both CT and MRI data to preserve real TMJ structures for printing (Garling, Jin, Yang, Khasawneh, & Harris, 2018). However, technical difficulties, high production cost and durability issues make it not feasible as a training model. Complete anatomical structures are not necessary for arthroscopy training model and thus the joint capsule design was developed independently.

There are about 10 different types of 3D printer technology available in the market. Connex 500 Multi-Material 3D printer (3D Printers, Toronto, Canada) used in this study is a Material Jetting (MJ) printer. It works similar to an inkjet printer by jetting tiny droplets of photopolymer materials and cures them with an ultraviolet (UV) light. Layers of materials were cured until an eventual 3D product materialised. It has the capability to print and combine different materials which is needed to fabricate the joint which has the hard (condyle) and soft (capsule) components.

Another printer used for this project was UPBOX 3D printer (Tiertime Technology, Beijing, China) which uses Fused deposition modelling (FDM) technology. This printer works by melting thermoplastic filament and extruding it through printer nozzle where the molten material then cools down and solidify. It was done in layers until the desired object is fully formed. Compared to Material Jetting printer, Fused Deposition Metal technology is more readily available and cheaper (N. Turner, Strong, & A. Gold, 2014). This printer was used to reduce the cost of the prototype.

The cost of 3D printing is determined by the resolution and materials used. 3D printing resolution is measure by 2D two planar dimensions (x and y) and a third z dimension. Resolution is normally in millimeter (mm) or micrometer (µm) for finer details. These measurements relate to the thickness of the material at xy dimension and z dimension.

Current commercial 3D printing company charges about RM 1
(USD 0.24)/g for printing of ABS material at a resolution of 200µm while higher resolution of 100µm is priced at RM 2 (USD 0.48)/g. Meanwhile, flexible printing material such as Tango Plus cost RM 4 (USD 1.92)/g for resolution of 100µm. This prototype was printed with 200µm resolution.

The cost of printing the hard tissue of the head and mandible is RM 400 (USD 96.41). For flexible tissue, the skin will cost the most at about RM 100 (USD 24.10) to print and must be regularly replaced after multiple punctures and training. TMJ joint and capsule will have to be replaced regularly after training and will cost about RM 24.10 (USD 24.10) per print.

To reduce the cost of replacement for the skin layer (Figure 4.6), a mould was printed (Figure 3.4). The mould cost RM 125 (USD 30.13) to print. This allow the skin to be fabricated by injecting commercial Room Temperature Vulcanizing (RTV) injectable acetic acid silicone. The silicone requires 24 hours to fully cure. This significantly reduce the replacement cost of the skin from RM 100 to RM 3 (USD 24.10 to USD 0.72).

The lifespan of TMJ capsule can be prolonged by repairing it with similar RTV silicone. A thin layer can be applied on puncture sites of the capsule and allow to cure for 24 hours. Unfortunately, after multiple penetration it has to be replaced and the replacement must be 3D printed. The capsule and discs are too delicate and difficult to be reproduced using similar mould to fabricate the skin. Hence the replacement cost for the training parts of this model is RM 103 (USD 24.82). Table 5.1 shows the cost of the fixed components and parts that need to be replaced after each simulation. The total printing cost for this prototype is RM 628 (USD 151.36). In comparison, Arealis et al reported that his arthroscopic skill simulator, built on web-cam and readily available hardware materials to be cost-effective. However, the actual figure of the construction cost was not mentioned in the paper.

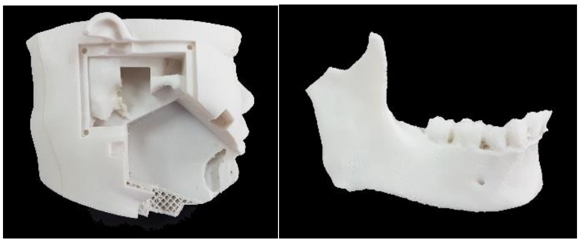
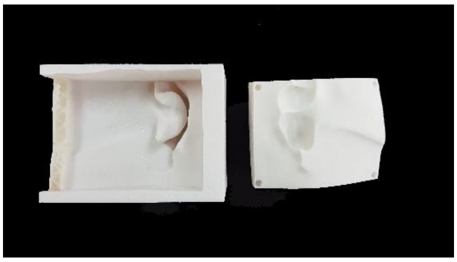
Component	**Fixed/Replaceable**	**Cost RM (USD)**
 Head and mandible	Fixed	RM 400 (USD 96.41)
 Silicone skin mould	Fixed	RM 125 (USD 30.13)
 TMJ	Replaceable	RM 100 (USD 24.10)
 Skin	Replaceable	RM 3 (USD 0.72)

Table 5.1: Fixed and replaceable components cost (*currency exchange in June 2019)

There are few weaknesses and limitations in this model. First, there is structural weakness. The capsule tends to tear after repetitive mandibular movement and manipulation. The model cannot reproduce the tensile and elasticity of real human TMJ capsule.

Second, there is only hinge movement during simulation of mouth opening. The forward sliding of condyle and subsequent movement of the articular disc anteriorly could not be replicated.

Although the capsule was able to retain water for arthrocentesis and arthroscopy training, high flow irrigation or increased water pressure will cause leakage. Arthrocentesis could be performed and on trial, up to 18ml of saline can be irrigated. There is no issue in practice of surgical marking, needle penetration and small volume irrigation of upper joint space but the capsule will not hold if large volume (200ml) of free flow normal saline is flushed through as per general arthrocentesis practice (Kuruvilla & Prasad, 2012; Nitzan et al., 1991).

Although irrigation of more than 100ml is desirable as per common practice, a study in 2018 by Grossmann et al went to show that 50ml of arthrocentesis irrigation is as effective as 200ml in pain reduction and increase in maximum incisal distance, protrusion and lateral excursion (E. P. Grossmann, Poluha Rl Dds, Iwaki, & Iwaki Filho, 2018). On the extreme, Bas et al found that irrigation volume of less than 10ml does not affect the success rate of arthrocentesis (Bas et al., 2019).

There were various researches conducted on surgical training for arthroscopy. Most of the development of training tools for arthroscopy practices were conducted in orthopaedic field on knees model. A comparison of various teaching techniques including cadaver and synthetic joint model concluded that cadaver-based teaching method to be more superior (Berman, Ben-Artzi, Fisher, Bass, & Pillinger, 2012).

However, there are limitations and restrictions in securing cadavers for surgical training.

As mentioned in the literature review, Kaduk and Koppe 2007 investigated and performed metric analysis of upper joint space of pigs' TMJ to evaluate its suitability as a model for arthroscopic TMJ surgery. Their study found similarities between human TMJ and pig's TMJ of about 25-30kg weight. Nevertheless, they did not investigate and validate its suitability as training model for arthroscopy. There is also cultural and religious limitation in using pig model for training among Muslim population.

The TMJ prototype that closely resemble this study were by Monje Gil et al. The prototype used by Monje were built using anthropometric measurement and incorporates the skin, subcutaneous tissue, parotid gland, facial nerve, temporal vessels, ligaments, and articular capsule. The biggest advantage of the prototype created in this study were the watertight property of the TMJ capsule. This allows irrigation and practice of arthrocentesis not achievable by Monje's prototype. Nevertheless, the model used by Monje Gil et al was better than our model in terms of anatomical accuracy and reproduction. Structures on the upper joint space were accurately replicated in all the 7 landmarks and can be visualised during arthroscopy diagnostic sweep. However, their study was on the validation of the prototype and the creation process were not discussed. The cost of the prototype was not mentioned but is estimated to be much higher compared to our model.

Further research and better models can be built based on the current prototype. Better materials could be studied to reinforce the current TMJ capsule to prevent leakage and tear while the maximum hydraulic pressure sustainable by the joint could be measured.

Using build in general surgery simulation in robotic surgery virtual simulator, Rajanbabu et al concluded that new surgeons were able to match the result of veteran surgeons after repetitive practice of the same exercise 6 times (Rajanbabu, Drudi, Lau, Press, & Gotlieb, 2014). It is our hope that with the current prototype, trainees and surgeons will be able to gain valuable arthrocentesis and arthroscopy simulation experience by repetitive practices on the fabricated model.

CHAPTER 6: CONCLUSION

6.1 Conclusion

We managed to fabricate a reliable and reusable training model with watertight TMJ capsule which allow simulation of arthrocentesis and arthroscopy diagnosis and lavage. This model can be used for simulation among OMFS residents. Detachable components such as the skin and TMJ allows replacement at much lower cost after each practice session. The blueprint in the form of STL file is available allowing other centres to print and build similar model for training.

6.2 Limitation of the study

There is mechanical limitation of the joint. The joint will break and leak after multiple punctures and movement of the TMJ. The poor elasticity of the material limits the movement of the articular disc and the condyle during simulation of mouth opening. Certain intracapsular anatomies such as pterygoid shadow and retrodiscal synovium were not replicated making it less realistic for arthroscopy diagnostic sweep.

6.3 Recommendation

We recommend improvement over the current training model for more realistic arthroscopy training experience. Mechanical properties such as water tightness and capsule elasticity can be improved to allow translation movement of the joint. Pathologies such as disc adhesion and perforation can be added to future models to extend the range of surgical simulation such as motor debridement, meniscal suturing and myotomy.

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