Rapid prototyping medical models for dysplastic hip orthopaedic surgery

Rapid prototyping medical models for dysplastic hip orthopaedic surgery

R Dhakshyani[1]*, Y Nukman[1], N A Abu Osman[2], A M Merican[3], and **J George[4]**
[1]Department of Engineering Design and Manufacture, University of Malaya, Kuala Lumpur, Malaysia
[2]Department of Biomedical Engineering, University of Malaya, Kuala Lumpur, Malaysia
[3]Department of Orthopaedic Surgery, University of Malaya, Kuala Lumpur, Malaysia
[4]Department of Biomedical Imaging, University of Malaya, Kuala Lumpur, Malaysia

The manuscript was received on 19 August 2009 and was accepted after revision for publication on 24 September 2009.

DOI: 10.1243/09544054JEM1785

Abstract: This research was carried out to show the usefulness of rapid prototyping (RP) medical models in dysplastic hip orthopaedic surgery. There is a lack of published information on the use of RP medical models in planning of dysplastic hip orthopaedic surgery, so this research was conducted to provide such information. Computed tomography (CT) of a patient with a dysplastic hip was used. Special medical software was used to prepare the three-dimensional model of the patient, which was then used to produce the RP medical models. These models were then given to the orthopaedic surgeons to plan for the dysplastic hip surgeries. Measurements on the CT scan data were taken before surgery. Finally, surgeons' comments on their experience of planning dysplastic hip surgery with the use of RP medical models were obtained. The CT scan measurements taken before surgery indicated the severity of the dysplastic hip in each patient. Surgeons found the RP medical models to be very useful in planning of surgery, as they helped them to make decisions, increased their confidence, and also reduced surgery time. The results obtained show the effectiveness of using RP medical models in planning of dysplastic hip orthopaedic surgery. This research provides an understanding of the use of RP medical models in planning of dysplastic hip orthopaedic surgery. Surgeons had fresh experience of using models that greatly influenced the success of the surgery.

Keywords: computed tomography, fused deposition modelling, medical model, dysplastic hip orthopaedic surgery, measurements

1 INTRODUCTION

Hip joint surgeries are usually complex and time-consuming. Therefore, minimizing the duration of the surgery should reduce the risk of complications during and after surgery. The principal criteria used in planning for the surgery are important to reduce complications and smooth the execution of the surgery. A new surgical method not only focuses on diagnosis, operative techniques, and patient management, but also prioritizes the code for care and operations [**1**]. This can be achieved using a method called the rapid prototyping (RP) modelling technique. The use of RP technology in the medical field is one of its most interesting applications.

Rapid prototyping involves fabrication of a prototype model precisely produced from three-dimensional (3D) medical image data [**2**, **3**]. Rapid prototyping is used to produce physical models of anatomic structures and these are very useful as a surgical aid, in diagnosis, training, and design; they can also be used to explain the surgical procedure to patients. Medical models are accurate physical replicas of human body parts, created using medical scan data and RP processes. The advantages of using these models are good accuracy, high quality, and reduced risk, which also improves patient rehabilitation and

**Corresponding author: Engineering Design and Manufacture, University of Malaya, Lembah Pantai, Kuala Lumpur 50603, Malaysia.*
email: aksyan@hotmail.com

surgeon's confidence during surgery. Moreover, surgeons like to have a physical model of their patient's anatomy, as it enables them to appreciate more fully the 3D object for the planning of surgery [**4**]. In physical modeling, the surgeon can hold, comprehend, and manipulate the object. The physical model provides improved visualization compared with that offered by two-dimensional (2D) and 3D data. Rapid prototyping produces complex features, which are essential to help surgeons in making important decisions. Besides this benefit, RP models can be used to design individual implants and prostheses, as a teaching tool for surgeons, and also as a communication tool between surgeons and patients. In custom fabrication of implants, the combination of computer-aided design (CAD), computer-aided engineering (CAE), computer-aided manufacturing (CAM), RP, rapid tooling (RT), and finite element method (FEM) enables researchers to study design and biomechanical strength and thereby provide useful information to surgeons prior to surgery [**5**, **6**]. Overall, the use of RP models not only helps surgeons to increase their level of performance in surgery, but also leads to improved patient care.

Diagnostic tools such as computed tomography (CT) are commonly used to describe, understand, and diagnose patients [**7**]. CT provides detailed information relating to the geometry and physical properties of skeletal structures [**8**] and CT is also an effective tool for understanding complex fracture patterns, especially when combined with multiplanar reconstruction of 2D reformatted images or 3D images [**9**]. This is an advantage because CT images can be effectively used for orthopaedic-related cases. Related research studies have been conducted widely on the use of RP in the medical field, such as for maxillofacial surgery and orthodontics [**10**, **11**], but its contribution to orthopaedics is still limited and requires further exploration. The use of RP is invaluable as a tool to assist in complex trauma and orthopaedic surgery. The application of RP can be used as a means to model human bones quickly for visualization and training, diagnostic and complex procedures for surgery planning, and as a reference model in the operating theatre. Bone anatomy can be modelled effectively to understand the complexity of the case, and this also helps to diagnose the degree of injury [**12**, **13**]. The use of an RP model can help to reduce surgery time. Collaboration between engineers and surgeons is therefore important to demonstrate the benefits of applying RP models in orthopaedics.

2 DYSPLASTIC HIP

The term dysplastic hip is used to refer to a range of development hip disorders. The range could include a hip that is mildly dysplastic, concentrically located, and stable, to a hip that is severely dysplastic and dislocated [**14**]. Those suffering from osteoarthritis can also develop an idiopathic disease such as a dysplastic hip. A dysplastic hip is a condition in which the acetabular roof is not properly developed and can be seen as shallow. This leads to a smaller surface for weight bearing, which implies larger force per unit area during daily activities and so, early degeneration is expected [**15**]. Changes in size, shape, and orientation of the acetabulum and femoral head are described as hip dysplasia, and this is a developmental abnormality also known commonly as a dysplastic hip [**16**, **17**]. There are differences that can be seen to distinguish clearly between adults with normal and dysplastic hips, as shown in Figs 1 and 2 respectively [**18**].

In a normal hip, the femoral head is covered well by the acetabular socket. The distance between the centre of the hip and the attachment of the abductor muscles is equal to the lever arm of these muscles. This distance is known as femoral offset. A longer distance means that less work is done by the muscle to push the limb to the side. The main difference in a dysplastic hip is that the acetabular socket of the hip joint is shallow and oval [**19**]. The roof of the acetabular socket is oblique in shape and therefore does not offer any resistance to the upward glide of the femoral head. The femoral head can be seen to be

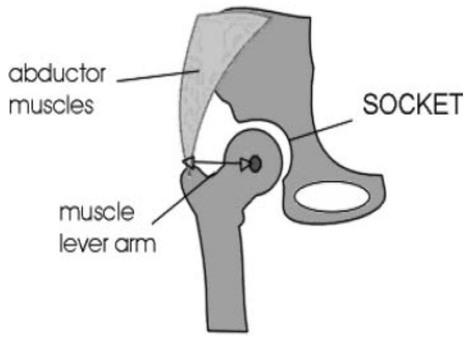

Fig. 1 Diagram of a normal hip

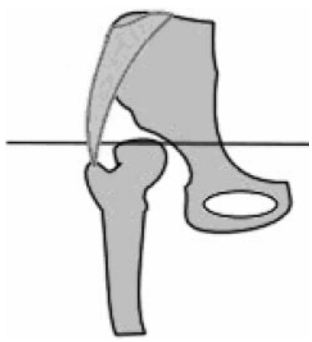

Fig. 2 Diagram of a dysplastic hip

deformed and is retained within the acetabular socket with the minimum coverage area. In other words, dysplasia of the human hip is characterized by insufficient anterolateral covering of the femoral head by the acetabulum [**20**]. The lever arm of the muscles is short, meaning that the femoral offset is short. This leads to the muscle being forced to work harder to move the limb. With the progress of time, this muscle will tend to fail owing to over-exertion and it becomes weak. A dysplastic hip, if not treated, will eventually lead to cartilage degeneration as a result of the increased stress in the joint. Therefore, the main goal in dysplastic hip surgery is to restore the contact between the femoral head and acetabulum [**21**], which is achievable.

The most important morphological measurements for dysplastic hips are the centre–edge angle, acetabular angle, depth-to-width ratio, and femoral head coverage by the acetabulum [**22**]. These morphological measurements are very important to the surgeons to determine the severity of the dysplastic hip and to plan for surgery. A CT scan of a patient prior to surgery can be used to determine these morphological measurements. The main problems faced by orthopaedic surgeons include making decisions on the reduction of the hip in acetabular reconstruction, accurate placing of bone grafting, and femoral shortening. It is important to secure the acetabular component's stability and coverage, and high hip centre, and to plan for the femoral shortening so as to avoid overstretching the neurovascular structures and to correct preoperative bony deformities. This is technically difficult and time-consuming, leading to increased surgical time. However, these problems can be solved by using dysplastic hip RP models. Therefore, the main objectives of the present research were to obtain dysplastic hip morphological measurements of patients before surgery to identify the severity of the dysplastic hip, and to assist the surgeons in planning and making decisions through using the RP medical models before conducting the actual dysplastic hip surgery.

3 METHODOLOGY

There are a few important procedures to carry out before obtaining the final output of the RP medical models, as shown in Fig. 3.

1. *Data acquisition*. A 3D digital image was obtained from the CT scanner. Scanning was carried out at 78 mA s and 140 kV. The CT data were acquired with a slice thickness of 1 mm. Patient scanning data were exported from the CT into the digital imaging and communication in medicine (DICOM) format and saved on to a compact disk.
2. *Data processing*. This is an important step that determines the quality of the RP medical models produced. Mimics software was used to convert the CT scanned image data from DICOM. The CT images were imported into Mimics software, processed to filter the required data, and the image files were extracted. Once loaded in the software, all images were registered accordingly and aligned according to orientation. Mimics software was used to perform segmentation of the anatomy through 3D selection and editing tools. Selection of the CT images was important, as it represented the desired anatomical part of the body, i.e. the pelvis, acetabulum, and femur, displaying the dysplastic hip region clearly. Thresholding was performed to create the first step of the segmentation mask. The threshold process enables differentiation of the bone from the surrounding tissue. This was then followed by region growing to split the segmentation object into separate masks. Manual segmentation was carried out, owing to the inconsistent density of the patient's hard tissue. Skill is required in this step. Pixels are removed in order to separate the parts. The CT scatters causing streaking, image noise, and image distortion, which were manually removed. The parameters selected for the 3D model were calculated and generated from the masks obtained. Subsequently, the digital model was remeshed to reduce the triangles and to smooth the model. Finally, the digital model was converted to a standard triangulation language (STL) format, which is readable by the fused deposition modelling (FDM) machine.

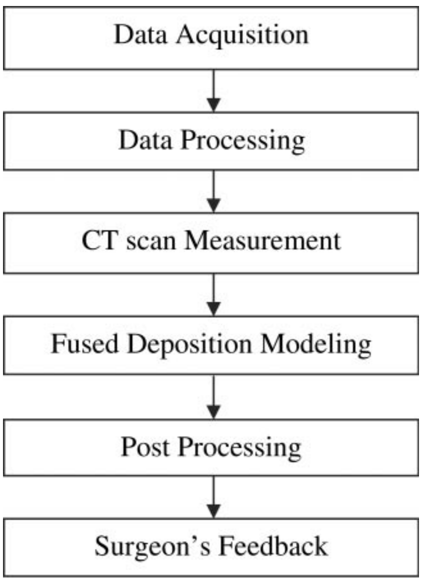

Fig. 3 Flow chart showing the research methodology

3. *Measurement of CT scans*. The important morphological measurements for a dysplastic hip are the centre–edge angle, acetabular angle, depth-to-width ratio, and femoral head coverage by the acetabulum; these were measured for each patient. This was carried out in the Mimics software. These morphological measurements are very important to the surgeons, as they determine the severity of the dysplastic hip. They also help the surgeons to classify the adult dysplastic hip based on the Crowe classification.
4. *Fused deposition modelling*. The type of RP machine used for the present research is FDM model machine type Dimension SST 1200es. Warming up the FDM machine took about 45 min. The STL file was opened using CatalystEx software. Then the build parameters and build orientation of the model were set before sending to the FDM machine for model building. The medical model part was orientated in an optimum position for building. The FDM machine process involved several steps. First, the tip extruded the filament of heated thermoplastic acrylonitrile butadiene styrene (ABS) plus, which moved in the x–y plane direction on the build platform to form the first layer. The platform was maintained at a lower temperature, which enabled the ABS plus material to harden quickly. Support material was generated during the build orientation of the RP model. Then, the extrusion head deposited a second layer on the first layer after the platform lowered. This process continued until the medical model was finally built. The model was built by the FDM machine based on a layer-by-layer concept.
5. *Post-processing*. This step was necessary to remove the support material that was attached to the FDM medical models. An ultrasonic bath containing soluble release solution was used for this purpose. The FDM medical models were immersed in the ultrasonic bath for 24 h, rinsed in running water, and dried.
6. *Surgeon's feedback*. The medical models were given to the orthopaedic surgeon for planning of dysplastic hip surgery. This is an important step as the surgeons play a crucial role in validating the fabricated FDM medical models.

4 RESULT

Model precision in the planning of surgery takes into account the CT scan accuracy and the FDM machine accuracy. The CT scan accuracy generally falls within 20 per cent of the slice data; therefore, CT data with a slice thickness of 1 mm gives accuracy of ± 0.2 mm. The FDM machine type Dimension SST 1200es (Stratasys, Eden Prairie) produces models with good accuracy of ± 0.254 mm.

Dysplastic hip parameters for each patient were measured from the CT scan data. The measurements obtained indicated the severity of the disease in each patient. Patients 1 and 3 had the left hip dysplastic, whereas patient 2 had the right hip dysplastic. The severity was classified based on Crowe classification. Patients 1 and 2 were classified as Crowe III and patient 3 was classified as Crowe IV. Table 1 shows the CT scan measurements obtained from the dysplastic hip patients.

The 3D medical models generated in Mimics software and FDM RP medical models produced for patients 1, 2, and 3 are shown in Figs 4 to 9 respectively. The times taken to build the RP medical models for patients 1, 2, and 3 were 21 h, 47 h, and 85 h respectively.

The RP medical models were given to the orthopaedic surgeons before dysplastic surgery. The orthopaedic surgeons (A. M. Merican, University of Malaya Medical Centre, 2009, personal communication; C. C. Tai, Universtiy of Malaya Medical Centre, 2009, personal communication; S. S. Jasmeet, Putrajaya Hospital, Malaysia, 2009, personal communication) found the models very useful in the planning of dysplastic hip surgery. The effect of model precision in the planning of surgery is great, as the measurements taken using the RP models were used to determine the implant sizes adopted in the surgery and helped to decide on bone grafting and length of femoral shortening. The orthopaedic

Table 1 CT scan measurements of dysplastic hip patients

Dysplasia parameters	Normal hip	Dysplastic hip: Patient 1 (Crowe III)	Patient 2 (Crowe III)	Patient 3 (Crowe IV)
Centre–edge angle (CE)	$>25°$ is normal [**12**]	19.64°	19.53°	19.46°
Coverage of femoral head by acetabulum	$<75\%$ is pathologic [**19**]	44.00%	32.70%	37.40%
Depth-to-width ratio	$\sim 60\%$ is normal [**19**]	70.00%	66.00%	46.00%
Acetabular angle (Sharp's)	$>10°$ is abnormal [**20**]	34.88°	38.50°	38.90°

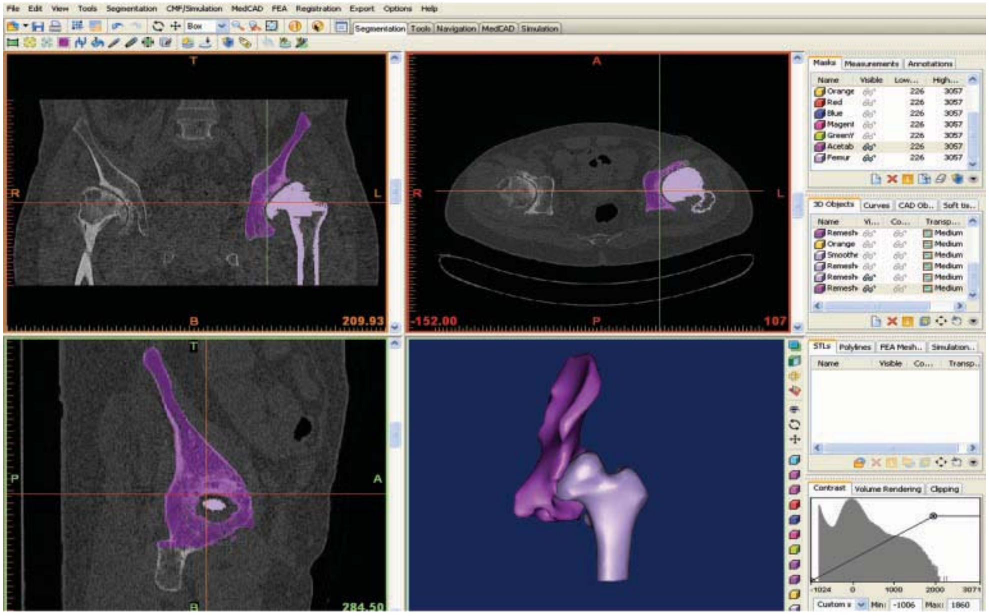

Fig. 4 A 3D dysplastic hip medical model of patient 1

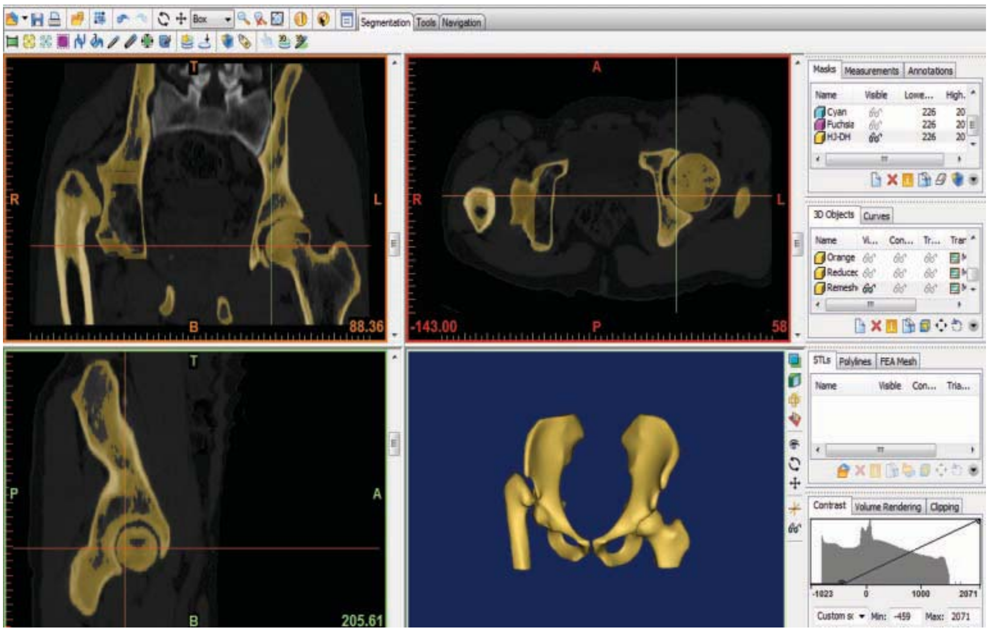

Fig. 5 A 3D dysplastic hip medical model of patient 2

surgeons found the differences to be minimal, at about ±0.2 mm (A. M. Merican, University of Malaya Medical Centre, 2009, personal communication; C. C. Tai, University of Malaya Medical Centre, 2009, personal communication; S. S. Jasmeet, Putrajaya Hospital, Malaysia, 2009, personal communication). The acetabular cup and implant sizes were determined exactly. An acetabular cup size of 46 mm and implant stem with femoral offset of ~35 mm were used during the dysplastic hip surgery of the patients.

The orthopaedic surgeons used a different surgical approach for each patient, which was planned using the RP medical models. The surgery method for patient 1 was based on the removal of the femoral head, which was replaced with a cobalt–chromium stem implant and acetabular cup made of ultra-high molecular weight polyethylene, which was placed at the acetabular region for hip stability. Bone grafting was also carried out for patient 1. Patient 2 had a titanium

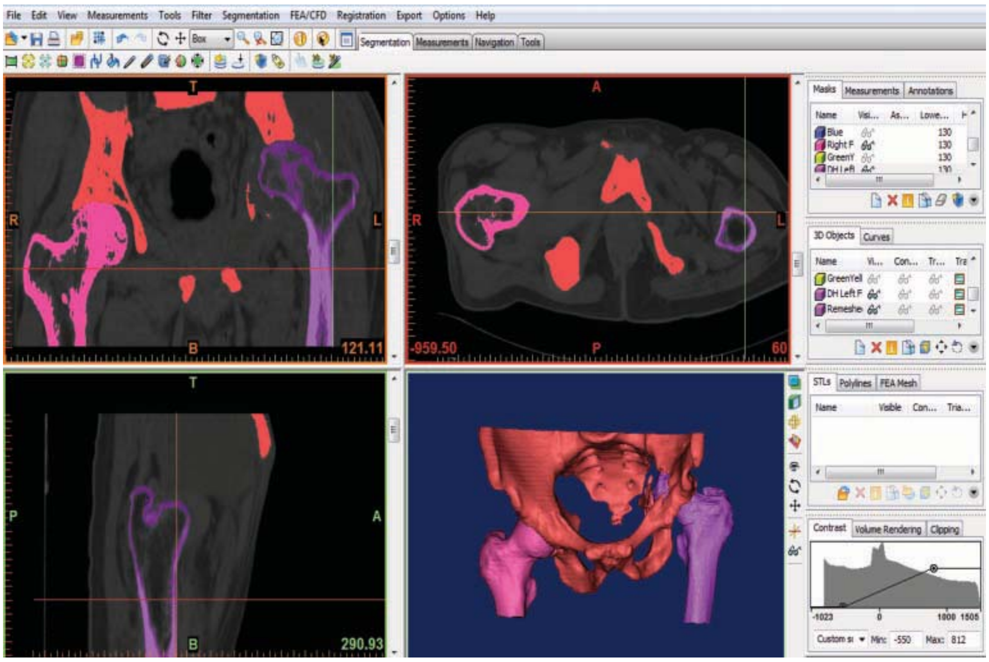

Fig. 6 A 3D dysplastic hip medical model of patient 3

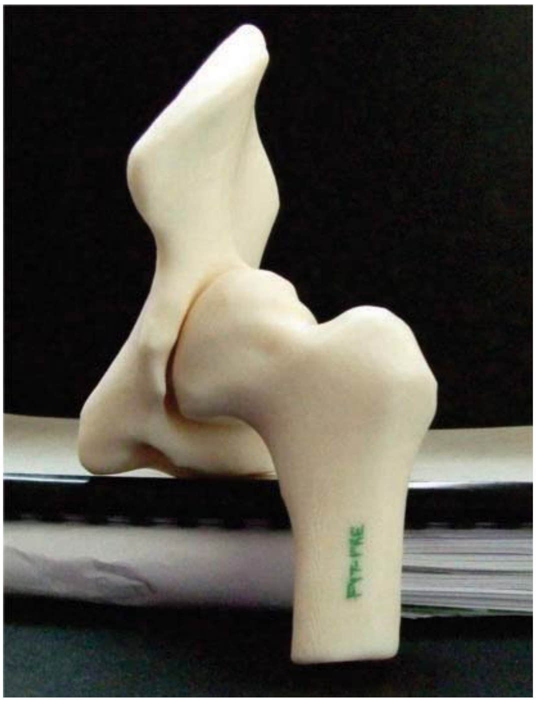

Fig. 7 A FDM RP dysplastic hip medical model of patient 1

Fig. 8 A FDM RP dysplastic hip medical model of patient 2

Fig. 9 A FDM RP dysplastic hip medical model of patient 3

stem implant inserted and a ceramic acetabular cup, but had to undergo femoral shortening by 4 cm to restore the hip stability. Patient 3 required an acetabular casing before the placement of the ceramic acetabular cup. Patient 3 also had a titanium stem inserted to restore the hip stability.

The outcome of the three dysplastic hip surgeries was successful. The orthopaedic surgeons were surprised and satisfied by the outcome from the RP medical models. They found that decisions made from radiographs alone do not provide as much information when compared with actually holding the model and rehearsing the surgery, which is made possible by the existence of the RP medical models. They also commented on the increase in their confidence level because they were able to prepare better before the actual surgery.

5 DISCUSSION

The precision of RP is driving towards the refinement of the algorithms for identifying surfaces and features from CT scan data. A CT scan machine gives good precision with high resolution. Based on this advantage, RP can be integrated for medical applications. From the surgeon's point of view, a requirement for model precision of about 0.2 ± 0.5 per cent is acceptable in medical applications (A. M. Merican, University of Malaya Medical Centre, 2009, personal communication; C. C. Tai, University of Malaya Medical Centre, 2009, personal communication; S. S. Jasmeet, Putrajaya Hospital, Malaysia, 2009, personal communication). Model precision in medical applications is required in prior fabrication of prostheses, templates, and implants which are used in joint replacement surgeries and revision surgeries.

The dysplastic hip is a developmental abnormality which requires the attention of orthopaedic surgeons to plan for successful surgery. The CT scan measurements provided the information regarding the important parameters of the dysplastic hip and also for the Crowe classification, which is a useful tool to classify the severity of the dysplastic hip. The CT scan was also used to measure the parameters, as the measurements are more accurate than from X-rays, which also tend to give limited information [**23–25**].

Planning towards a dysplastic hip surgery involves considering various surgical techniques to secure the hip stability, such as selection of implant sizes, bone grafting, femoral shortening, high hip centre, and leg length discrepancy [**26**]. The RP medical model enabled the orthopaedic surgeons to determine the surgical approach and to rehearse on the model before performing the actual surgery.

Rapid prototyping medical models allows rapid manufacture of accurate 3D models of the dysplastic hip [**27**]. These models were very helpful in preoperative assessment, severity classification, and preoperative planning of dysplastic hip surgery. The RP medical model produced using FDM is made of acrylonitrile butadiene styrene thermoplastic material, which is robust and has good strength but can be cut using the operating theatre tools [**28**].

An orthopaedic surgeon gets to view, handle, and practice on the physical model, which is an actual anatomical replica of the dysplastic hip. The surgeons stated that decisions they made using radiographs to plan for surgery were different compared with their decisions when they were given the RP medical models. As an example, bone grafting had been planned for patient 2, but with the use of the RP medical model, the orthopaedic surgeon changed his decision because bone grafting was considered not to be necessary. This change in the pattern of decision making was also attributed to the fact that the surgeons could view the dysplastic hip region clearly on the model, in exactly the same way as when the region is viewed on the patient in the operating theatre. In addition, the surgeons found that the use of the RP medical models in planning the dysplastic hip surgery improved their understanding of the respective cases and helped to reduce surgery time. They also found that using the RP medical model enabled better communication between surgeons in order to study each case and exchange views on the most suitable surgical technique.

This research clearly shows the advantages of the RP medical models in planning of dysplastic hip surgeries, which also provided the orthopaedic surgeons with a new experience to enhance their skills further.

6 CONCLUSION

Preoperative surgical planning is a very important step. Rapid prototyping medical models are an important tool to aid in orthopaedic surgery. The use of RP medical models improves the quality of the preoperative planning, increases surgeons' confidence, reduces the complexity of the surgery, reduces surgery time, ensures successful surgery outcome, and a faster patient recovery can be expected. Surgeons can choose the appropriate operative approach prior to actual surgery, which also reduces the risk of the surgery. The many advantages and the potential for using RP medical models provide sound justification for further exploration of this technique in orthopaedic surgeries.

ACKNOWLEDGEMENTS

This research was supported by the Sponsored Research Unit, University of Malaya (research grant PS094/2008C). The authors would also like to thank Dr Jasmeet for providing the dysplastic hip patients' CT scan data.

REFERENCES

1 **John, E. M.** What's new in orthopaedic surgery. *J. Am. Coll. Surg.*, 2004, **199**(6), 924–931.

2 **Adam, M.** and **Slawomir, M.** Stereolithography – the choice for medical modelling. *Acta Bioengng Biomech.*, 2004, **6**(1), 13–24.

3 **Petzold, R., Zeilhofer, H. F.,** and **Kalender, W. A.** Rapid prototyping technology in medicine – and applications. *Computerized Med. Imaging and Graphics*, 1999, **23**, 277–284.

4 **Sam, M. W. III, Quyen, M. S. T., Adrian, D. B. S.,** and **Ronald, E. B.** Building anatomical models from CT and MRI scans for orthopedic preoperative planning and custom implant construction. *IEEE, Southern Biomedical Engineering Conference Proceedings*, 1997, **1**, 466–469.

5 **He, J., Li, D., Lu, B., Wang, Z.,** and **Zhang, T.** Custom fabrication of composite tibial hemi-knee joint combining CAD/CAE/CAM techniques. *Proc. IMechE, Part H: J. Engineering in Medicine*, 2006, **220**(H8), 823–830.

6 **Pattijn, V., Samson, I., Vander, S. J., Van, A. R., Swaelens, B.,** and **De, B. V.** Medical image based, preformed titanium membranes for bone reconstructions: design study and first clinical evaluation. *Proc. IMechE, Part H: J. Engineering in Medicine*, 2002, **216**(H1), 13–21.

7 **Berce, P., Chezan, H.,** and **Balc, N.** The application of rapid prototyping technologies for manufacturing the custom implants. In Proceedings of the ESAFORM Conference, Cluj-Napoca, Romania, 2005, pp. 679–682.

8 **Riccardo, L., Fabio, B., Cinzia, Z.,** and **Marco, V.** Specialised CT scan protocols for 3-D pre-operative planning of total hip replacements. *Med. Engng Physics*, 2004, **26**, 237–245.

9 **Marco, F.** and **Gian, A. R.** CT of pelvic fractures. *Eur. J. Radiol.*, 2004, **50**, 96–105.

10 **Douglas, M. E., David, C., Stephen, S.,** and **James, M.** An opinion survey of reported benefits from the use of stereolithographic models. *J. Oral Maxillofacial Surg.*, 1999, **57**, 1040–1043.

11 **Bal, S., Satyajit, N., Yannis, P.,** and **Andrew, A.** Preliminary study of rapid prototype medical models. *Rapid Prototyping J.*, 2001, **7**(5), 275–284.

12 **Jeffrey, D. M.** and **Thomas, A. E.** General orthopedic principles. *The Aging Skeleton*, 1999, **V**, 383–397.

13 **Potamianos, P., Amis, A. A., Forester, A. J., McGurk, M.,** and **Bircher, M.** Rapid prototyping for orthopaedic surgery. *Proc. IMechE, Part H: J. Engineering in Medicine*, 1998, **212**(H5), 383–393.

14 **Carol, D.** and **Karen, R.** Development dysplasia of the hip. *Lancet Semin.*, 2007, **369**, 1541–1552.

15 **Umer, M., Thambyah, A., Tan, W. T. J.,** and **Das, D. S.** Acetabular morphometry for determining hip dysplasia in the Singaporean population. *J. Orthop. Surg.*, 2006, **14**(1), 27–31.

16 **Mavcic, B., Pompe, B., Antolic, V., Daniel, M., Iglic, A.,** and **Kralji-Iglic, V.** Mathematical estimation of stress distribution in normal and dysplastic human hips. *J. Orthop. Res.*, 2002, **20**, 1025–1030.

17 **Yu-Ping, S., Matthew, N. H. W.,** and **Wee-Ning, C.** Slotted acetabular augmentation in the treatment of painful residual dysplastic hips in adolescents and young adults. *J. Formos Med. Ass.*, 2008, **107**(9), 720–727.

18 *Disease.* Available from http://www.totaljoints.info (access date 20 April 2009).

19 **Remzi, I. T., Burak, B.,** and **Nadir, S.** Total hip arthroplasty in the treatment of development dysplasia of the hip. *Acta Orthop. Traumatology Turcica*, 2007, **41**(1), 80–86.

20 **Borut, P., Vane, A., Agles, I., Anton, J., Veronia, K. I.,** and **Blanz, M.** How should dysplastic human hips be evaluated. *Cellular Molecular Biol. Lett.*, 2002, **7**(1), 144–146.

21 **Bin, L., Hongbing, L., Wenli, C., Xiang, L., Jie, M.,** and **Zhengrong, L.** Computer aided diagnosis and treatment planning for development dysplasia of the hip. *Proc. SPIE*, 2005, **5744**, 781–786.

22 **Delaunay, S., Dussault, R. G., Kaplan, P. A.,** and **Alford, B. A.** Radiographic measurements of dysplastic adult hips. *Skeletal Radiol.*, 1997, **26**, 75–81.

23 **Derek, R. A., Jeffrey, D. T.,** and **Douglas, D. R.** Clinical evaluation of the hip: radiologic evaluation. *Operative Techqs Orthop.*, 2005, **15**, 182–190.

24 **Saikia, K. C., Bhuyan, S. K.,** and **Rongpar, R.** Anthropometric study of the hip joint in north-eastern region population with computed tomography scan. *Indian J. Orthop.*, 2008, **42**(3), 260–266.

25 **Dandachli, W., Witt, J. D., Shah, Z., Richards, R.,** and **Hall-Craggs, M.** CT based measurement of femoral head coverage in normal and dysplastic hips. *J. Bone Jt Surg.*, 2008, **90–B**(II), 315.

26 **Michael, T.** *Hip dysplasia*. Available from http://www.orthopaedia.com (access date 4 June 2009).

27 **Hurson, C., Tansey, A., Donnchadha, O., Nicholson, P., Rice, J.,** and **McElwain, J.** Rapid prototyping in the assessment, classification and preoperative planning of acetabular fractures. *Injury, Int. J. Care of the Injured*, 2007, **38**, 1158–1162.

28 **Meakin, J. R., Shepherd, D. E. T.,** and **Hukins, D. W. L.** Fused deposition models from CT scans. *Br. J. Radiol.*, 2004, **77**, 504–507.