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Application of three-dimensional printing for pre-operative planning in hip preservation surgery

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ABSTRACT

Three-dimensional printing is a valuable modality with broad clinical applications. Hip preservation surgery outcomes are dependent on correction of morphological abnormalities that may be optimally visualized with three-dimensional models. To assess the efficacy of three-dimensional models for patient and trainee education and to determine its benefits during pre-operative planning in hip preservation surgery. Sixteen patients with hip pathology were selected. Computed tomography was utilized to generate three-dimensional models. Customized Likert-style questionnaires were given to 10 hip preservation surgeons, 11 orthopedic surgery residents and 10 patients. All residents strongly agreed or agreed that the three-dimensional hip models helped them to understand patients' pathology. All but one patient agreed that the models assisted in their understanding of the treatment plan. Surgeons concurred that although they do not routinely order three-dimensional models, their use would improve trainee and patient education, especially when treating atypical osseous pathomorphologies. Three-dimensional models are tools that can help surgeon, trainee and patient understanding and participation in treatment of complex hip disorders. Patients and trainees agree that the prototypes enhanced their educational experience, as the surgeon can directly demonstrate complex morphological abnormalities. Trainees can therefore gain a better understanding of hip pathologies and treatment. As patients better understand their hip disorder, they can more fully participate in shared treatment decision-making.

Level of Evidence: Level IV, Retrospective Case Series

INTRODUCTION

Three-dimensional (3D) printing is an accessible, rapid method to produce custom physical models that are transcending traditional methods of production amongst many fields, including medicine [1]. Three-dimensional printing has been used for purposes from organ fabrication to pharmaceutical research with three main areas of research focusing on anatomic models for pre-operative planning and education, surgical instruments and implants [1]. Rapid prototyping (RP) of models facilitates cost-effective production of custom medical products [2]. 3D models have been successfully utilized in joint reconstruction and arthroplasty, trauma, pediatrics, spine, hand, shoulder and elbow, foot and ankle, oncology and sports medicine [3]. While models are typically created from computed tomography (CT) images, based on osseous anatomy, magnetic resonance imaging (MRI) may also be used to create bone and soft tissue (vessel, nerve, ligament, tendon, muscle, cartilage) models [4, 5]. These models may then be used for education, research and clinical care, including surgical planning.

The outcomes of hip preservation surgery rely heavily upon structural correction of osseous pathomorphology. Cam and pincer morphology, dysplasia, femoral and acetabular version/torsion, subspine morphology, ischiofemoral (both lesser and greater trochanter) and trochanteric–pelvic relationships are just a few entities that static or dynamic visualization via 3D modeling is greatly enhanced. It is well documented that hip arthroscopy has a significant learning curve, with complications, re-operations and conversions to total hip arthroplasty based on both surgical technique and patient selection [6, 7]. The number (career volume) required to achieve proficiency may be as high as 519 surgical procedures [8]. There are both technical and cognitive limitations in interpreting potential and actual mechanical collisions between femur and pelvis that can complicate both open and arthroscopic procedures [9]. Previous investigations have utilized collision detection software to two-dimensionally view three-dimensional images to better illustrate the femoral and pelvic interactions [10–12]. To the authors' knowledge, there have been no studies that have utilized 3D-printed models to illustrate the same.

The usefulness of 3D hip models as standard of care in the evaluation of patients undergoing hip preservation surgery has not been established for surgeons, trainees or patients. The purpose of this investigation was to determine the utility of 3D-printed hip models in the evaluation and management of patients with hip pain undergoing hip preservation surgery. The authors hypothesized that 3D-printed hip models would be highly useful to surgeons, trainees and patients in the evaluation and management of patients with hip pain undergoing hip preservation surgery.

MATERIALS AND METHODS

Local institutional review board approval (IRB approved 4 June 2018) was obtained for this retrospective case series. Between August 2016 and August 2018, 16 patients (17 hips) had 3D models created based on CT of the hip and/or pelvis. Utilizing methods derived from Anderson *et al.*, a processing pipeline of reconstructing the 2D CT images into 3D replicas of the pelvis and femurs was created. Image reconstruction utilized CT axial images centered about the pelvis and femurs with slice thickness of 2–2.5 mm [13]. Images were first converted to visualization ToolKit (VTK) files using ImageJ (National Institute of Health, Bethesda, MD, USA). ParaView (Kitware, Clifton Park, NY, USA) was then used for 3D analysis of modeled defects and holes, with subsequent manual repair. A stereolithographic (STL) file was derived from post-processing in MeshMixer, (Autodesk, San Rafael, CA, USA) and printed via 3D printer (MakerBot Replicator + 3D printer, MakerBot Industries, LLC, Brooklyn, NY, USA).

The selected 3D printer utilized additive layer manufacturing, where the machine ejects successive layers of strands of molten plastic that build up the model from series of cross sections. These fine layers, which correspond to the virtual cross sections from the STL file, fuse and solidify instantaneously due to the low melting point of the plastic. This process repeats, creating the model layer by layer as it is iterated at an ascending height. To achieve a reasonable size model that fits the 3D printer building plate; each model was scaled down to 70–75%. To ensure a structural rigid model, polylactic acid filament was used with infill of 10%. Printed models were cleaned and sanded to rid any artifacts of the 3D rendering and to mimic a bony surface. This process was repeated separately for creation of the femoral segments and pelvic segment for each patient.

Unique surveys were created for three groups (Supplement 1): (i) hip preservation surgeons; (ii) orthopedic trainees and (iii) patients. Each survey was electronically self-administered via SurveyMonkey (SurveyMonkey, San Mateo, CA, USA). All survey participants were instructed to not discuss their responses. All but 4 of 32 total questions were in Likert-style response format rated from 1 (strongly agree) to 5 (strongly disagree).

RESULTS

Twelve of 16 included patients underwent a total of 13 hip arthroscopies. The average age at time of surgery was 37 with an average BMI of 24.6. Eight of 10 patients were female.

Intra-operatively, 11 cam lesions, 8 pincer lesions and 12 AIIS lesions were decompressed (Table I). All 12 hips also had chondrolabral pathology requiring repair with an average traction time of 47.1 min. There was one patient with a diagnosis of femoroacetabular impingement (FAI) who had a traumatic hip dislocation 7 months post-op that required repeat surgery. The cause of the dislocation is unknown. The patient was found to have a thin capsule during the first surgery. A plication was performed during the hip arthroscopy.

Of the 12 patients who underwent surgery, 6-week post-operative radiographs showed good cam correction with no fracture or dislocation. All patients reported improvement or resolution in hip pain. Not enough information is available to report on post-operative outcome scores. Other than the one traumatic hip dislocation, none suffered intraoperative complications nor infection, neuropraxia, hip dislocation, DVT or PE.

Eight ABOS certified hip preservation surgeons at different institutions responded to the survey. These surgeons had 6.4 ± 2.4 years (mean ± SD) of experience after fellowship training in Orthopedic Surgery Sports Medicine (7 out of 8) or after a 1-year hip preservation surgery fellowship (1 out of 8). In addition, all eight surgeons had specific hip preservation surgery training during, after, or

Table I. Case demographic distribution

Pt	*Age (years)*	*Sex*	*BMI*	*Side*	*Lesion type*	*TT (min)*	*X-ray*
1	22	M	NA	L	Pincer	42	Corrected
2	32	F	22.35	R	Cam, AIIS	50	Corrected
2	32	F	22.35	L	Pincer, AIIS	44	Corrected
3	31	F	25.84	R	Cam, AIIS	37	Corrected
4	51	F	28.00	L	Cam, AIIS	35	Corrected
5	46	F	26.54	L	Cam, Pincer, AIIS	59	Corrected
6	16	F	18.51	L	Cam, Pincer, AIIS	35	Corrected
7	58	F	22.27	R	Cam, Pincer, AIIS	67	Corrected
8	49	F			Pincer, IFI		
9	19	F	22.22	R	Cam, AIIS	55	Corrected
10	18	M	21.43	R	Cam, AIIS	35	Corrected
11	74	F	20.00	R	Cam, Pincer, AIIS	30	Corrected
12	19	M	33.00	L	Cam, Pincer, AIIS	35	Corrected
13	46	M	NA	R	Cam, Pincer, AIIS	75	Corrected
14	59	M			Post op outside provider surgical complication, limited femoral neck bone stock		
15	28	F			Cam, dysplasia		
16	38	F			Cam, Pincer		

TT, traction time; IFI, ischiofemoral impingement; X-ray, 6-week post-operative radiograph findings; AIIS, anterior inferior iliac spine impingement.

in between residency, fellowship, or attending surgeon positions. Eleven surgical residents between PGY-1 and 5 at one institution responded to the trainee surveys. Ten patients' of the primary investigator's patient population responded to the survey.

Surgeons strongly agreed that 3D printed models would improve their surgical treatment of patients with atypical cam morphology with scale response = 1.8 ± 0.9 (mean ± SD) but not necessarily typical cam morphology (3.1 ± 1.5). Agreement amongst surgeons was also not as strong for whether 3D models would aid in their surgical treatment of protrusion acetabulae (3.0 ± 1.1), type 3 AIIS morphology (2.3 ± 1.0) or other less common osseous patho-morphology (2.4 ± 1.2). Surgeons most strongly agreed (1.5 ± 0.8) that 3D-printed models would improve their ability to teach trainees. Nearly all of the surgeons strongly agreed (1.6 ± 0.9) that 3D-printed models would improve their ability to have shared decision-making discussions with patients. While most surgeons do not obtain 3D models (4.3 ± 1.0), nearly all of the surgeons (1.6 ± 0.7) would pay <$100 if the surgeon was the source of payment for the 3D-printed model.

A summary of trainee and patient responses can be found in Tables II and III, respectively. Trainees strongly agreed that 3D models were superior to radiographs, CT and MRI in helping them understand hip pathology. They also strongly agreed that 3D models would help their understanding across the breadth of orthopedic subdisciplines, most notably with trauma and adult reconstruction cases. Patients strongly agreed that 3D models helped them understand the pathology present in their case. All agreed or strongly agreed that the models made them more comfortable with their surgical procedure. While none of the patients believed they should pay for the model, half agreed they would pay $50 if absolutely necessarily while the other half would pay more.

Table II. Trainee survey frequency distribution (n = 11)

	Likert scale										
Q #	*1*	*2*	*3*	*4*	*5*						*Average Likert scale*
1	10	1	0	0	0						1.09
2	10	1	0	0	0						1.09
3	8	3	0	0	0						1.27
4	9	2	0	0	0						1.18
5	9	2	0	0	0						1.18
6	10	10	5	6	8	8	5	8	5	0	NA
7	10	1	0	0	0						1.09

NA, not applicable.

Table III. Patient survey frequency distribution (n = 10)

	Likert scale					
Q #	*1*	*2*	*3*	*4*	*5*	*Average Likert scale*
1	1	2	NA	NA	NA	1.67
2	1	1	NA	NA	NA	1.50
3	1	NA	NA	NA	NA	1.00
4	NA	NA	NA	NA	NA	NR
5	NA	NA	NA	NA	NA	NR
6	1	NA	NA	NA	NA	1
7	NA	NA	NA	NA	NA	NR
8	4	6	0	0	0	1.6
9	0	1	4	3	2	NA
10	5	3	1	1	0	NA

NR, no response; NA, not applicable.

DISCUSSION

FAI can be successfully treated with non-surgical and surgical methods, often with hip arthroscopy. Mechanical and cognitive limitations to understand the consequences of unique and pathological hip anatomy may constrain the improvement of these procedures. In this study, we illustrated the way 3D models of the hip are built, described our use of 3D models in hip preservation surgery, and reported surgeon, trainee and patient opinion on 3D model use. Our results can be better understood in the context of current literature describing the use of 3D models in improving hip preservation interventions through pre-operative planning and education.

Some data have shown that three-dimensional printing for pre-operative planning has been an effective tool to evaluate the feasibility and accuracy of several complex orthopedic procedures [1, 3, 4, 10–12, 14]. From neurosurgery to orthopedics, surgeons have found 3D printed models useful in evaluating the approach to anatomically complex procedures and preparing customized interventions [1, 3, 4, 14–19]. Zeng *et al.* demonstrated that pre-operative planning with virtual surgical software augmented with 3D printed models resulted in more precise and efficient acetabular fracture reductions [16]. Bagaria *et al.* reported that RP models of complex fractures achieved near perfect reduction and reduced operating time, subsequently reducing patient anesthesia exposure and intraoperative blood loss [17]. They were also able to choose the exact surgical tools and implants they needed prior to surgery, reducing the amount of time needed to prepare excess equipment for the OR [17]. Singare *et al.* found that by utilizing 3D RP models they could plan, evaluate and execute their intraoperative plan more efficiently leading to a less invasive procedure [19].

Our findings that surgeons better understand and treat complex hip pathology with the use of 3D models concur with the literature. Three-dimensional models serve as a tool for surgeons to better understand severely abnormal anatomy as well as rehearse surgical approaches [20]. While virtual two- and three-dimensional renderings of bony architecture have been available for some time, studies suggest that student's visuospatial understanding of anatomy is superior with physical models [21–23]. This difference may be due to the phenomenon that humans understand the shape of three-dimensional objects better when utilizing both visual and haptic feedback [24]. The tactile and optic experience of interacting with a 3D model provides surgeons with a more thorough and confident understanding of the anatomy, which better prepares them for complex procedures. Case series have also demonstrated that 3D models allow surgeons to prepare for intellectual challenges in a stress-free environment, allowing them to focus intra-operatively on approach and performance rather than problem-solving. This preparation also decreased the amount of time stocking the OR with excess equipment, as instrumentation specific to the patient's operation was already chosen [1].

These factors could help surgeons more easily overcome the cognitive challenges of hip arthroscopy, by helping them visualize their plan and improve the patients understanding of the plan. The residents' improved understanding of the procedure when utilizing the model is particularly important given the concerns about young surgeons undertaking arthroscopy [25]. It's been suggested that 3D models can be especially useful in surgeries of the hip where precision is important to ensure adequate limb length and rotation to facilitate in weight bearing and activities of daily living [18].

Surgeons, trainees and patients all agreed or strongly agreed that utilizing these models improved their understanding of the patient's unique pathology, with various positive ramifications. Surgeons believed that the improvement would enhance their performance and trainees believed that 3D models were far superior to 2D imaging and that a printer should be available for their education. Surgeons most strongly agreed that 3D models would aid in their ability to teach residents and their residents' understanding. Patients understood their pathology so much better that they were willing to financially invest in this educational tool.

Limitations of the current study include model, technological and study-specific factors. Narrow diversity of 3D printing materials means that soft tissues, like chondrolabral structures, cannot be reproduced for pre-operative planning. Printing the model also takes several hours which prevents intraoperative adjustments to the model. Other limitations of the methods include the intellectual and capital investments related to software and hardware and the significant knowledge needed to operate the programs. Technical issues such as distortion of CT images in conversion to 3D at articular surfaces of the joint secondary to inadequate resolution will likely evolve with progression of imaging technology. The small number of cases, and short follow-up compliance in this pilot case series provides a limited sample in assessing the impact that these methods have on patient outcomes. Finally, the questionnaires evaluating surgeon, resident and patient experiences could not be independently validated.

Future studies may demonstrate quantitative evidence of decreased operation time, less anesthesia time, traction and fluoroscopy time and improved patient outcomes and education. Further pilots may utilize independently validated surveys and comparison to a control group to better understand how 3D models impact trainee understanding and education.

In concordance with the literature, our study suggested that surgeons believe that three-dimensional models have the potential to increase the precision and time efficiency of hip arthroscopy [4, 16, 17]. Access to 3D printers can be limited due to monetary reasons and unavailability of skilled personnel to create the models. The 3D printer costs around $3000 and around $70 per kg for material. There are relatively low maintenance fees. Currently, models require ∼2 h of image preparation and 11 h of printing time each. The highest cost burden is for the personnel to run the printer. Reductions in time and cost can be expected in the future in accordance with other technological innovations. Future literature should seek to quantitatively demonstrate how 3D models used in pre-operative procedures can lead to more reliable, effective and time-efficient surgeries.

CONCLUSION

Three-dimensional models are tools that can help surgeon, trainee and patient understanding and participation in treatment of complex hip disorders. Patients and trainees agree that the prototypes enhanced their educational experience, as the surgeon can directly demonstrate complex morphological abnormalities. Trainees can therefore gain a better understanding of hip pathologies and treatment. As patients better understand their hip disorder, they can more fully participate in shared treatment decision-making.

SUPPLEMENTARY DATA

Supplementary data are available at *Journal of Hip Preservation Surgery* online.

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CONFLICT OF INTEREST STATEMENT

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