Computer Aided Diagnosis and Treatment Planning for Developmental Dysplasia of the Hip

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ABSTRACT

The developmental dysplasia of the hip (DDH) is a congenital malformation affecting the proximal femurs and acetabulum that are subluxatable, dislocatable, and dislocated. Early diagnosis and treatment is important because failure to diagnose and improper treatment can result in significant morbidity. In this paper, we designed and implemented a computer aided system for the diagnosis and treatment planning of this disease. With the design, the patient received CT (computed tomography) or MRI (magnetic resonance imaging) scan first. A mixture-based PV partial-volume algorithm was applied to perform bone segmentation on CT image, followed by three-dimensional (3D) reconstruction and display of the segmented image, demonstrating the special relationship between the acetabulum and femurs for visual judgment. Several standard procedures, such as Salter procedure, Pemberton procedure and Femoral Shortening osteotomy, were simulated on the screen to rehearse a virtual treatment plan. Quantitative measurement of Acetabular Index (AI) and Femoral Neck Anteversion (FNA) were performed on the 3D image for evaluation of DDH and treatment plans. PC graphics-card GPU architecture was exploited to accelerate the 3D rendering and geometric manipulation. The prototype system was implemented on PC/Windows environment and is currently under clinical trial on patient datasets.

Keywords: Developmental dysplasia of the hip, acetabulum, partial-volume segmentation, quantitative measurement, virtual treatment planning, GPU programming, 3D imaging

1. INTRUDUCTION

Developmental dysplasia of the hip (DDH) is a spectrum of disorders affecting the proximal femur and acetabulum or the hips that are subluxatable, dislocatable, and dislocated [1, 2]. In the United States, DDH occurs in approximately 1.5% in neonates on average [3]. Worldwide reported incidence varies and occurs in approximately 1% [4]. Early diagnosis and treatment is extremely important because failure to diagnose and/or improper treatment can result in significant morbidity [5, 6]. DDH is an evolving process, its physical findings on clinical examination change. Clinical screening for hip dysplasia was already instituted, where imaging plays the essential role, yet early detection remains challenging. Conventionally, physicians made diagnoses and treatment plans only based on findings from X-ray radiographs or two-dimensional (2D) images, which might cause many post-operation problems because of incomplete description and indirect view of the anatomical information [1, 6]. To accurately classify and treat DDH, recently many researchers have employed 3D CT/MRI (computed tomography/magnetic resonance imaging) and virtual planning system as an alternative technique [6, 7, 8].

The goal of DDH treatment is to restore contact between the femoral head and the acetabulum. Close reduction is the initial attempt on neonates and young infants. When child is more than 2 year old, open reduction is performed with some standard procedures such as Salter procedure, Pemberton procedure or Femoral Shortening osteotomy [6]. Accurate planning of the reduction operation and quantitative measurement of the outcome are the key factors for the cure and healthy development. Due to the disease complexity and the limitation of current standard procedures based on 2D images, a fully 3D-based virtual planning system is a potential alternative to improve the reduction operation and outcome measurement as well as early detection. To build a computer based 3D model to implement DDH on

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screen diagnosis and virtual treatment planning, the following techniques are crucial: accurate bone segmentation from CT/MRI images; 3D reconstruction and interactive rendering to demonstrate the anatomic structure of acetabulum and its spatial relationship to the femurs for visual judgment; accurate quantitative analysis of the maturity of acetabulum through some quantitative indexes measured on the 3D images; visual rehearse of several standard osteotomy procedures to implement virtual treatment planning on the screen.

The purpose of this work is to build such a computer platform to provide DDH screening. We have designed and implemented a computer aided system for the diagnosis and treatment planning of this disease. With the design, the patient first receives a CT scan to generate tomographic images. A mixture-based PV (partial volume) algorithm is applied to perform segmentation on the images to separate the bone from the surrounding soft tissues, which further are classified into the acetabulum, left and right femurs. A graphical module is then developed to fulfill the 3D reconstruction and display the segmented bone in a 3D view to show the special relationship between the acetabulum and the femurs for visual judgment. Several standard procedures, such as Salter procedure, Pemberton procedure and Femoral Shortening osteotomy, are simulated to visually rehearse treatment plans on the screen. Quantitative measurement of Acetabular Index (AI), Femoral Neck Anteversion (FNA) and Center-Edge Angle (CEA) are performed on the 3D image for evaluation of DDH and treatment plans.

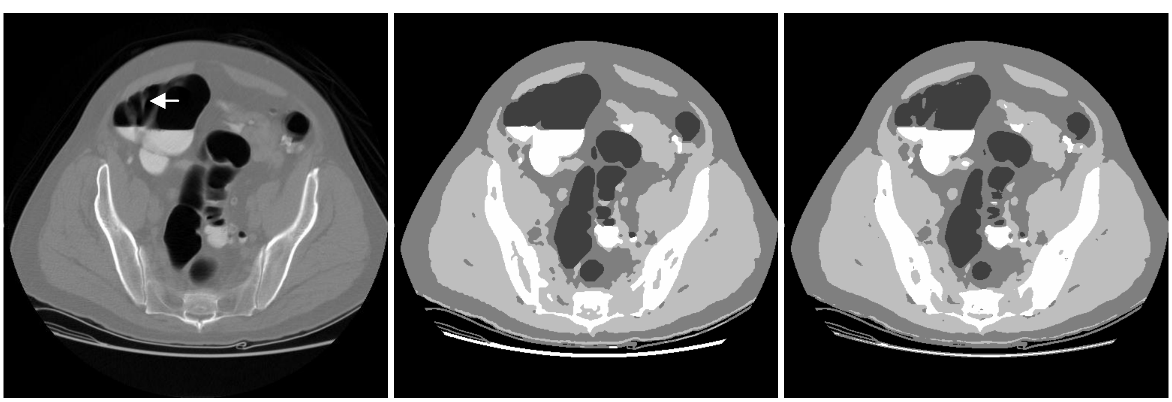
In the following sections, we give our detailed design and implementation of the prototype system, which includes mixture-based PV algorithm for bone segmentation; quantitative measurement of AI and FNA on 3D image; 3D reconstruction, rendering and geometric manipulation through PC graphics-card GPU hardware programming; virtual treatment planning of acetabular osteotomies and femoral shortening osteotomy on the screen. We show results and give our conclusions in the last two sections.

2. BONE SEGMENTATION

It is crucially important to accurately segment the bone from CT/MRI images to facilitate the quantitative analysis and visualization of the clinically significant features toward the diagnosis, treatment/surgical planning and follow-up evaluation. Partial volume effect, especially weak edge effect, is an inherent obstacle for segmentation of tissues like the bone from CT/MRI images, and may result in significant error in quantitative image analysis [9]. A logical solution is to determine each tissue percentage within each image voxel, which we call a mixture. PV model has already been proposed for segmentation of multi-spectral magnetic resonance images [10-12], based on the EM (expectation-maximization) algorithm [13]. Extension to CT image segmentation was also explored recently [14, 15]. This PV-based CT image segmentation was then applied here for DDH clinical application.

2.1. PV image segmentation

We adopted the normal-distributed PV model without the sub-sampled label modeling [10] and utilized a Markov random field (MRF) spatial prior to perform mixture segmentation in a MAP (maximum *a posteriori*) framework in both the incomplete [11] and complete [12] data-sampling spaces of the EM algorithm. The detailed algorithm derivation and presentation for CT image segmentation are given in [14, 15] and some preliminary results are reported below.



(a) (b) (c)

Figure 1: Clinical patient CT image study. (a) shows the original image; (b) is the hard segmentation by our previous MAP-MRF-based method [16]; and (c) is the converted hard segmentation from our current PV method of Figure 2 below.

2.2. Segmentation result

Our PV segmentation algorithm was tested on clinical CT patient images. Figure 1(a) above shows the acquired CT image, which consists of four classes: air, soft tissue, muscle and bone. The MAP-MRF-based hard segmentation result [16] is shown in Figure 1(b). Figure 1(c) shows the converted hard segmentation result of our current PV method, which is derived from Figure 2 below. Both our current PV method and previous MAP-MRF-based algorithm provide similar hard segmentations, but the former provides more rich information on each mixture in each voxel, while the later only provides the global information of the mixture summation in each voxel. This advantage of PV segmentation is clearly shown by Figure 2.

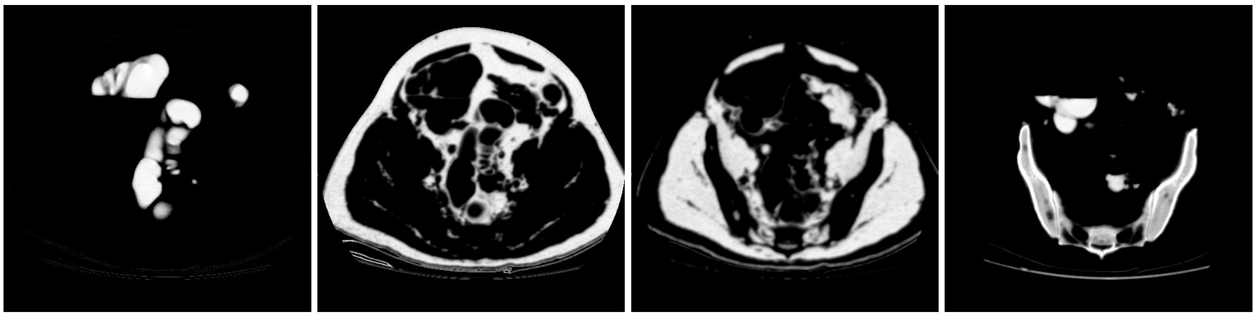


Figure 2: The PV segmentation results for the CT study (same image as shown in Figure 1). From left to right -- air, soft tissues, muscle, and bone.

3. 3D QUANTITATIVE MEASUREMENT

The maturity of acetabulum can be qualified through quantitative analysis [1, 2, 6]. Commonly used quantitative indexes include: Acetabular Index (AI) which measures the apparent slope of the acetabular roof to assess the dysplastic hip; Femoral Neck Anteversion (FNA) which distinguishes femoral abnormality; and Center-Edge Angle (CEA) which is used for postoperative evaluation. While quantitative measurement is conventionally performed directly from the 2D slice images, the outcome might be less accurate. For example, while performing AI measurement directly on 2D images can only obtain one AI value corresponding to the plane perpendicular to the ground, however, the measurement on 3D image can not only obtain all the AI parameters on the edge around the acetabulum semi-sphere but also exhibit this acetabulum characteristic in a curve in three dimensions. Our primary focus is performing quantitative measurements of AI, CEA and FNA on 3D images through interaction, which is described below.

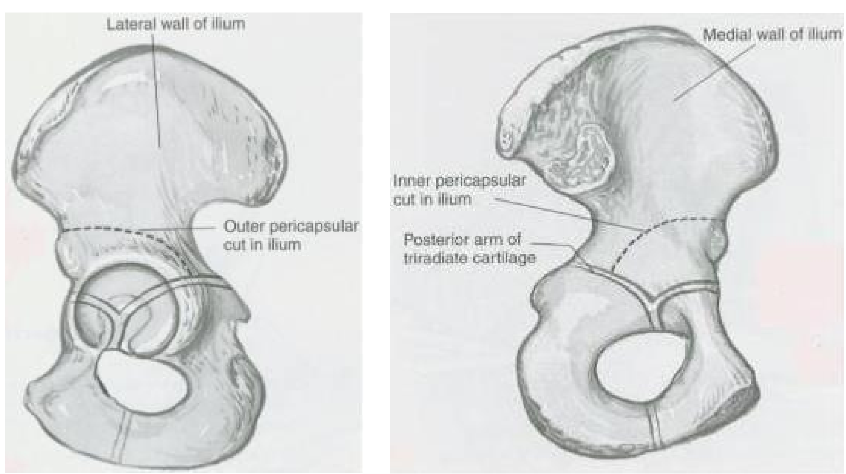


Figure 3: The ilium and Y-shape cartilage (left: lateral wall, right: medial wall).

For AI measurement, there is a Y-shape cartilage on each lateral wall of the ilium, as shown in Figure 3. The center points on both triradiate Y-cartilages are first interactively positioned on the 3D image. The horizontal line (Y-Y line) that connects these two center points is defined as the rotation axis. Crossing the Y-Y line, a clip plane is set up which will intersect with the margin of the acetabulum. The angle between Y-Y line and the line connecting the center point to the margin point is calculated, which shows the apparent slope of the acetabular roof at the setting. Interactively rotating this clip plane around Y-Y line, we obtain AI values corresponding to 0 to 360 degrees of rotation. Plotting these AI values into a 2D coordinate system, we obtain a distribution of AI around the margin of acetabular semi-sphere. The distribution curve will be further compared to the normal distribution of AI for quantitative evaluation.

The measurement of CEA is obtained in a similar way. It also consists of multiple values corresponding to different rotation angles and is particularly useful for the postoperative evaluation of a treatment plan.

The calculation of FNA is illustrated in Figure 4. Assume a coronal plane (Plane C in the figure) passing through the diaphysis of a femur and a line connecting the center point of the femoral head (Point A) and the center point of any transversal slice on the neck of the femur (Point B). The angle between the coronal plane and the line is FNA measurement. The settings of the coronal plane and points A and B are all made on the 3D image through interaction.

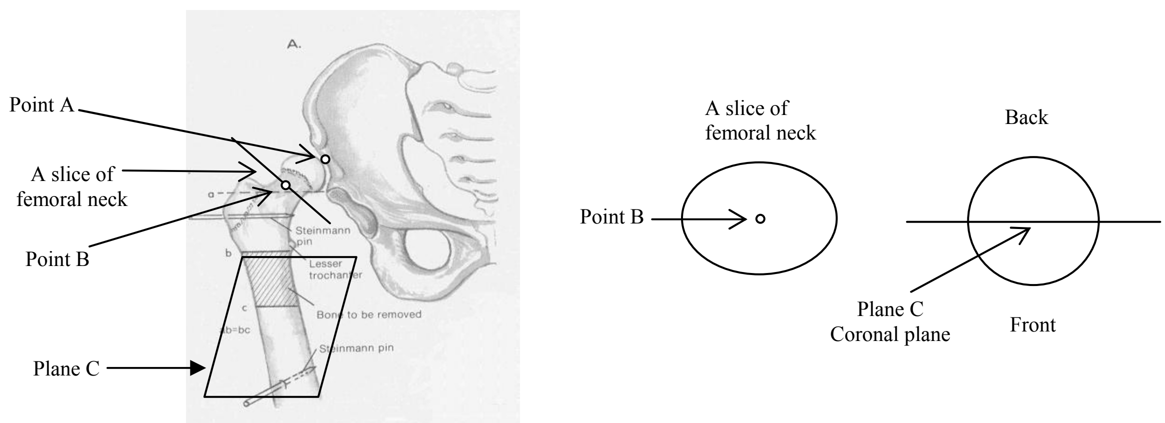


Figure 4: Calculation of FNA.

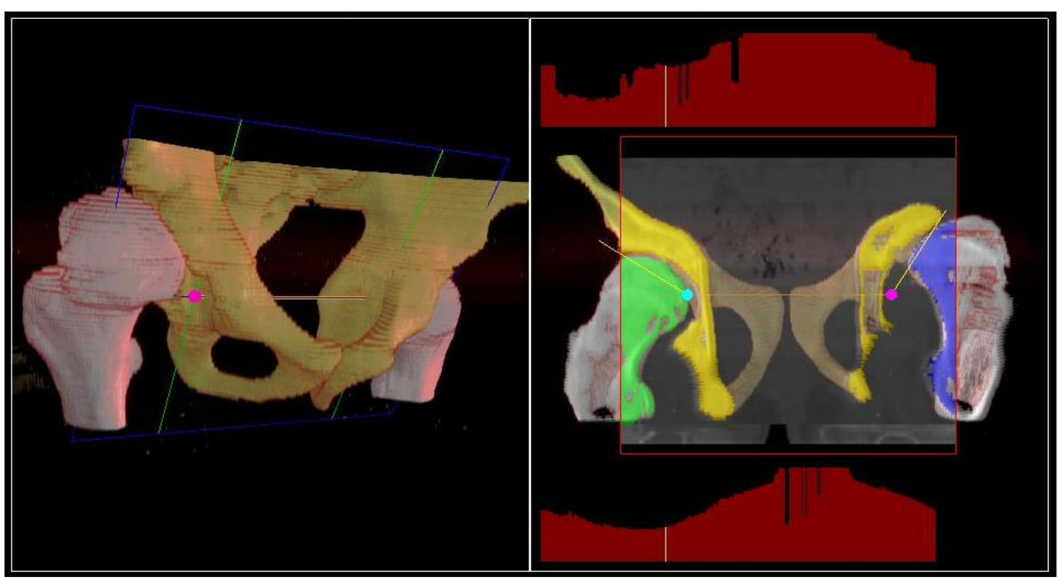


Figure 5: Acetabular maturity evaluation -- quantitative AI measurement on 3D image. (Left -- REV): 3D display of the ilium and femurs, and the setting of a clip-plane for AI measurement. (Right -- BEV): AI curves, sampled image on the clip-plane, and the clipped 3D structures.

Figure 5 is a snapshot of the display of the AI measurement. The left picture displays the 3D ilium and femurs from REV (room-eye-view). A clip-plane is set interactively and intersects with acetabulum, on which the AI is measured. The right picture displays the sampled image on the clip plane but from BEV (beam-eye-view), therefore this 2D image is always displayed perpendicular to the view direction. Also displayed is the 3D structure of the ilium and femurs but clipped by the clip plane from the front to expose the inner structure where the AI measurement is performed. Two curves corresponding to the left and right acetabulums are displayed transparently overlay the picture, showing the distribution of AI.

4. 3D RECONSTRUCTION AND TREATMENT PLANNING

Physicians conventionally make diagnoses and treatment plans solely based on findings from plain 2D radiographs. Incomplete description and indirect view of anatomical information might be the cause of many post-operation problems [2, 6]. Recently 3D CT has been employed as an alternative technique [6, 7]. Our work is to build a computer based 3D model for DDH diagnosis and virtual treatment planning, which is outlined below.

4.1. 3D model of the prototype system

With our 3D model, the patient receives a CT scan first to generate the tomographic images. The hip CT image is then segmented by the mixture-based PV segmentation algorithm to extract the bone from the surrounding soft tissues, which are further classified into acetabulum, left and right femurs through interaction and 3D region growing. A 3D reconstruction procedure is followed to create a 3D texture image from the segmentation result and display this 3D image on the screen to demonstrate the anatomic structure of the acetabulum and its spatial relationship with the femurs for a visual judgment. Several standard procedures, *i.e.*, the Salter procedure, the Pemberton procedure and Femoral Shortening osteotomy are simulated to visually rehearse treatment plans on the screen. Quantitative analysis is performed to measure AI, CEA and FNA on this 3D image, and this functional module is called before and after a virtual treatment planning to evaluate DDH and the treatment plans. A patient database management module is embedded to manage the patient dataset and is used for disease diagnosis and treatment follow-up. The functional flowchart of this DDH prototype system is shown in Figure 6.

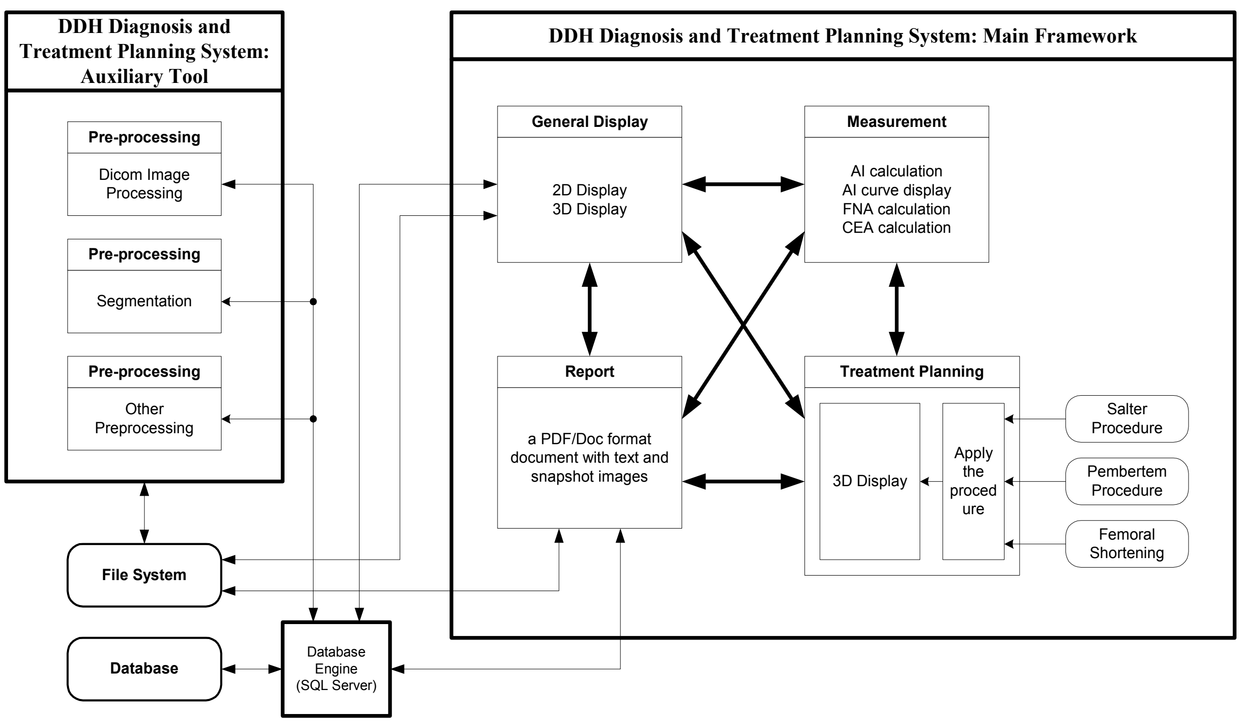


Figure 6: Functional flowchart of the proposed DDH prototype system.

4.2. Virtual treatment planning

One major aim of the design of this prototype system is virtual treatment planning in which some standard open treatment procedures can be visually simulated on the screen. The designed virtual simulations include Salter procedure, Pemberton procedure, and Femoral shortening osteotomy. All these simulations require accurate geometric manipulation, frequent interaction, and fast reconstruction on 3D image. GPU-based rendering and geometric operation will be the fundamental of this functional module.

The 3D simulation of the Salter procedure and the Pemberton procedure is fulfilled through a series of interactive operations on 2D images. We have a BEV display when performing AI measurement (color plot 1 or Figure 5 right). Since the normal AI is less than 30 degrees, when rotating clip plane around Y-Y line, we select some typical positions, such as $\pm 30°$, $\pm 45°$and $\pm 60°$, and test AI values at these degrees. If AI value acquired at a degree is not under the normal range, a series of interactive operations are performed on this BEV image to find the parameters that control a bend of the acetabular roof at this degree. Using these parameters as samples, an interpolation is carried out on the 3D image to control a bend of the entire acetabular roof. Different models are developed corresponding to different procedures of Salter or Pemberton osteotomy. After interpolation, AI measurement is performed on the modified 3D image to evaluate the simulated plan.

This simulation is directly performed on the 3D image. Two clip planes are interactively set to simulate the shortening procedure. The remainder femoral head is shifted and/or rotated to the center of the acetabulum to obtain an acceptable FNA (Figure 4). The coronal plane is already known. The center point of the femoral head is interactively set on the 3D image. A transversal slice is also set interactively on the neck of the femur. With the center point of the femoral head being the shift target and a line connecting this point and the center point of the transversal slice being the rotation axis, a geometric shifting and/or rotating operation is performed on the remainder femoral head to fulfill the simulation of this shortening procedure (Figure 7). The FNA and CEA measurements are then followed to evaluate the simulation.

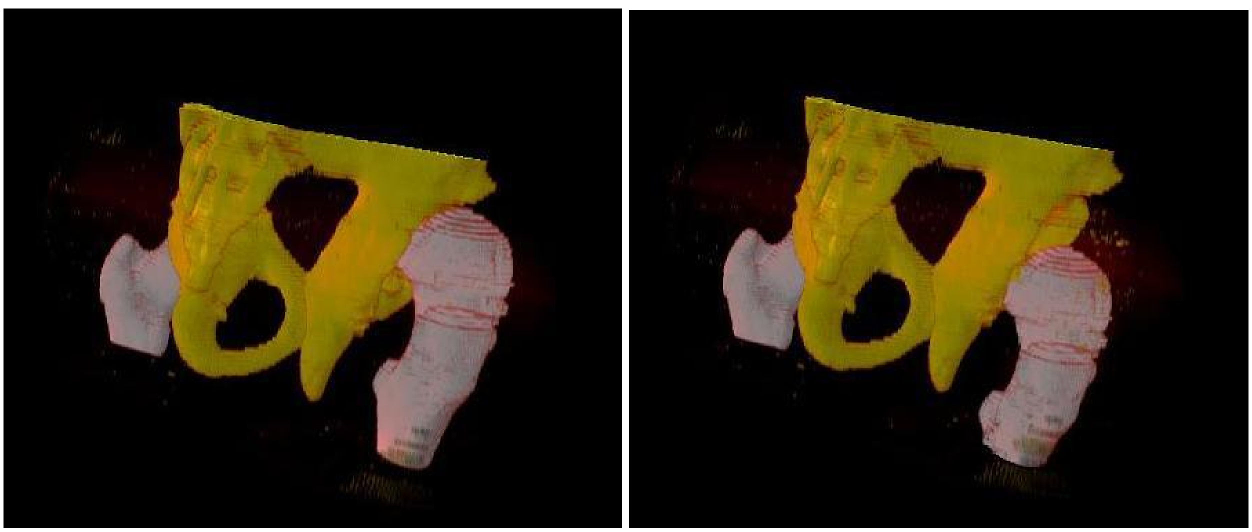


Figure 7: Simulation of the femoral osteotomy through GPU programming. Left: dislocated abnormal femur. Right: the femur is shift/rotated to normal position.

4.3. Implementation

Effective 3D reconstruction and interactive rendering are advantageous for computer-based clinical applications. Recently there is a trend that the configurable graphical pipeline is replacing the fixed functional pipeline, which can significantly improve the behavior and efficiency of graphical rendering through GPU programming [17, 18]. Clinical applications like DDH require not only a fast rendering to demonstrate 3D anatomical structure for visual judgment but also complicated geometric manipulation on 3D image to rehearse a treatment plan. Our preliminary work has applied this technique to 3D reconstruction and virtual treatment planning.

Our graphical rendering is texture-based. The 3D reconstruction module creates a 3D texture image from the segmentation result, which will further feed to volume rendering module that is implemented with direct support from GPU through a fragment program. Typical treatment procedures are simulated through interactive manipulation of the geometric objects on screen through subtle GPU vertex/fragment programming. For example, to simulate a femoral shortening osteotomy, we relocate the abnormal femur by shifting or rotating the dedicated geometric object among the 3D image (Figure 7, left). A GPU vertex program is constructed to parallel map the target objects, which are a set of voxels, onto a new desired coordinate, and then followed by the use of the same fragment program to render this new 3D images (Figure 7, right).

5. RESULTS

A framework for DDH diagnosis and treatment planning was developed. A mixture-based PV algorithm was adapted to perform bone segmentation, which demonstrated that the partial volume effects between the bone and tissues can be precisely detected. The quantitative measurements such as AI, FNA and CEA were performed on 3D image, providing more information and showing more accuracy for maturity qualification. Several open procedures were virtually simulated to rehearse treatment plans. GPU hardware programming ability was explored for interactive 3D image rendering and effective geometric object manipulation.

The prototype system was built on MS-Windows/PC and supports database management across the LAN (Local Area Network). The underlying platform is constructed by MS.NET Framework (interface), SQL Server (database engine), ADO.NET (database management), OpenGL/OpenGL extensions (graphical rendering), and MS-VC++. Figure 8 is a typical layout of the interface to perform quantitative measurement with this prototype system. With the interface, the segmentation result is displayed in pseudo-colored 2D slices. The anatomic structure of the acetabulum is fully demonstrated though 3D reconstruction and interactive display in 3D view. Quantitative measurement, either before or after virtual surgery planning, is performed with feedback interactively though the interface.

The system is currently under clinical trial with patient datasets. The differences between pre- and post-operation will be compared by the system.

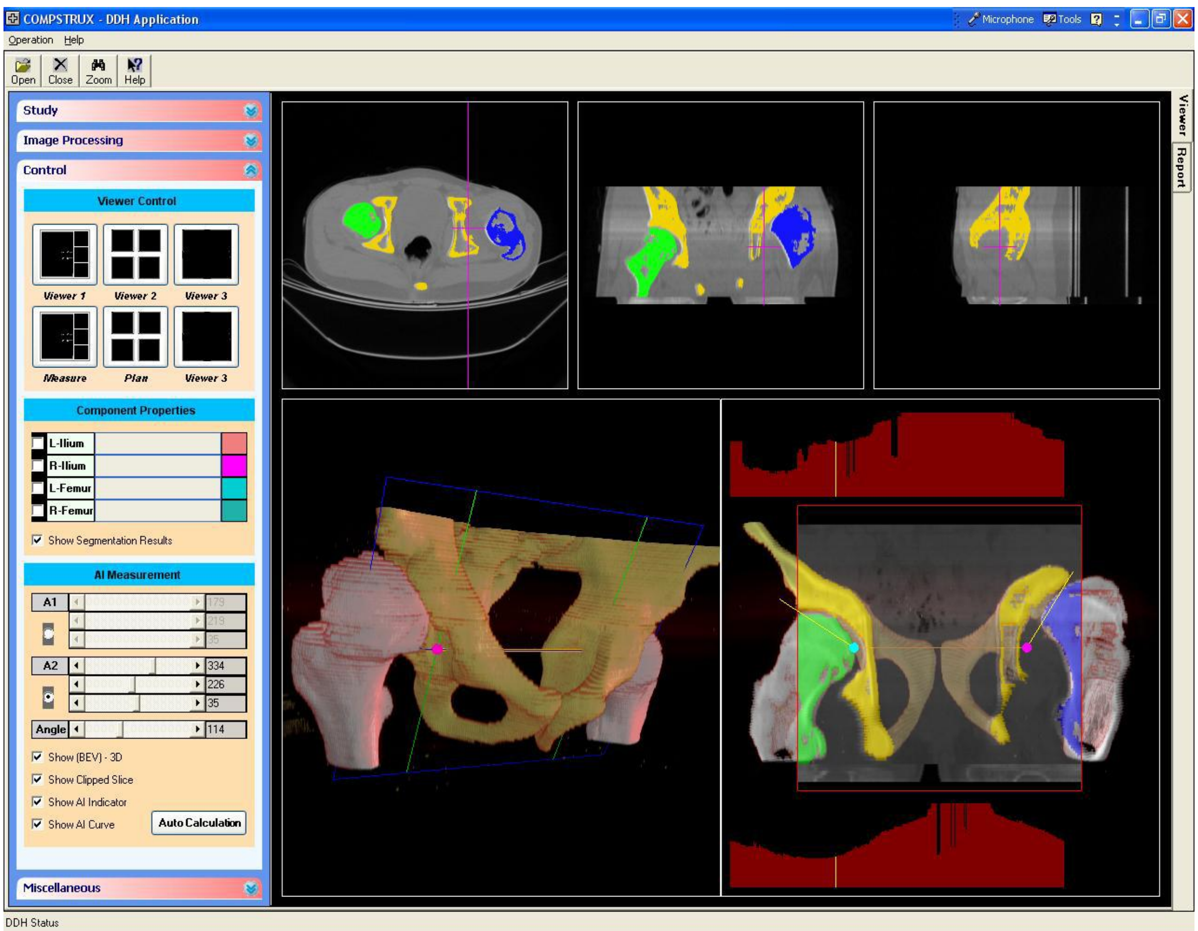


Figure 8: Display and interface of the DDH prototype system with quantitative measurement.

6. CONCLUSION

We have built a computer-based 3D model to implement DDH screening. We applied image processing and GPU-based graphical rendering techniques to DDH diagnosis and treatment planning. Integration of these techniques into a framework will provide physicians an interactive, quantitative and accurate tool for DDH diagnosis and management. The system allows surgeons to reconstruct stereoscopic model from the patient's specific CT images and rehearse surgical procedure with interactive methods. It also allows surgeons to choose proper operative schemes prior to actual surgery and accordingly reduces the risk of surgical operation.

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