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Computer-aided Surgical Planning of Anterior Cruciate Ligament Reconstruction in MR Images

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Abstract

Anterior cruciate ligament (ACL) injury causes knee joint instability, and effects on sports performance. Therefore, ACL reconstruction is essential to keep their high performance. It is well known that the outcome of ACL reconstruction is strongly related to the placement and orientation of the bone tunnel. Therefore, optimization of tunnel drilling technique is an important factor to obtain satisfactory surgical results. Current procedure relies on arthroscopic evaluation and there is a risk of damaging arteries and ligaments during surgery. The damages may reduce the accuracy and reproducibility of ACL reconstruction. As a postoperative evaluation method, a quadrant method has been used to evaluate the placement and orientation of the bone tunnel in X-ray radiography. This study proposes a computer-aided surgical planning system for evaluating ACL insertion site and orientation using magnetic resonance (MR) images. We first introduce MR image based the quadrant method to determine the ACL insertion site for preoperative patients. It also evaluates the 3-D spatial relationship between the planning femoral drilling hole and arteries around the femoral condyle. This system has been applied to ACL injured patients, it may increase the accuracy and reproducibility of ACL bone tunnel, and it can evaluate a risk of damaging the surrounding arteries and ligaments.

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Keywords: Anterior Cruciate Ligament Reconstruction; Magnetic Resonance Image; Bone Tunnel; Computer-aided Surgical; Quadrant Method

1. Introduction

Anterior Cruciate Ligament (ACL) injury causes knee joint instability, and affects sports performance. Therefore, ACL reconstruction is essential to keep their high performance and important to prevent secondary osteoarthritis.

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ACL reconstruction surgery opens femoral and tibial bone tunnels to insert implant ligaments. Yagi *et*. *al*. proposed a double bundle method [1] which inserts two ligaments; one is called anteromedial band (AMB), and the other is called posterolateral band (PLB).

It is well known that the outcome of ACL reconstruction is strongly related to the placement of the bone tunnel [2]. Therefore, optimization of tunnel drilling technique is an important factor to obtain satisfactory surgical results. In the current procedure, an operator determines the femoral bone tunnel opening site under the condition of using an arthroscope, and there is a risk of damaging arteries and ligaments during surgery. The damages may reduce accuracy and reproducibility of ACL reconstruction.

As a postoperative evaluation method, the quadrant method was proposed by Bernard and Hertel [3]. The method evaluates the placement of the bone tunnel using a lateral 2-D X-ray radiography image of the knee joint. It has been used in many clinical studies, and has provided important results such as dependency of ACL reconstruction outcome on bone tunnel placement [2], epidemiological studies on ACL insertional sites, and so on. However, there are some limitations of using 2-D X-ray radiography; the accuracy depends on patient pose during image acquisition, and it cannot evaluate the orientation of bone tunnel.

In order to overcome these limitations caused by using 2-D X-ray radiography images, the quadrant method has been applied to 3-D X-ray computed tomography (CT) images [4]. In post-processing, we can synthesize a pseudo X-ray radiography image with any knee pose. The method evaluates the bone tunnel placement on the synthesized pseudo X-ray radiography image using the quadrant method. In addition, it can evaluate the 3-D bone tunnel placement, 3-D orientation of bone tunnel, and tunnel shape on the bone surface. A limitation of the method is that it cannot evaluate soft tissues such as ligaments.

Both of 2-D X-ray radiography based and 3-D X-ray CT based methods have not been applied to preoperative planning because they are invasive to the human body due to X-ray exposure. With the accurate preoperative planning, we can expect good outcome and high reproducibility of ACL reconstruction. It requires 3-D insertion site and orientation of expected bone tunnels, and surrounding arteries, ligaments, and muscles. For the purpose, magnetic resonance (MR) images should be used because MRI is noninvasive and can take 3-D sectional images of the knee joint with high spatial resolution and high contrast. However, there are no studies for surgical planning of ACL reconstruction using MR images.

In related studies, there are some computer-aided diagnosis (CAD) systems for ACL reconstruction. Ref [5]-[9] proposed 2-D/3-D image registration of multidetector-row CT (MDCT) and digital radiography (DR) based three-dimensional moving state analysis of ACL injured knee. Ref [10]- [13] evaluate the movement of fixing tool for an implanted ligament.

This study proposes a computer-aided surgical planning system for evaluating ACL insertion site and orientation using MR images. First, we apply the quadrant method to MR image to determine the ACL insertion site. It also evaluates 3-D spatial relationship between the planning femoral drilling hole and arteries around the femoral condyle. The optimization of tunnel drilling increases the accuracy and reproducibility.

2. Preliminaries

2.1. Subject and Materials

We recruited a subject whose left knee ACL was injured. We had obtained informed consent from the subject according a procedure approved by the local ethics committee (Hyogo College of Medicine, JAPAN). Before the ACL reconstruction, we took axial T2-weighted MR image and MR angiography (MRA) image of the injured knee joint using 3.0 Tesla MRI Scanner (Achieva 3.0T TX, Philips Medical Systems Co. Ltd., USA). T2-weighted images are good for observing anatomical structure, and MRA images are good for observing arteries. The both images were spatially aligned. Acquisition parameters were as follows; the number of slices was 220, image matrix was 512×512 voxels, FOV was 170 mm × 170 mm, slice thickness was 1.2 mm, repetition time (TR) was 23.4 msec, echo time (TE) was 10.9 msec, and flip angle (FA) was 15 deg. Figure 1 and Figure 2 show knee MR image and knee MRA image at the same location, respectively.

The knee joint consists of the muscle, the fat, the arteries, the ligaments, and the femoral and the tibial bones. The bony region consists of the cancellous bone, the cortical bone, and the cartilage. In T2-weighted MRI, the water, and the fat take higher signal than the bone, and in MRA images, arteries have higher signal than others.

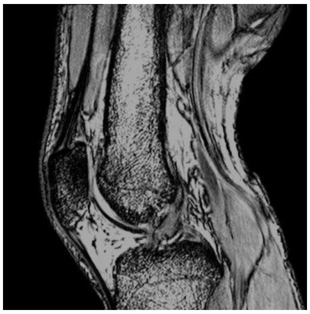

Fig. 1. Knee T2-weighted MR image.

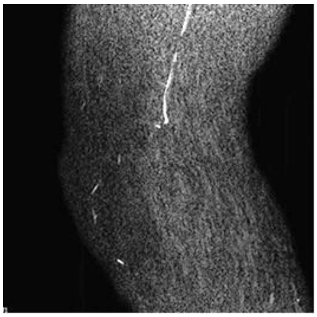

Fig. 2. Knee MRA image.

2.2. Quadrant Method

As a postoperative evaluation method, Bernard and Hertel proposed the quadrant method [3]. It evaluates the placement of the bone tunnel based on the Blumensaat's line in X-ray radiography. Figure 3 shows the Blumensaat's line, which corresponds to the roof of intercondylar notch of the femur, as seen with a brighter line on the lateral radiograph. A quadrant method evaluates the bone tunnel based on a sagittal plane using 4 by 4 grid aligned to the Blumensaat's line. The other sides of the grid circumscribe the bony region on lateral radiograph. The Blumensaat's line side is called high, and the opposite side is called low. Lateral or medial condyle side is called deep, and the opposite side is called shallow.

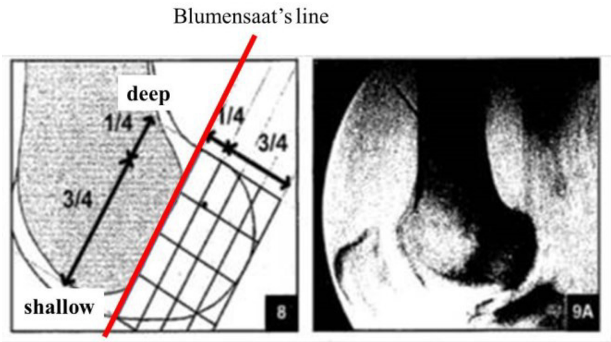

Fig. 3. Quadrant method (Ref[3]).

3. Proposed Method

Figure 4 is a flowchart of the proposed method. The method first segments the bony region composing from the cortical bone, the cancellous bone, and the cartilage. Then, it extracts the surface of the bony region called bony surface voxels. Next, the bony surface voxels are projected in parallel to a lateral plane. The projected image is similar to a lateral radiograph image of the knee. The ACL femoral attaching site is localized by the quadrant method, and is inversely projected to 3-D voxel space to obtain the 3-D ACL attaching site. In MRA images, arteries are described with high MR signal. The method segments the high MR signal region as the artery region.

So far, the method obtains the bony region, 3-D ACL insertion position, and the surrounding artery region. Finally, this system synthesizes the 3-D fusion rendering image, and polar coordinate system description of the surrounding knee arteries in which the ACL insertion position is the origin.

In the following, details of proposed method is described.

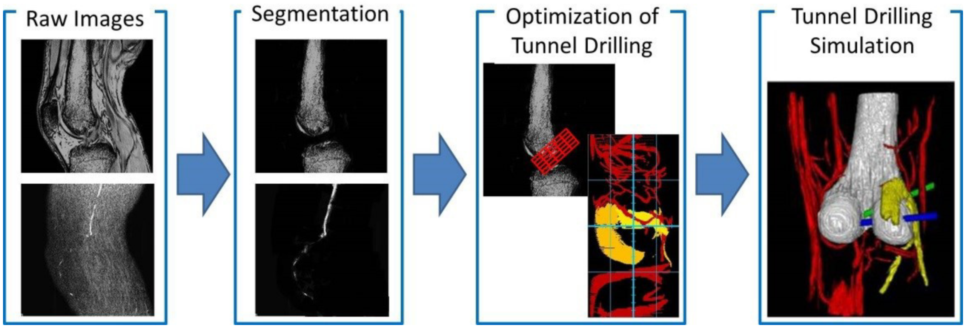

Fig. 4. Flowchart of the proposed system.

3.1. Segmentation

In MRA image, arteries take high signal. Threshold processing can segment the artery region. T2-weighted knee MRI consists of muscle, fat, arteries, ligaments, and bones. Moreover, the bony region consists of the cancellous bone, the cortical bone, and the cartilage. In T2-weighted MRI, water, blood, and fat take high signal, and the fat and cartilage around cortical bone take higher signal than cortical bone. There are some studies to classify the knee MR images [14], although, the segmentation accuracy is insufficient. Therefore, this study segments the bony region, the ligaments, and the arteries manually.

3.2. Generation of Pseudo Lateral Radiograph

The quadrant method uses the Blumensaat's line in a lateral radiograph. The proposed method synthesizes a pseudo lateral radiograph image from MR images. The bony region consists of the cancellous bone, cortical bone, and cartilage. The cancellous bone is surrouned by the bony region. And, the cortical bone locates on the bony surface. The cortical bone takes higher signal than the cancellous bone in a lateral radiograph.

The proposed method synthesizes a pseudo lateral radiograph image using the bony surface voxels. The bony surface voxels are defined as voxels that belong to the bony region and one or more adjacent voxels are not bony region. The bony surface voxels are projected in parallel to a projection plane. According an equation of synthesizing digitally reconstructed radiograph (DRR) [15], value of pixel p on the projection plane is defined by;

$$f(p) = \alpha \sum_{v \in R(p)} \exp(-\mu(v)) \text{ and} \tag{1}$$

where $R(p)$ is a set of voxels that are on perpendicular to the projection plane and through pixel p, and $\mu(v)$ is attenuation coefficient of voxel v. Because the voxel is either bony surface voxel or others, it can be defined by Eq. (2).

$$\mu(v) = \begin{cases} \mu_B & \text{if } v \in R_B \\ \infty & \textit{othres} \end{cases} \tag{2}$$

That is, Eq (1) can be rewritten by;

$$f(p) = \kappa N(p), \tag{3}$$

where $N(p)$ is the number of bony surface voxels are on perpendicular to the projection plane and through pixel p.
The projection plane is manually determined so that the contours of the medial and lateral posterior condyles overlap in the projected image

3.3. Quadrant Method on Pseudo Lateral Radiograph

The method estimates the AMB and PLB attaching sites based on the quadrant method and statistical information. Figure 5 shows a schematic diagram of 3-D ACL attaching sites estimation method. The Blumensaat's line is determined manually on the pseudo lateral radiograph, and the grid of the quadrant method is defined as follows; the high is the Blumensaat's line, the low is parallel to the Blumensaat's line and overlapped with the posterior contour of medial and lateral condyle, the deep and the shallow is proximal and distal side of the intersection of the Blumensaat's line and the bony contour.

Table 1 average ACL attachment position obtained from some studies using cadaver. ACL attachment position is confirmed by surgeons, and the quadrant method has been applied to measure the positoin. The proposed method regards the average ACL attachment positoins as the 2-D AMB and PLB attaching sites of this subject The estimated 2-D sites are inversely projected to 3-D bony region contour, and the 3-D ACL attaching sites are obtained.

Table 1. Average of ACL insertion position (Ref[16]).

	AMB (%)	PLB (%)
Deep-Shallow	21.5	32.0
High-Low	23.1	48.8

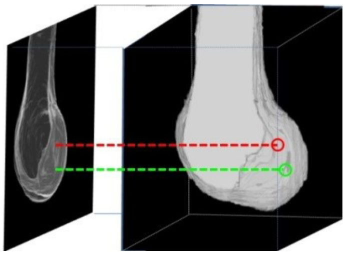

Fig. 5. Flowchart of the proposed system.

3.4. Computer-aided planning method of tunnel orientation

We first define the AMB and the PLB coordinate systems, X_{AMB}-Y_{AMB}-Z_{AMB} and X_{PLB}-Y_{PLB}-Z_{PLB}. Figure 6 shows the coordinate system. The origin of the AMB coordinate system is set to the estimated AMB attaching site. X_{AMB} is parallel to the projection axis, Y_{AMB} is parallel to the femoral bone axis, and Z_{AMB} is the outer-product of X-axis and Y-axis. PLB coordinate system is also defined as well using PLB attaching site.

The proposed method visualizes arteries and ligaments surrounding the femoral condyle on the polar coordinate system as shown in Fig. 7. In this figure, ϕ is an orientation angle from the lateral to the superior, and θ is an orientaion angle from the lateral to the anterior. That is, this study represents tunnel drilling angle using these two angles, ϕ and θ. In X_{AMB}-Y_{AMB}-Z_{AMB} coordinate system, θ is a rotation angle along Z_{AMB} axis, and ϕ is a rotation angle with Y_{AMB} axis.When there are arteries and/or ligaments on an orientation, the tunnel drill will damage them on that orientation. Using this figure, we can evaluate the risk of damaging by tunnel drilling.

In preoperative planning, surgeons determine the AMP and the PLB bone tunnel drilling position in order so that bone tunnels avoid arteries and ligaments. A diameter of the bone tunnel is 5 mm. When a surgeron gives the orientation, drilling space is visualized on the 3-D rendering image. Using these images, the surgeron optimizes the bone tunnel orientation so that the expected outcome is maximized and the soft tissue damage is minimized.

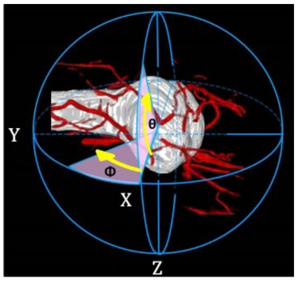

Fig. 6. Coordinate system.

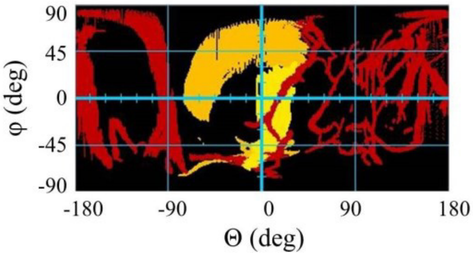

Fig. 7. Visualization of surrounding arteries (red) and ligaments (yellow).

4. Experimental Results

Figure 8 shows a raw T2-weighted MR image of the subject. Figure 9 and 10 show the segmented bony region, and the segmented ligament region (red region), respectively. Figure 11 shows the subject's knee MRA image, and Figure 12 shows the segmented arteries. Figure 13 shows the volume rendering image of the segmented bony region (gray), the ligaments (red) and the arteries (yellow). The segmentation was performed with MIPAV [17], and the segmentation results were confirmed by three well-trained orthopedicians. These results showed that the relationship among the bone, the ligaments, and the arteries can be confirmed easily.

Fig. 8. Raw MR image.

Fig. 9. Bony region.

Fig. 10. Ligament.

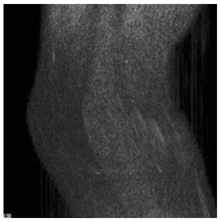

Fig. 11. Raw MRA image.

Fig. 12. Arteries.

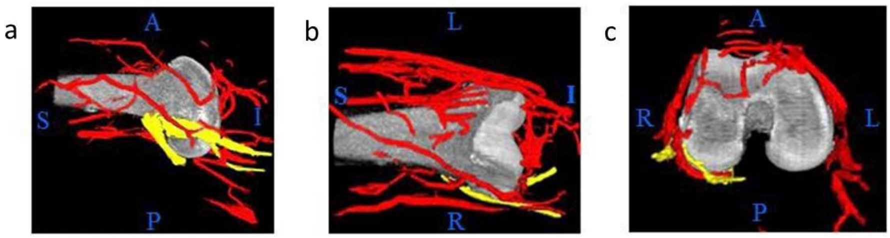

Fig. 13. Volume rendering image. Left: lateral view, middle: anterior view, right: body axis view.

Figure 14 shows the bony surface voxels. Using the bony surface voxels, pseudo lateral radiograph was syntheized as shown in Fig. 15. The projection angle was determined by the orthopedicians so that bottom and the posterior contour of the lateral and the medial condyles overlap. We can definitely find the Blumensaat's line, which is appeared between the gray region and the whiter region. This result shows that the proposed method can describe Blumensaat's line even if using the MR image.

Using the detected Blumensaat's line, the method estimated the AMB and PLB attaching sites as shown in Figure 16. Figure 17 shows the 3-D position of AMB and PLB attaching sites obtained by from 2-D to 3-D inverse-projection technique. These results were confirmed by orthopedicians, and the estimated positions were within usual attaching sites.

Fig. 14. Bony surface voxels.

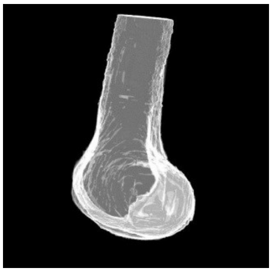

Fig. 15. Pseudo lateral radiograph.

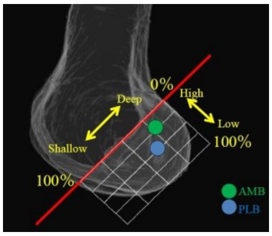

Fig. 16. Estimated insertion sites.

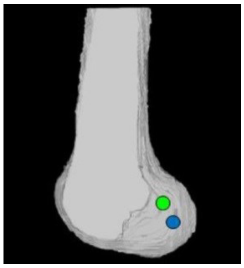

Fig. 17. 3-D insertion site.

Figure 18 (a) and (b) show the segmented arteries and ligaments to evaluate the AMB and the PLB tunnel directions, respectively. These figures are polar coodinate views. ϕ and θ are expeced drilling angles, and the origin is lateral direction. The red region show the arteries and the others are ligaments. Using the images, we can understand the arteries and the ligaments by tunnel drilling with the drill orientation degrees. An orthopedician determined the bone tunnel drilling orientation using these visualizations. The determined drilling orientations of the AMB and the PLB bone tunnel were (θ, ϕ)=(50,20) and (θ, ϕ)=(-15,15), respectively, and is described as white dots in Fig. 18.

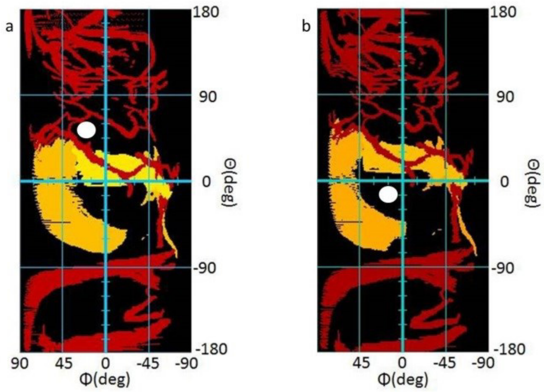

Fig. 18. ACL tunnel direction evaluation (a) AMB tunnel direction; (b) PLB tunnel direction.

Figure 19 shows the tunnel drilling simulation result with the determined angles. The green and blue cylinders are bone tunnels of the AMB and the PLB, respectively. As shown in these images, the bone tunnels avoid damaging the arteries and ligaments, and a collision between the AMB and the PLB bone tunnels.

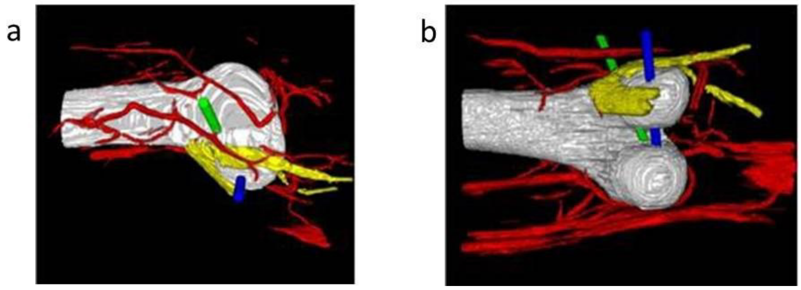

Fig. 19. Tunnel drilling simulation.

5. Conclusion

This paper has introduced a computer-aided surgical planning system for evaluating ACL insertion position and orientation using MR images. The experimental results showed MRI can be an alternative to radiographic evaluation which is the current gold standard for determination of the ACL insertion position. One new finding is that the quadrant method can be applied to MR images.

In the future, we will automate segmentation of the bony region, the ligaments, and the arteries, image orientation determination in pseudo lateral radiograph synthesis, and Blumensaat's line detection.

Acknowledgments

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