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2D-3D registration for 3D analysis of lower limb alignment in a weight-bearing condition

SHIM Eungjune[1,2] KIM Youngjun[1,2] LEE Deukhee[1,2]
LEE Byung Hoon[3] WOO Sungkyung[4] LEE Kunwoo[4]

Abstract. X-ray imaging is the conventional method for diagnosing the orthopedic condition of a patient. Computerized Tomography(CT) scanning is another diagnostic method that provides patient's 3D anatomical information. However, both methods have limitations when diagnosing the whole leg; X-ray imaging does not provide 3D information, and normal CT scanning cannot be performed with a standing posture. Obtaining 3D data regarding the whole leg in a standing posture is clinically important because it enables 3D analysis in the weight bearing condition. Based on these clinical needs, a hardware-based bi-plane X-ray imaging system has been developed; it uses two orthogonal X-ray images. However, such methods have not been made available in general clinics because of the hight cost. Therefore, we proposed a widely adaptive method for 2D X-ray image and 3D CT scan data. By this method, it is possible to three-dimensionally analyze the whole leg in standing posture. The optimal position that generates the most similar image is the captured X-ray image. The algorithm verifies the similarity using the performance of the proposed method by simulation-based experiments. Then, we analyzed the internal-external rotation angle of the femur using real patient data. Approximately 10.55 degrees of internal rotations were found relative to the defined anterior-posterior direction. In this paper, we present a useful registration method using the conventional X-ray image and 3D CT scan data to analyze the whole leg in the weight-bearing condition.

§1 Introduction

Currently, three-dimensional diagnosis of the orthopedic condition is widely used in the medical field. For example, Computerized Tomography (CT) scanning has become an essential method for diagnosing and analyzing a patient orthopedic condition. This multi-sliced image data provides three-dimensional information, so that it can be visualized in 3D space and

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offers rich and precise visual information. The volume rendering method is a representative illustration of 3D visualization of CT volume data by a generalized voxel model [9]. However, CT scan data has its limitation in terms of diagnosis of the whole leg condition. In case of whole leg orthopedic analysis, it is important that the patient posture is bearing weight. Foot posture, arch formation, swelling, bony deformities, bruising, or skin breaks of the leg may be revealed and be possible to visually surveyed in the weight-bearing posture [1]. Conventional CT scanning is conducted in the supine posture, thus it would be difficult to accurately diagnose the whole leg condition only with this method. X-ray images are obtained in the standing posture; therefore, this method allows the acquisition of images in upright, weight-bearing posture and can image the full length of the body. The X-ray method is a conventional method to analyze the whole leg, but a single X-ray image is not amenable to in 3D analysis.

To compensate these drawbacks, there are bi-plane X-ray imaging systems, such as the EOS Imaging System which can simultaneously take posteroanterior (PA) and lateral images [13]. Normally, it is possible to three-dimensionally analyze the whole leg by utilizing these two orthogonal X-ray image and 3D data such as CT or geometrical mesh data [12], [15]. These methods offer relatively accurate 3D information of patient leg in the standing posture, but they require special equipment to acquire the data, and therefore, are not only expensive, but also difficult to adapt to conventional radiography systems.

For these reasons, we propose a 2D-3D registration method and simulation, and visualization software aimed at femur bone that uses a single X-ray image. Our proposed method uses a single X-ray image, and a 3D geometrical model segmented from CT scan data. This method is useful not only for diagnosing patient condition, but also for deriving a large amount of medical data for use in research. For example, if we need a large number of weight-bearing 3D data for research, obtaining new bi-plane X-ray data would be expensive and time consuming. However, using the proposed method will enable us to use the conventional X-ray and CT data that are already obtained and stored so far, thus it has advantages in collecting data in terms of cost and time.

§2 Methods

Figure 1 shows an overview of our registration method. By the obtained 3D geometrical data and conventional single X-ray image, registration is conducted. Firstly, we generated a virtual X-ray image by simulating X-ray imaging system for this process. Secondly, edge filtering is applied to both virtual and real X-ray images. Thirdly, the generated virtual radiograph pixel values are compared with the relevant pixels in a real radiograph, and similarity value scores are created in real time. Simultaneously, the registration algorithm searches the correct transformation of 3D geometrical data.

An accuracy test was also conducted replacing the captured virtual X-ray image as the real image in this process. This method enables to calculate orientation accuracy of the proposed method. Finally, we applied our proposed method to real patient data. Using X-ray and CT

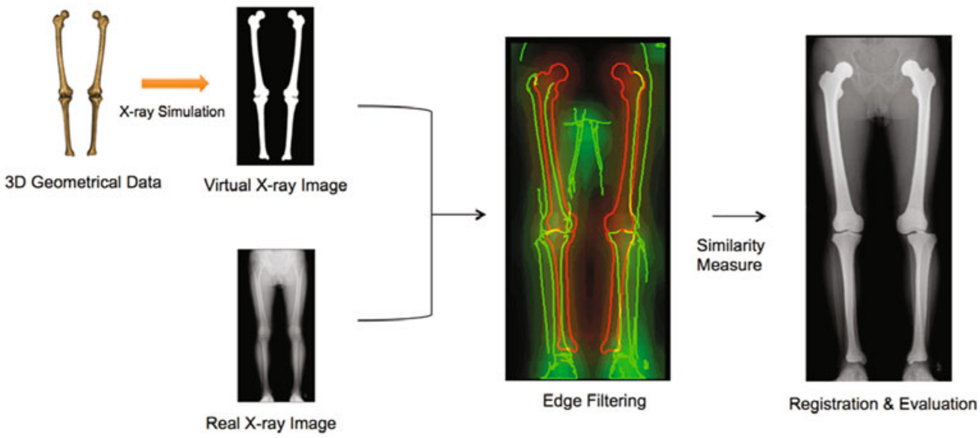

Figure 1: Overview of the registration method. 3D geometrical data is originated from the same patient of the real X-ray image

data obtained for three patients, we calculated the angle differences between the true anterior-posterior (A-P) and manually defined femoral local A-P vector. The result of image alignment, and rotation angle differences are also introduced in this paper; these results can yield a useful diagnosis method for femoral orthopedic conditions.

2.1 Data preparation

2.1.1 Data segmentation

Segmentation of 3D geometrical data is performed based on the original CT data, so as to optimize our registration algorithm. Performing registration requires a large number of transformation operations on the 3D data. On average, 3D rendered CT data contain much more voxel information than the associated mesh data; this gap might result in registration performance speed differences. Because our registration method must search a large range of space, fast (real-time) rendering of 3D data is important. For this reason, we first segmented femur data in the raw CT data. From the stacked image data in the CT slices, surface 3D models are calculated and reconstructed. The region of interest (ROI), selected in the segmentation process is converted into a 3D surface model by a marching cube algorithm that takes the partial volume effect into account, leading to more accurate 3D models [7], [10].

2.1.2 Generate virtual X-ray

By the segmented femur mesh model, the virtual X-ray is simulated in 3D virtual space, which follows the same condition as the real field: The detector plane position is 200 cm away, and the patient is standing 195 cm from the X-ray source. In this condition, shadow mapping is conducted on the detector plane. The mesh model casts a shadow on the ray from the point of light source. From the light source point of view, the cast shadow is perspective-projected onto the detector plane. The projected shadow-map information is stored in the form of a texture in the z-buffer (or depth buffer) [14]; this information can be converted into a binary image. Figure 2 shows the visualized process and the resultant image of our virtual X-ray simulation process. The generated virtual X-ray image is 512×256 pixel, binary with black background and a white shadow image. In this case, if the projected femur model of the virtual X-ray image is the same as the real radiograph, we can assume that the 3D model transformation is the same as that of the real X-ray image patient.

Meanwhile, If raw CT scanned volume data can be used for the target 3D data, Digitally Reconstructed Radiograph(DRR) imaging method can be used for rendering virtual X-ray [4]. Since we are using mesh model for target data, this method is not available for now.

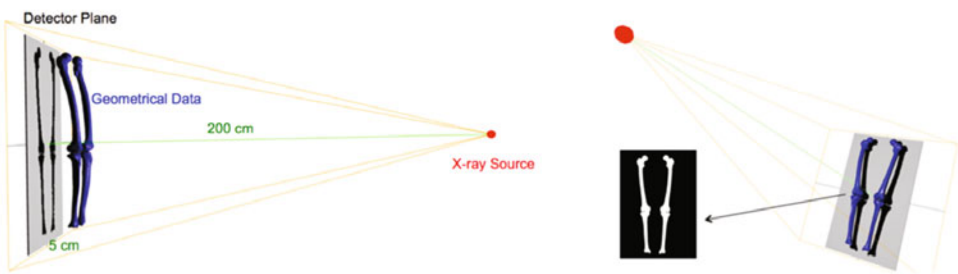

Figure 2: Virtual X-ray simulation the cast shadow from the X-ray source projected on the virtual detector plane.

2.1.3 Image preprocessing

Whereas the real X-ray image displays contains a lot of information such as skin, soft tissues and the pelvic bone in addition to the femur and tibia, the virtual radiograph image is stored as binary image without gradient. Because of that, some image preprocessing is needed to reduce the difference of two images in pixel noises. Canny edge [5] and Gaussian blur filtering were applied on both virtual and real radiograph(see Figure 3). By Canny edge, most of soft tissues or unnecessary noises of the real X-ray image are removed, and most of the femur contours remain. The Canny edge filtered binary image generates the total contour of the femur model, which reduces most errors when comparing the two images. The filtered binary image from the first step shows the detected edge. Gaussian blur is applied several times with different blurring range parameters. The resulting image generates weights around the edge contour; therefore, it enables the searching algorithm to find its optimal position more easily.

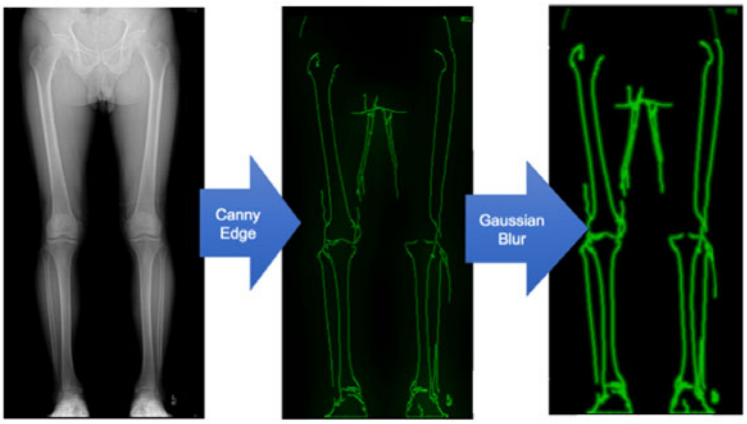

Figure 3: Image Preprocessing procedures

2.2 Registration methods

2.2.1 Similarity measurement

Similarity measurement is a process to quantify the degree of similarity, between the virtual image (A) and the actual radiograph image (B) after image preprocessing [11]. There are many kinds of similarity metric; the value of a similarity metric becomes optimal when the pieces of pixel information on the two images being compared are maximally similar to each other. We selected the normalized correlation coefficient (NCC) from the various metrics In our method, we nullify the measuring similarity when the virtual image pixel value is zero, such that it can locally measure similarity where the femur in virtual image exists. The NCC is defined as follows:

$$NCC(A,B) = \frac{\sum_{i=1}^{n}(A_i \cdot B_i)}{\sqrt{\sum_{i=1}^{n}(A_i^2) \cdot \sum_{i=1}^{n}(B_i^2)}} \tag{1}$$

2.2.2 Simulated annealing

A simulated annealing algorithm was chosen as the optimization methods; it is a probabilistic and heuristic approach that introduces the concept of annealing into the optimization problems [3]. In the proposed algorithm, the image similarity is calculated via the NCC which repeatedly scores the current node, and tries to search for the global maxima. In addition to the original concept of this algorithm, several factors and parameters are added in order to reduce unnecessary search and optimize searching range.

Algorithm 1 displays the pseudocode of our implemented simulated annealing for registration method. The *temperature* value, which decreases as iterations go on, decides the rigid target data's translate and rotation range. Also, in order to avoid local minima, the accepted condition is randomly chosen if the evaluation function does not return better status for processing node. The error value *err*, also helps our method to avoid local minima, and unnecessarily long searching time.

Algorithm 1 Simultaed Annealing for Registration

```
procedure SIMULATED ANNEALING
    iMax ← 1000
    temperature ← 1
    prevScore ← NCC(A,B)
    err ← 0
start:
    translateRange ← e^temperature × random(−1, 1)
    rotationRange ← −e^temperature × random(−1, 1)
    targetMesh → Translate(translateRange)
    targetMesh → Rotate(rotateRange)
    currentScore ← NCC(A,B)
loop:
    if currentSocre > prevScore then
        err ← 0
        goto next
    else
        if random(0, 1) > AcceptCondition(temperature) then
            //Return to prev status
            targetMesh → Translate(−translateRange)
            targetMesh → Rotate(−rotateRange)
            goto next
        else
            err ← 0
            goto next
next:
    temperature ← temperature − temperature/iMax
    goto start
```

2.3 Experiment

2.3.1 Accuracy test

To test the accuracy of this method, an ideal transformation of the registration result is needed. The real radiograph image that we obtained does not have the subject model 3D information, i.e., several experimental X-ray image models are captured as the “gold standards”. By these captured gold standard virtual X-ray images instead of the real image, registration was performed. By this method, it is possible to compare the orientation information from the mesh after registration, and the orientation information from the mesh in the captured virtual image. To carry out this experiment, ten cases of virtual radiograph and their calculated orientation information were prepared. The sample images were stored in 512×256 pixel JPEG file. The orientation information was defined as the femoral A-P vector Euler angle: angle difference on inferior-superior (I-S) axis and the right-left (R-L) axis.

2.3.2 Defining femoral orientation

To define 3D coordinate of the X-ray imaging environment, we defined an axis in patient coordinate system. We defined the origin of coordinate system and axis using the X-ray source transformation matrix. For example, the A-P vector of the world system is defined as the X-ray source view-direction vector, and the I-S vector is defined as the X-ray source up vector. Because the proposed virtual X-ray simulating method uses perspective-projection, its view matrix can easily be defined. In terms of the femoral local coordinates the center positions of femoral medial, lateral condyles and the femoral head are used [6], [8] (Figure 4). By using least squares method, the fitting sphere can of three femoral heads can be defined, and the center position can be calculated (Figure 5). The femoral A-P vector was defined based on the axis orientation. Using this world coordinate of the X-ray system and the local coordinate of the femur, it is possible to define the femur model orientation in the X-ray coordinate system. In this paper, the A-P axis vector of the world coordinate is defined as the true A-P (see Figure 4).

The Euler angle difference between femoral A-P vector and the true A-P vector can be used as an index to analyze the femoral orthopedic condition [2]. In order to show medical significance of the proposed method, we also conducted an experiment for pilot study to apply registration method on real X-ray image and 3D data, so that we can use in medical application. For this study, we obtained three patients' CT scanned data and single X-ray image taken at the waist down. 3D mesh data were segmented from CT volume, and our method was applied on them. The registered 3D data were originally obtained in supine posture, that is not bearing weight, but relocated to patient's standing posture. These results shows that we can obtain 3D data of whole leg in weight bearing condition using conventional CT and X-ray data. Each patient's rotation angle difference between true A-P vectors and femoral A-P vectors after registration was also compared.

§3 Results

3.1 Accuracy test results

Table 1 shows the angle difference between ideal(gold standard) and registered 3D femoral models on I-S and R-L axes. The average angular error rate on I-S axis is 0.54°, and the average error rate on R-L axis is 1.80°. All the error rates on I-S axis value are less than 1.0° degrees, and the error value on R-L axis showed relatively unstable result. The maximum error rate on I-S axis is 0.94°, and the maximum error rate on R-L axis is 3.98°. In most cases, R-L axis error rates are higher than I-S axis error rate.

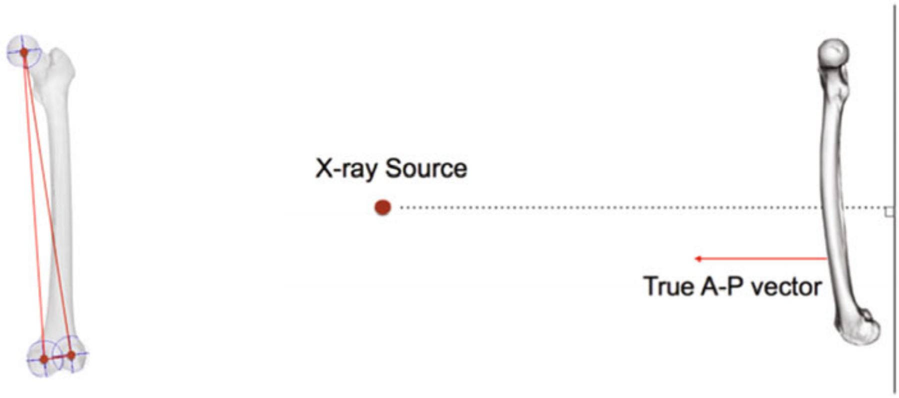

Figure 4: Femoral A-P vector(left) and true A-P vector(right). Femoral A-P is a normal vector of three femoral head's center(left)

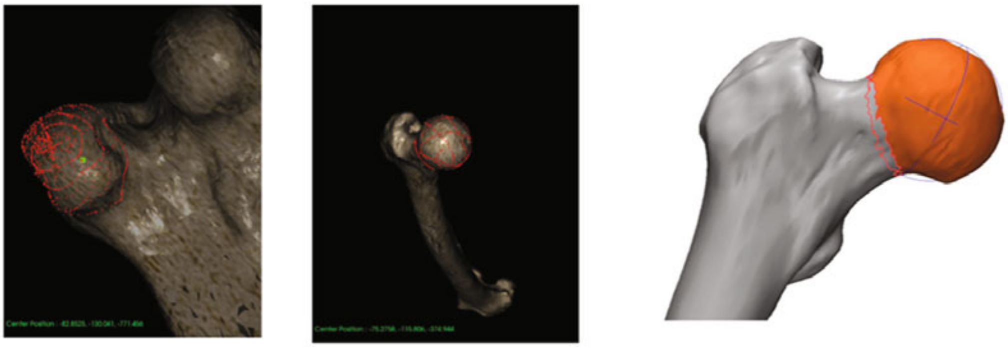

Figure 5: Fitting sphere and its center position of condyle and head center generated from mesh surface points' positions.

3.2 Registration results

Figure 7 shows the edge-filtered, projected, and registered results of our conducted pilot study for three real patients' data. The red curves on the images represent the 3D data of femur and tibia, and the green curves represent the X-ray image. They are accurately aligned as can be seen with the unassisted eye. These 3D data can be regarded as relocated from supine posture state to weight-bearing state. After registration, we also calculated the Euler angle difference between true and femoral local A-P vector.

Figure 8 shows the result of registration on a real X-ray image. On average, 10.55° of internal rotations on the I-S axis, and 3.93° of rotations on the R-L axis were found relative to the defined A-P direction. With this result, there is no significant value of the R-L axis angle difference; however, on the I-S axis angle, there is a noteworthy effect: The angle difference on the I-S axis of the femur showed that every femur captured on the X-ray was internally

Data	Axis	
	I-S	R-L
Data1 Left	0.08	1.68
Data1 Right	0.17	1.17
Data2 Left	0.94	2.01
Data2 Right	0.33	0.01
Data3 Left	0.85	2.73
Data3 Right	0.48	0.44
Data4 Left	0.86	2.43
Data4 Right	0.49	3.29
Data5 Left	0.69	0.22
Data5 Right	0.54	3.98
Average	0.54	1.80

Table 1: Results of virtual accuracy test : rotation angle difference of femoral A-P vector compare to the gold standard(Unit:°)

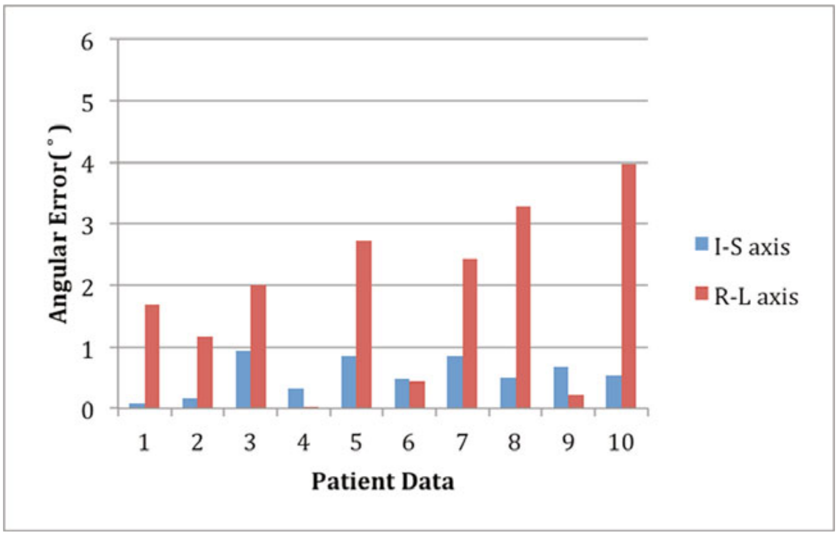

Figure 6: Results of the accuracy test.

rotated in some degrees; every A-P vectors of left femur bones was pointing to the right side as compared with the true A-P vector, and every right femur A-P vector was rotated to the left side (see Figure 8). The accuracy test showed reliable registration results for the I-S axis rotation angle; this result phenomenon seems worthy of further medical research.

§4 Discussion

Our registration method can three-dimensionally diagnose the orthopedic condition of a patient's whole leg in the weight-bearing posture, which was impossible using conventional X-ray imaging or CT/MR scan. The accuracy test for the registration results showed that

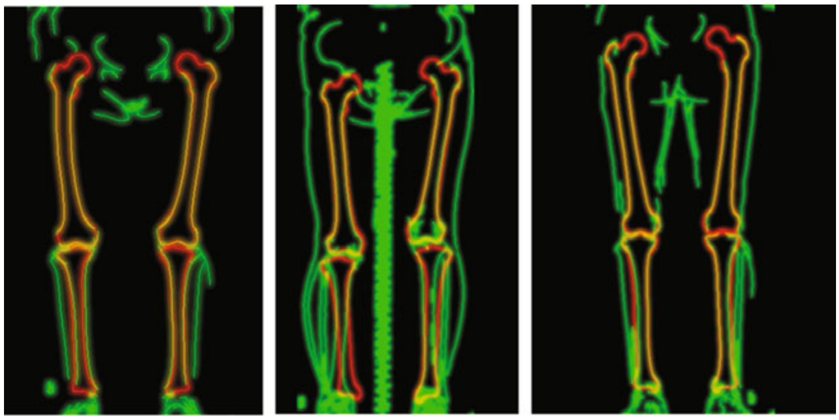

Figure 7: Registration results: For three patients' data, femur bones are aligned onto the image.

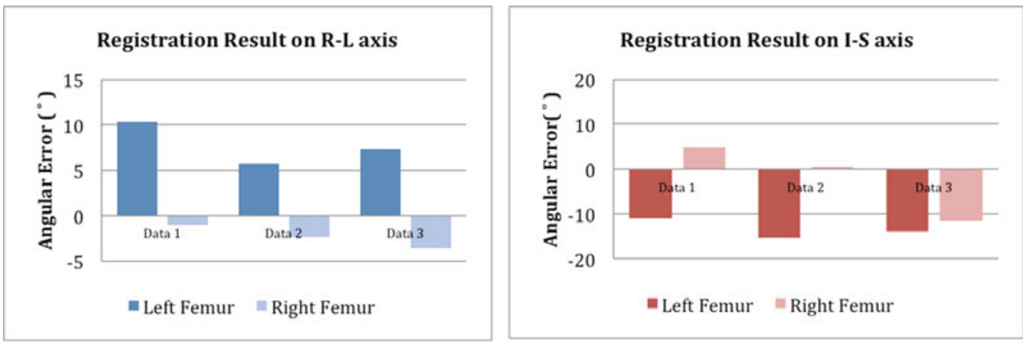

Figure 8: Registration results : rotation angle difference between femoral A-P and true A-P vector.

the proposed registration method could estimate the three-dimensional orientation information from the femur projected X-ray image. The error rate on the I-S axis angle difference was reliable that the maximum error was less than 1.0° from the registration results. Similar registration approaches [12], [15] have been introduced using conventional CT scan data and X-ray image obtained by special bi-plane X-ray imaging equipment [13]. However, comparing with those methods, the proposed method can offer credible three-dimensional information using only conventional X-ray image and CT scan. It means that, this method can be cost-effective and adaptable for wide-range of orthopedic analysis by conventional X-ray image. For example, it could draw meaningful statistical orthopedic information in weight-bearing condition as obtained in our pilot study, with large number of patient data could show more significant tendency. Our pilot study with three patients presented that every patient femoral A-P vector was internally rotated a bit.

From the accuracy test results, the angular accuracy improvement is required, especially on the R-L axis angle. For example, our simulated annealing algorithm applied only basic parameters, and this could be improved to reduce optimization time and produce accurate results. The accuracy and operation time are highly dependent on initial condition of input data. NCC value can be used to compare the score of the neighboring node only during the searching algorithm. Therefore, if there is a metric that can measure the degree of alignment, less than NCC, it might be more effective to decide when to finish the algorithm, and where to search from the current state. To investigate the virtual X-ray image quality is also an important topic. For example, instead of using mesh data, using raw volume-rendered CT scan images would generate a virtual X-ray image that is more similar to the real one. The similarity value from this image and the real X-ray image can be regarded as more reliable measurement than contour-based images similarity. Volumetric are computationally heavier than the mesh data, so this might be take more operation time than mesh-based registration. Comparison of usefulness between the volumetric and mesh-based registration methods could be another meaningful future work.

§5 Conclusion

Conventional medical data acquisition methods such as CT scanning or X-ray imaging have limitations in three-dimensionally diagnosing the whole leg in orthopedic condition. We presented a useful registration method using the conventional X-ray image and 3D CT scan data to analyze the whole leg in weight-bearing condition. The proposed method does not require expensive equipment, and it is adaptable with the conventional X-ray imaging system. We presented a three-dimensional registration and visualization method to conduct accurate registration. The accuracy test demonstrated reliable results in case of the rotation angle on the I-S axis. It is meaningful that we can estimate orthopedic condition of femur in 3D using a single conventional X-ray image. The proposed method can be used to analyze three-dimensional orientations of femur from an X-ray image, and this information can offer statistical founding based on a large amount of medical data. Further researches for reducing error, stabilizing registration result, and optimizing the algorithm are required more work, although this method proposes general outlines of 3D analysis using a conventional X-ray image.

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[1] Center for Bionics, Korea Institute of Science and Technology, Korea.

[2] Department of Biomedical Engineering, University of Science and Technology, Korea.

[3] Department of Orthopaedic Surgery, Kang-Dong Sacred Heart Hospital, Hallym University Medical School, Korea.

[4] Mechanical Engineering, Seoul National University, Korea.

Email: junekim@kist.re.kr(Youngjun Kim), oselite@naver.com(Byung Hoon Lee)