

Six Degree of Freedom Calculation Based on Principal Component Analysis for the Knee Joint in MDCT Image

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Abstract—The anterior cruciate ligament (ACL) injury can cause a reason of instability along anterior - posterior translation at extension. Thus, it is important to examine the knee joint quantitatively for understanding clinical outcome. However, an quantitative calculation method of the knee joint has not been reported. Therefore, we have developed six degree of freedom (6 DOF) calculation based on principal component analysis (PCA) for the knee joint in multi-detector row computer tomography (MDCT) image. The proposal method was applied to six ACL injured knees obtained at two periods. As a result, the proposed methods could calculated 6 DOF of the knee joint quantitatively.

Keywords- Six Degrees-of-freedom; ACL Reconstruction; MDCT Image; Image Analysis

I. INTRODUCTION

The ACL injury can be a reason of instability along anterior-posterior direction at extension. It might result in working and daily life faced to obstacles. As examination methods of the ACL injury, manual tests have been proposed, however, it is difficult to calculate an attitude of the knee joint by using a general commercial device quantitatively. Therefore, this study sets a goal to calculate 6 DOF of the knee joint from MDCT image. In the experiment, the accuracy of the proposed method was examined for 6 DOF of the knee joint.

II. PRELIMINARY

A. MDCT(Multidetector - row CT) Device

An MDCT device is a CT (Computed Tomography) device with the multi-row detector. The MDCT device has thinner thickness and higher resolution than the CT. The MDCT image was obtained for patients performed with ACL reconstruction. One slice consists of 512×512 ($X \times Y$) voxels (TABLE I). The number of slices (Z) differ from patient to patient. The range of image was 5 cm proximal from the femur epicondyle and 5 cm distal from the tibial tubercle (Fig. 1).

TABLE I. ACQUISITION PARAMETERS

Resolution [pixel]	512×512
Color Depth [bits]	16
Slice Thickness [mm]	1.0
The Number of Slice	201~202
Pixel Spacing [mm]	0.5

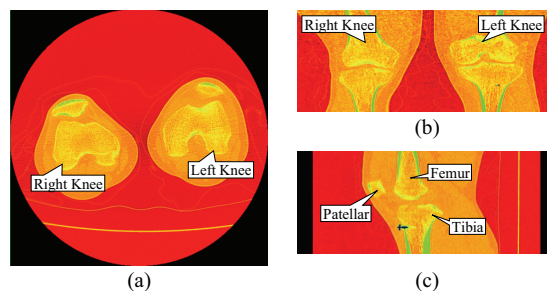


Figure 1. An Example of MDCT Image: (a) Axial (X-Y plane), (b) Coronal (X-Z plane), and (c) Sagittal (Y-Z plane).

B. ACL Injury

The ACL is a ligament which connects the femur and tibia, and plays a role of preventing an excessive anterior translation of the knee during knee rotation [1]. The ACL injury happens with high frequency among sports trauc injuries, and can cause a reason of increase of instability along anterior - posterior translation at extension [2]. When no treatment is applied to the ACL injury, it can result in secondary injuries (i.e., meniscus injury, articular cartilage lesion, etc.). Also, because a self-reparation of the ACL is rare due to its low healing ability, operative treatment is preferred rather than conservative treatment when instability of daily life is high for an active young person or a person with multiple ligament injuries [3-4].

C. ACL Reconstruction

The ACL reconstruction has two techniques, that are single bundle technique and double bundle technique. The single and double are performed with one and two grafts, respectively [5]. In both of techniques, a bone tunnel(s) is/are required so that the graft is passing through it. Especially, two bone tunnels in double bundle technique are called as anteromedial (AM), and posterolateral (PL) as shown in Fig. 2.

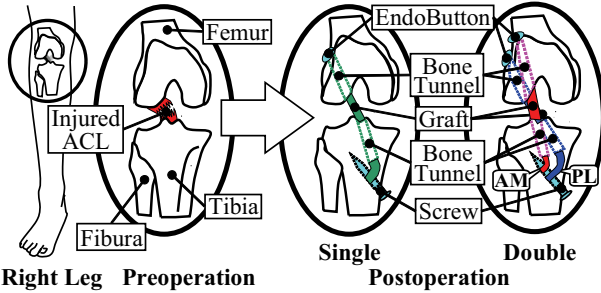


Figure 2. ACL Reconstruction.

D. Definition of Coordinate Systems

Coordinate systems are necessary to a quantitative evaluation by three dimensional attitude of the knee joint (Fig. 3). The coordinate systems consist of an anterior axis, lateral axis, distal axis, and origin point [6-8]. The coordinate systems are determined based on anatomical points and axes [9].

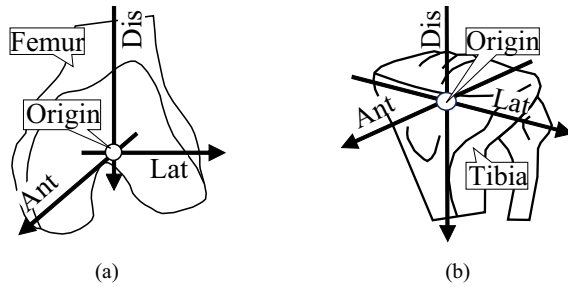


Figure 3. The coordinate systems. (a) The femur coordinate system. (b) The tibia coordinate system.

E. Six Degrees of Freedom

In the three dimensionnal space, total degree of freedom is six for summation of three translational DOF and three rotational DOF. This study calculates 6 DOF of the femur and tibia in MDCT image for analysis of attitude of the knee joint (Fig. 4).

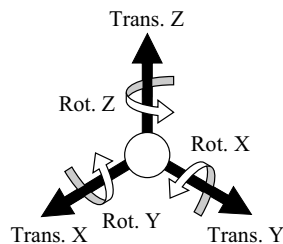


Figure 4. 6 DOF.

III. PROPOSED METHOD

The proposed method consists of three steps as shown in Fig. 5. The first step is determination of the coordinate systems in the femur and tibia. The second step is registration of the images in the femur and tibia. The third step is validation of the registration accuracy. The last step is evaluation of the 6 DOF for the coordinate systems.

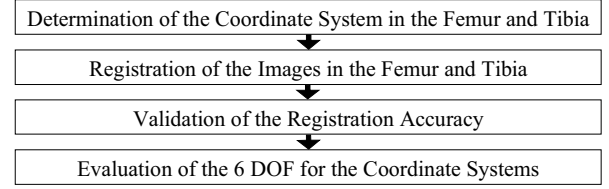


Figure 5. Procedure of proposal method.

A. Determination of the Coordinate Systems in the Femur and Tibia

The coordinate systems of the femur and of the tibia are determined from the information obtained by the following procedure.

1) The femur coordinate system

The femur coordinate system consists of five steps as shown in Fig. 6. The first step is determination of the distal axis. The second step is determination of the anterior direction in axial image. The third step is determination of the lateral axis. The fourth step is determination of the anterior axis. The last step is determination of the origin point.

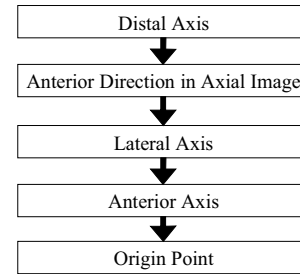


Figure 6. Procedure of the femur coordinate system.

a) *Distal axis*: The femur is depicted as comparatively circle in proximal slice. The gravity points of the proximal femur are detected, and are used as two points making the distal axis (Fig. 7).

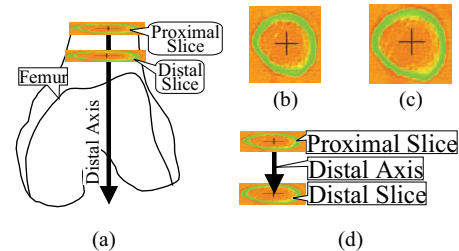


Figure 7. Distal axis: (a) the distal axis of the femur, (b) the proximal slice of the femur image, (c) the distal slice of the femur image, and (d) the calculated distal axis.

b) *The anterior direction in axial Image:* The epicondyles, which are necessary for determining the lateral axis and the anterior direction, are determined. Therefore, we determine the anterior direction in axial image.

Top(t), bottom(b), right(r), and left(l) points in each slice of the femur are detected (Fig. 8 (a)). Then, $t(i)$, $b(i)$, $l(i)$, and $r(i)$ that coordinate values of the s -th slice of the femur are calculated from

$$\begin{cases} 0 \leq l(s) \leq r(s) \leq X \\ 0 \leq t(s) \leq b(s) \leq Y \end{cases}, \quad (1)$$

where s is the slice number of the image, X and Y are the maximum coordinate values of the image, respectively.

The area of the rectangle based on these four points are calculated. Then, difference $dif_y(s)$ of t and b , and difference $dif_x(s)$ of l and r are calculated from

$$\begin{cases} dif_x(s) = |r(s) - l(s)| \\ dif_y(s) = |t(s) - b(s)| \end{cases}. \quad (2)$$

The slice with the maximum area is searched, then used as a target slice for the following process (Fig. 8 (b)). Then, an area $A(s)$ is calculated for each slice from

$$A(s) = dif_x(s) \cdot dif_y(s). \quad (3)$$

Then, the slice with the maximum area $slice_{max}$ is calculated from

$$slice_{max} = \arg \max_{s \in [0, S-1]} (A(s)), \quad (4)$$

where S is the number of slices of the image.

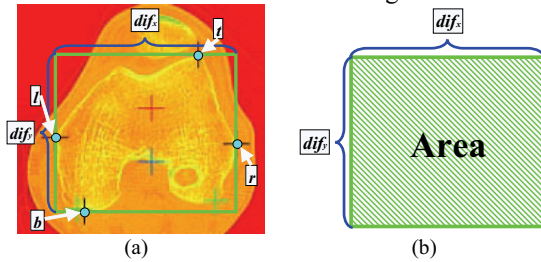


Figure 8. The slice with the femur maximum area: (a) the feature points (t , b , l , r) of the femur image on the slice, and (b) the rectangle area of the femur image on the slice.

The intersection point of the target slice and the distal axis is regarded as the center point. Two points are searched so that the distances between the center point and two points are longest among the contour of the bone. Then the two points are determined as two postepicondyle points for analyzing a notch position. The bisector line is calculated from two epicondyle points and the center point. Then, the maximum evaluation function R is calculated from

$$R = \arg \max_{i \in [0, 2\pi-1]} (A(i) \cdot B(i)), \quad (5)$$

where A and B are the differences of the center point of distal axis and postepicondyles on the slice. The notch position is determined by the bisector line and the contour of the femur (Fig. 9).

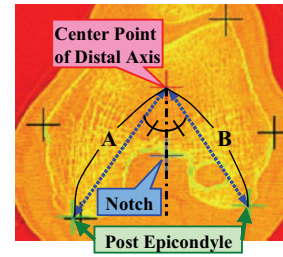


Figure 9. The notch on the slice of the maximum rectangle area.

The anterior direction of the femur is determined by connecting the notch and center point (Fig. 10).

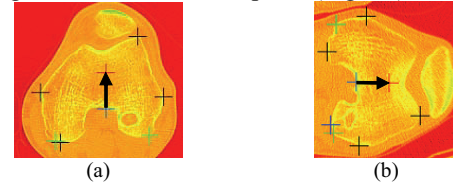


Figure 10. Anterior direction in axial image: (a) the upward position of the knee image, and (b) the rightward position of the knee image.

c) *Lateral axis:* Vertical vectors that indicate contour points from anterior axis are calculated (Fig. 11 (a)). The longest vector is regarded as the epicondyle. The longest vector of the medial and lateral are determined as the medial and lateral epicondyles, respectively (Fig. 11 (b)). The lateral axis is determined by connecting the medial and lateral epicondyles (Fig. 12).

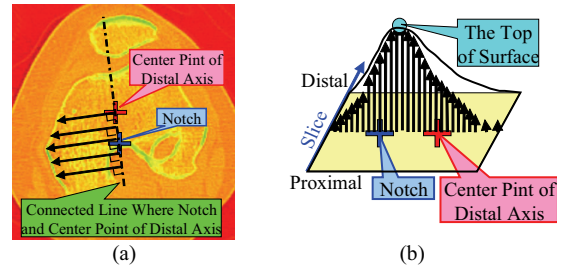


Figure 11. The calculation of the top on the epicondyles: (a) the top on contour side in a slice, and (b) the three dimensional top of surface of the epicondyle.



Figure 12. The determined epicondyles: (a) the medial epicondyle, and (b) the lateral epicondyle.

d) *Anterior axis:* The anterior axis is an outer product of the distal axis and the lateral axis.

e) *Origin point:* The middle point of the segment that connects the epicondyles is determined as the origin point of the coordinate system (Fig. 13). Then, the origin point $\vec{o}(o_1, o_2, o_3)$ is calculated from

$$\vec{o} = \left(\frac{m_1 + l_1}{2}, \frac{m_2 + l_2}{2}, \frac{m_3 + l_3}{2} \right), \quad (6)$$

where $\vec{m}(m_1, m_2, m_3)$ and $\vec{l}(l_1, l_2, l_3)$ are the medial and lateral epicondyles.

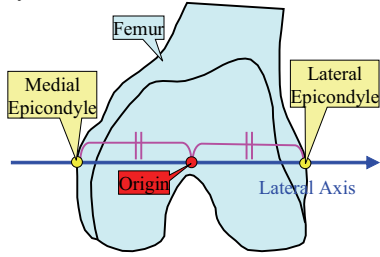


Figure 13. The origin point.

2) The tibia coordinate system

The tibia coordinate system consists of three steps as shown in Fig. 14. The first step is determination of the distal axis. The second step is determination of the anterior axis and lateral axis. The last step is determination of the origin point.

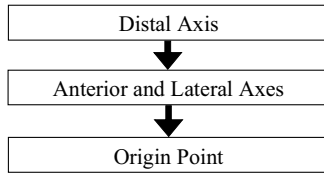


Figure 14. Procedure of the tibia coordinate system.

a) *Distal axis*: The tibia is depicted as comparatively circle in distal slice. The gravity points of the distal region of the tibia are detected, and are used for making the distal axis based on principal component analysis (Fig. 15).

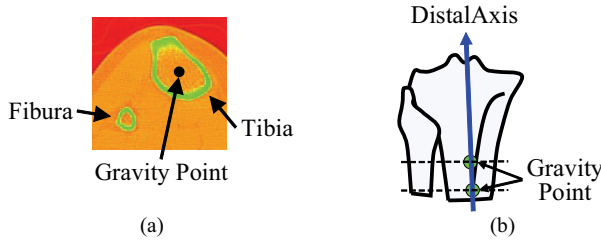


Figure 15. Determining the distal axis: (a) the gravity point on the axial image, (b) the distal axis.

b) *Anterior and lateral axes*: The plane which has the maximum area and is perpendicular to the calculated bone axis, is searched. Anterior axis and lateral axis are derived from the maximum area on the plane. At first, the gravity point of the bone profile is calculated. Here, two orthogonal lines are assumed so that the intersection point is located as the gravity point. The intersection points of the lines and the bone profile are regarded as points A, B, C, and D, respectively. These four distances (a, b, c, and d) from the gravity points to the four points are inserted by the following evaluation function R,

$$R_{\max} = \arg \max_{i \in [0, 2\pi-1]} \frac{a(i) \cdot b(i) \cdot c(i)}{d(i)}, \quad (7)$$

The orthogonal lines are rotated based on the gravity point so that the evaluation function R is the maximum value. In the situation, the lines AB and CD are defined as the lateral and anterior axes, respectively.

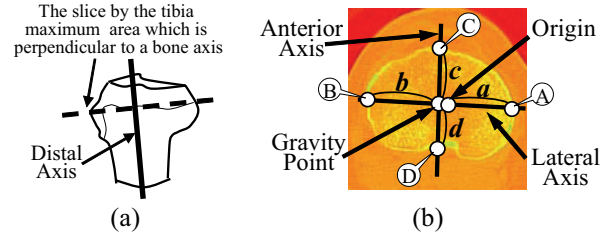


Figure 16. The tibia coordinate system: (a) The slice by the tibia maximum area which is perpendicular to a bone axis, (b) the anterior axis, the lateral axis and the origin point.

c) *Origin point*: The origin of a coordinate system is determined as a middle point of the line AB (Fig. 16). Then, the origin point $\vec{o}(o_1, o_2, o_3)$ is calculated from

$$\vec{o} = \left(\frac{a_1 + b_1}{2}, \frac{a_2 + b_2}{2}, \frac{a_3 + b_3}{2} \right), \quad (8)$$

where $\vec{a}(a_1, a_2, a_3)$ and $\vec{b}(b_1, b_2, b_3)$ are the medial and lateral epicondyles.

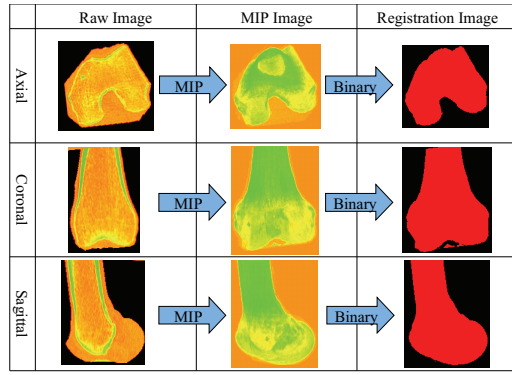
B. Registration of the Images in the Femur and Tibia

The 6 DOF is quantitatively evaluated in comparing to preoperative and postoperative data. In general, different acquired period data have tendency to make a little bit different coordinate system each other. To reduce the error, the data are unified by registration, and is evaluated in same coordinate system. The coordinate system are unified by registration of preoperative data and postoperative data.

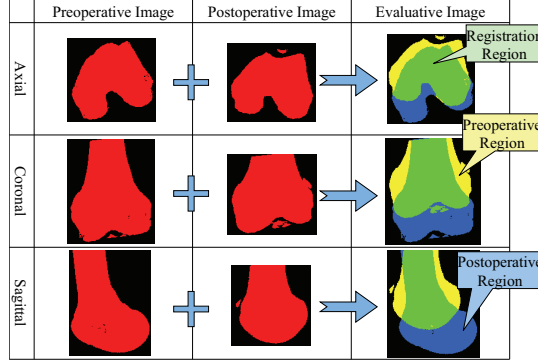
Evaluation of registration is performed by using matching rate. The matching rate is calculated in each three planes (i.e., axial plane, coronal plane, and sagittal plane). The target data are projected to each planes by using maximum intensity projection (MIP) method (Fig. 17). The projected data are transformed to binary data by thresholding. These processing are applied for preoperative and postoperative data. A matching rate R is a value calculated by the following equation,

$$R = \frac{1}{2} \cdot \frac{S_1 + S_2}{S_1 \times S_2} S_R, \quad (9)$$

where S_R is an area of number of overlapped pixels of preoperative and postoperative data, S_1 and S_2 are areas of preoperative data and postoperative data, respectively.



(a)



(b)

Figure 17. The evaluation of the registration: (a) Maximum Intensity Projection, and (b) the registration image.

The precise registration is performed so that the femur region of postoperative data are mostly overlapped to preoperative data (Fig. 18). After registration, the coordinate system determined from preoperative data are also used for postoperative data. It results that both of preoperative and postoperative data are evaluated on the same coordinate system.

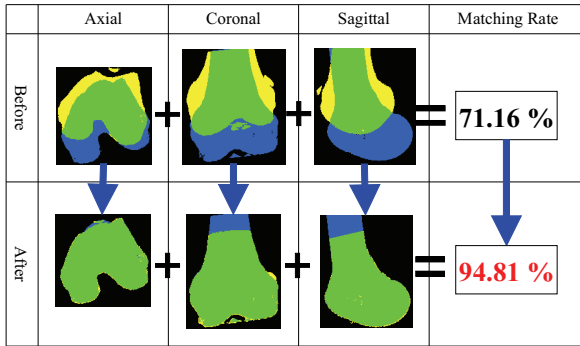


Figure 18. The precise registration.

C. Accuracy Validation of the Registration

An accuracy validation of the registration is used by the position of the screw. The intensity of screw is higher than a peripheral bone and an organization of the muscle etc. (Fig. 19 (a)). Only screw is extracted from the MDCT image (Fig. 19 (b)) by binarization with high thresholding value. The gravity point of the extracted object voxel is regarded as a barycentric position of the screw (Fig. 19 (c)).

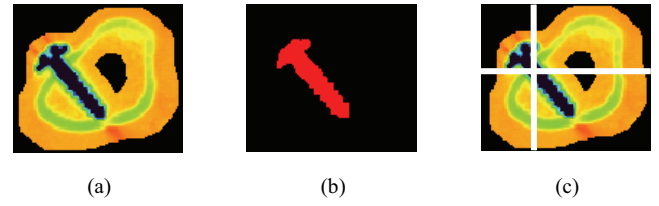


Figure 19. Evaluation of the knee joint pose.

The screw position was calculated by using the bone coordinate system of the tibia (Fig. 20). The validation of the registration accuracy is used by the position of the screw.

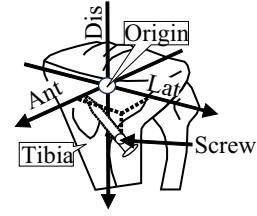


Figure 20. Evaluation of the screw.

D. Evaluation of the 6 DOF for the Coordinate Systems

Based on the femur and 6 DOF of the tibial coordinate system that we pursued, we evaluate attitude of the knee [10-11]. In general, range of motion is calculated by using this 6 DOF.

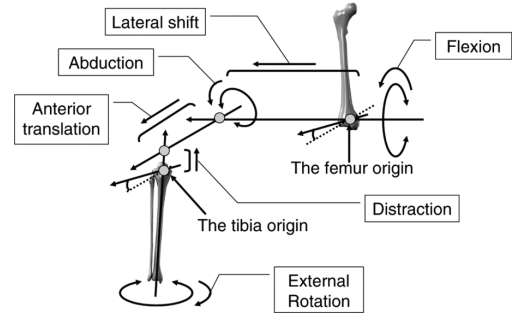


Figure 21. Evaluation of the knee joint pose.

IV. EXPERIMENTS

The subjects was fewer, because this study is a pilot study. The proposed method was applied for four subjects with single bundle that has informed consent. The sex was two males and one females. The age was 36.67 ± 13.50 (23-50). The injured knee was one right knee and two left knees (TABLE II). The one preoperative and one postoperative MDCT images were evaluated for each subjects. Quantitative comparison with the injured knee and the intact knee was performed.

TABLE II. SUBJECTS DATA

Subject	Sex	Age	Bundle	Injured Knee
1	F	37	S	L
2	M	23	S	R
3	M	50	S	L

V. RESULTS

The time-depend displacements of the screw was shown in TABLE III. The time-depend displacements of the screw were -0.28 ± 0.44 mm (anterior), 0.09 ± 0.25 mm (lateral), -0.07 ± 0.37 mm (distal), and 0.56 ± 0.24 mm (3D). "3D" was the three-dimensional time-depend displacement.

TABLE III. THE TIME-DEPEND DISPLACEMENTS OF THE SCREW.

Subject	Anterior	Lateral	Distal	3D
1	-0.79	0.24	-0.16	0.84
2	-0.02	0.23	0.34	0.41
3	-0.03	-0.20	-0.39	0.44

The results of evaluations were shown in TABLES IV - VI. In the tables, the 6 DOF (anterior, lateral, distal, flexion, rotation, and valgus) were evaluated at pre-time and post-time. The changes between the pre-time and post-time were tabulated. The difference was calculated by subtracting the injured knee from the intact knee.

TABLE IV. THE EVALUATION OF THE INJURED KNEE.

		Injured Knee (A)					
		Anterior	Lateral	Distal	Flexion	Rotation	Valgus
1	Pre-time	25.09	11.66	128.83	17.64	11.74	3.58
	Post-time	14.24	3.01	92.16	16.64	28.27	2.54
	Change	-10.85	-8.65	-36.67	-1.00	16.53	-1.04
2	Pre-time	14.46	30.56	146.52	2.52	13.90	16.56
	Post-time	10.00	17.45	126.72	5.00	9.74	11.88
	Change	-4.46	-13.11	-19.80	2.48	-4.16	-4.67
3	Pre-time	20.73	19.37	105.62	12.49	9.56	0.85
	Post-time	20.80	11.48	121.90	3.87	30.77	0.13
	Change	0.07	-7.88	16.28	-8.61	21.20	-0.72

(Anterior, Lateral, Distal: (mm), Flexion, Rotation, Valgus: (degree))

TABLE V. THE EVALUATION OF THE INTACT KNEE.

		Intact Knee (B)					
		Anterior	Lateral	Distal	Flexion	Rotation	Valgus
1	Pre-time	16.99	0.80	95.92	8.73	8.94	5.06
	Post-time	11.13	0.74	77.49	16.57	10.84	4.48
	Change	-5.86	-0.05	-18.42	7.84	1.91	-0.58
2	Pre-time	24.13	21.63	142.45	19.01	16.28	12.68
	Post-time	15.52	10.20	124.01	14.78	7.22	14.61
	Change	-8.60	-11.43	-18.44	-4.23	-9.06	1.93
3	Pre-time	21.20	6.45	97.63	6.89	17.70	4.50
	Post-time	17.66	14.22	105.23	14.01	17.80	5.79
	Change	-3.54	7.77	7.60	7.12	0.10	1.28

(Anterior, Lateral, Distal: (mm), Flexion, Rotation, Valgus: (degree))

TABLE VI. THE EVALUATION OF THE DIFFERENCE.

		Difference (B-A)					
		Anterior	Lateral	Distal	Flexion	Rotation	Valgus
1	Pre-time	-8.10	-10.86	-32.91	-8.91	-2.81	1.48
	Post-time	-3.11	-2.27	-14.67	-0.07	-17.43	1.94
2	Pre-time	9.67	-8.93	-4.06	16.49	2.38	-3.88
	Post-time	5.52	-7.25	-2.71	9.78	-2.52	2.73
3	Pre-time	0.46	-12.92	-7.98	-5.60	8.14	3.65
	Post-time	-3.14	2.74	-16.67	10.14	-12.96	5.66

(Anterior, Lateral, Distal: (mm), Flexion, Rotation, Valgus: (degree))

VI. DISCUSSION

The time-depend displacement (0.56 mm) of the screw was as small as the resolution (0.50 mm) of the image. The determination was no tendency in a direction of the displacement. This accuracy error was very small.

The changes of the injured knee were larger than the intact. It implies that the 6 DOF of the injured knee is effected by operation. The difference of post-time was close to zero more than pre-time. It might be that the 6 DOF of the injured knee was modified as the 6 DOF of the intact knee by the operation.

VII. CONCLUSION

We have proposed an analysis method of 6 DOF in the knee joint. The proposed method was applied for three patients of single bundle technique. The subjects was fewer, because this study is a pilot study. As a result, the proposed method could calculate the 6 DOF in the knee joint. This accuracy error was very small. It might be that the 6 DOF of the injured knee was modified as the 6 DOF of the intact knee by operation. We can apply the 6 DOF to the clinical examinations. This future work is to apply this method for many subjects.

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