ROBUST ESTIMATION OF KNEE KINEMATICS AFTER TOTAL KNEE ARTHROPLASTY WITH EVOLUTIONAL COMPUTING APPROACH

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ABSTRACT

Analyzing knee kinematics after total knee arthroplasty (TKA) has been attracting considerable attentions because the knee kinematics can be used to evaluate TKA patients and to evaluate TKA operations and design of knee implants. Knee kinematics can be estimated by 2-D/3-D image registration from 3-D computer-aided design (CAD) models of knee implants to 2-D X-ray image. Although there are many studies for estimating knee kinematics, they have common problems that are dependency on initial pose/position and falling into local maxima. This study proposes a robust 2-D/3-D image registration method based on evolutional computing. The evolutional computing has both characteristics of global search performance and of local search performance. The characteristics are suitable for solving the problems of 2-D/3-D image registration. The proposed system has been evaluated by applying it to computer-synthesized images, X-ray images of phantoms, and X-ray images of TKA patients.

Index Terms— Total Knee Arthroplasty, 2-D/3-D image registration, Optimization, Evolutional computing

1. INTRODUCTION

3-D Kinematic analysis of artificial knee implants *in-vivo* is one of main topics in the research field of total knee arthroplasty (TKA). TKA is an operation that replaces the damaged human knee with artificial knee implants composed of femoral component and tibial tray. In order to diagnose the implanted knee, to evaluate operating method of TKA, or to evaluate design of knee implants, many researchers have been investigating 3-D knee kinematics of artificial implants *in-vivo* after TKA.

To investigate the 3-D kinematic analysis, there are approaches based on acceleration/gyro sensors, video analysis and image registration using X-ray images. Each of them has advantages and disadvantages. Especially, image registration of X-ray images has been attracting considerable attentions because of high accuracy of estimating knee kinematics. Some methods for analyzing X-ray images have been proposed by Banks [1][2], Komistek [3], Yamazaki [4], Kobashi [5], and others. They take static 2-D X-ray image with fixing the knee at an arbitrary pose or dynamic 2-D X-ray fluoroscopy images with flexing/extending the knee joint. 3-D pose/position of knee implant can be estimated by 2-D/3-D image registration from 3-D computer-aided design (CAD) data of knee implant to 2-D image. And, to estimate 3-D kinematics, knee flexion/extension (f/e) angle, internal/external rotation (i/e) angle and varus/valgus (v/v) angle are quantified from 3-D pose/position of the knee implants.

Almost conventional methods have common problems that are dependency on the initial pose/position and falling into local maxima. They find a solution by searching for a parameter space near the initial pose/position parameters. In order to search the solution, many optimization algorithms can be applied: Greedy, ε-Greedy, steepest ascent algorithm, Boltzman Machine, Simulated Annealing (SA), *etc*. When they are applied to 2-D/3-D image registration, it may be difficult to find the global solution because there are many local maxima/minima.

This article proposes a robust method for estimating the 3-D knee kinematics from X-ray static image. The proposed method is based on 2-D/3-D image registration from 3-D CAD data to 2-D X-ray image. The novelty of the proposed method is an algorithm of searching pose/position parameters; the new searching algorithm is based on evolutional computing (EC). The method generates plural solutions of candidate by randomly moving and rotating pose/position, and finds local solution by Greedy algorithm for each candidate. Then, a part of local solutions is selected by elite preserving and roulette selection, and they are passed to the next generation. By iterating random initialization, local searching and selection, the global solution will be found. The benefit of the method is robustness for the initial solution, and it is validated by simulation experiments and comparison with Greedy algorithm and SA.

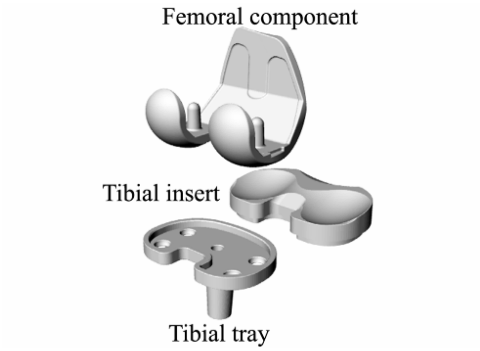


Fig 1. Knee implants.

2. PRELIMINARIES

2.1. Knee Implants

In this study, we have used Posterior Cruciate Retaining (PCR) type knee implant, that was produced by Japan Medical Materials Corp., Osaka, JAPAN, and were received an approval of the clinical use from the Ministry of Health and Welfare, JAPAN. The 3-D geometric models of both types of knee implant are provided by stereolithography (STL) format. The rendering image of the 3-D geometric model is shown in Fig. 1. The knee implant mainly consists of a femoral component, a tibial tray and a tibial insert. The femoral component and the tibial tray are made of metal, and the tibial insert is made of polyethylene.

2.2. X-ray Image

In X-ray images, the femoral component and the tibial tray appeared with lower intensity than surrounding soft tissues because X-rays are absorbed by metal, and the tibial insert appeared with equivalent intensity to soft tissues. The X-ray films are scanned by using an optical scanner with a spatial resolution of 360 dpi and a pixel resolution of 8 bits while 0 means black and 255 means white. In this study, a value stored in a pixel is treated as intensity. And, X-ray source position was calibrated by using our configured calibration jig as described in Ref. [6].

2.3. Knee kinematic angles

The proposed system quantifies three knee kinematic angles of the knee implants that represent the relationship between the femoral component and the tibial tray for clinical research and diagnosis. The knee kinematic angles; f/e angle, i/e angle, and v/v angle, are quantified from 3-D pose/position of femoral component and of tibial tray using a method proposed in Ref. [5]. The quantification method is based on a joint coordinate system defined by Grood *et al*. [7] that has been widely used to analyze kinematics of the knee motion. The conceptual diagram is illustrated in

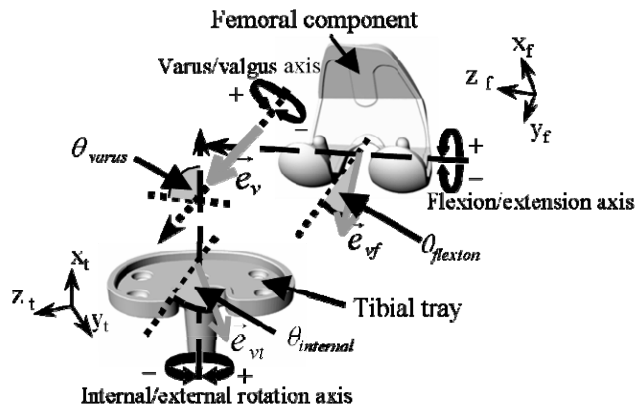


Fig 2. Definition of knee kinematic angles (Left knee).

Fig. 2. In case of the right knee, only the sign of i/e rotation angle is opposite.

3. 2-D/3-D IMAGE REGISTRATION WITH EVOLUTIONAL COMPUTING

Finding 3-D pose/position of the knee implant from 2-D X-ray image is to estimate appropriate rotation angles and appropriate translation distances in which the projected image using the parameters is same as the silhouette of the component in the given X-ray image. The proposed method finds rotation and translation parameters based on EC scheme because EC can overcome local maxima of energy field. In the following, procedure of estimating pose/position of each knee implant with EC is described. This procedure is applied to each of femoral component and tibial tray.

[Procedure of pose/position estimation with EC]
[Parameters]
Number of solutions: N_c
Number of generations: N_g
[Step 1] [Initialize]
[Step 1-1] [Parameters]
1) Set generation number, *cnt*, to 1.
2) Set full width of half maximum (FWHM) of rotation angle, δ_{rot}, and translation distance δ_{trans}.

[Step 1-2] [Initial solution]
1) Input initial pose/position, **R**, by a user using graphical user interface (GUI) of the configured system. Only this step requires a user interaction.
2) Duplicate the initial solution to all parents.

[Step 2] [Create children]
[Step 2-1] [Elite selection]
1) Select an elite solution with the maximum matching score among the parents, and duplicate it to a child.
2) Rotate and translate the solution of the child. The rotation angle and translation distance are determined randomly using Gaussian distribution

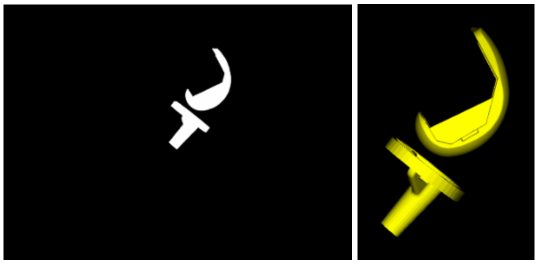


Fig 3. Left; (a) computer synthesized image, and right; (b) truth pose/position.

Table 1. Truth values of pose/position. F.: Femoral component, T.: Tibial tray.

	pose [quaternion parameters]				position [mm]		
	w	x	y	z	x	y	z
F.	0.344	0.618	0.355	-0.611	254.0	123.2	-105.7
T.	0.624	0.300	0.648	-0.317	233.4	125.9	-92.4

with FWHM of δ_{rot}, and δ_{trans}, respectively.

[Step 2-2] [Roulette selection]

1) Randomly select a solution among the parents in which the probability of selecting the solution is determined by the matching score.
2) Rotate and translate the solution of the child. The rotation angle and translation distance are determined randomly using Gaussian distribution with FWHM of δ_{rot} and δ_{trans}, respectively.
3) This step is iterated until the number of children becomes N_c.

[Step 3] [Update parameters]

1) Optimizing each solution of children by using Greedy algorithm.
2) Decrease the FWHM of Gaussian distributions, δ_{rot} and δ_{trans}, by multiplying a decreasing parameter τ.
3) Increase the generation number.

[Step 4] [Termination condition]

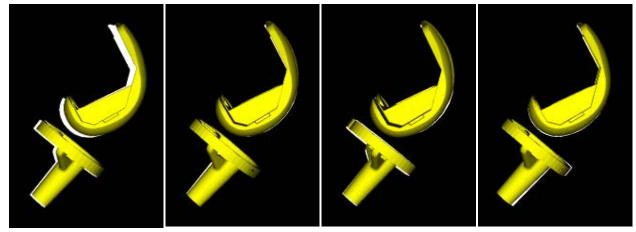
1) If the generation number is higher than N_g, select a solution with the maximum matching score, and terminate this procedure. Otherwise, go to Step 2.

[End]

The matching score used in the above procedure is calculated using a definition of fuzzy image matching proposed by Kobashi *et al.* [5].

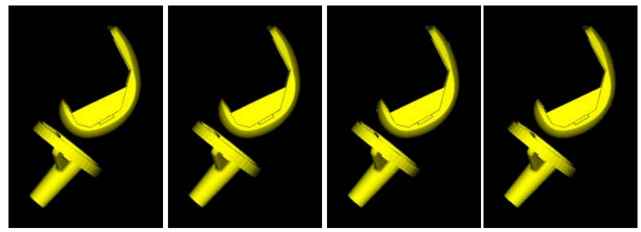
4. EXPERIMENTAL RESULTS AND DISCUSSION

To quantitatively evaluate the proposed method and to compare with Greedy algorithm and SA, all of the methods were applied to a computer synthesized image shown in Fig. 3 (a). The image was synthesized by projecting the knee implants with pose/position parameter shown in Table 1 in which X-ray position was [246.07, 127.14, -1452.85] mm. The knee kinematic angles were f/e angle of 68.9, i/e angle of -2.86 and v/v angle of 0.41 deg. The analyzing parameters were initial FWHM of Gaussian distributions δ_{rot} and δ_{trans} of 4.1 deg and 1.00 mm, respectively, decreasing parameter τ of 0.75, number of solutions N_c of 10, and number of generations N_g of 10.



(a) Case 1. (b) Case 2. (c) Case 3. (d) Case 4.

Fig. 4. Initial pose/positions.



(a) Case 1. (b) Case 2. (c) Case 3. (d) Case 4.

Fig. 5. Estimated pose/positions.

Table 2. Evaluation and comparison of estimated knee kinematic angles [deg]. RMSE; root mean squared error.

		Init	Greedy	SA	EC
case 1	f/e	-1.08	0.94	-0.16	-0.01
	i/e	2.73	3.1	0.02	-0.39
	v/v	-0.97	-6.7	0.06	0.04
case 2	f/e	2.04	1.01	0.22	-0.09
	i/e	-6.65	-2.31	-1.88	-0.67
	v/v	-2.29	-1.89	0.11	-0.03
case 3	f/e	-0.44	-0.59	0.12	-0.18
	i/e	7.63	6.13	9.25	-0.22
	v/v	-6.80	-0.49	-0.44	-0.06
case 4	f/e	1.21	-0.38	-0.16	-0.09
	i/e	-1.44	-0.30	0.17	-0.08
	v/v	0.05	-0.05	-0.01	0.01
RMSE		3.78	2.94	2.73	0.24

Initial pose/positions were determined by randomly rotating and translating from the truth pose/position. The rotation angle and translation distance were randomly determined using a Gaussian distribution with FWHM of 4.1 deg and 1.0 mm. Fig. 4 shows 4 cases of initial pose/positions.

Experimental results with the proposed method were shown in Fig. 5. And, the estimation errors of knee kinematic angles were shown in Table 2, 3 and 4. In addition, the results with Greedy algorithm and simulated annealing algorithm are appended. In these tables, 'Init', 'Greedy', 'SA', and 'EC' denote estimation errors with initial pose, Greedy algorithm, simulated annealing algorithm, and the proposed method, respectively. All of the methods used the same initial pose/position. The results showed that the proposed method with evolutional computing approach produced the superior estimation results than the other methods.

Table 3. Evaluation and comparison of estimated position of femoral component [mm].

		Init	Greedy	SA	EC
Case 1	x	2.82	1.82	-0.08	-0.09
	y	-0.75	-1.75	0.01	0.03
	z	-0.37	-0.37	0.98	-3.06
Case 2	x	0.60	0.60	-0.10	-0.07
	y	-1.22	-0.22	0.01	-0.03
	z	-2.46	2.54	-2.66	-0.64
Case 3	x	-0.08	-0.08	0.45	-0.10
	y	-1.06	-0.06	-0.02	0.01
	z	-1.77	-0.77	-2.66	-2.20
Case 4	x	-0.09	-0.18	-0.04	-0.17
	y	-0.85	-0.03	-0.01	0.09
	z	-1.00	2.86	-1.21	-2.15
RMSE	x	1.44	0.96	0.23	0.11
	y	0.99	0.88	0.01	0.05
	z	1.61	1.96	2.04	2.19

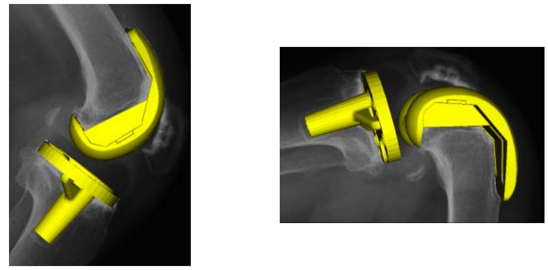
Table 4. Evaluation and comparison of estimated position of tibial tray [mm].

		Init	Greedy	SA	EC
Case 1	x	0.00	0.37	-0.04	0.19
	y	0.01	-0.19	-0.03	-0.06
	z	0.00	-10.61	-0.62	-8.63
Case 2	x	1.48	0.48	0.19	0.03
	y	0.76	-0.24	0.08	-0.05
	z	-2.77	-0.77	-0.11	-0.92
Case 3	x	0.14	0.14	-0.23	0.03
	y	-0.30	-0.30	0.00	-0.09
	z	-1.45	-4.45	-2.32	-6.24
Case 4	x	-0.14	0.04	-0.12	0.13
	y	-0.34	-0.06	-0.05	-0.07
	z	-1.05	-2.30	-1.70	-6.91
RMSE	x	0.75	0.31	0.16	0.12
	y	0.44	0.22	0.05	0.07
	z	1.65	5.88	1.47	6.36

Next, the proposed method was applied to two poses of a same TKA patient volunteer. The experimental results and the estimated knee kinematic angles were shown in Fig. 6 and Table 5, respectively. They showed that the proposed method can be applied to the X-ray images of TKA subjects, and produced effective clinical results.

5. CONCLUSIONS

This paper proposed a robust pose/position estimation method. By introducing evolutional computing approach into parameter optimization process, the method took an ability of finding global solution from a large amount of location solutions. The computer simulation experiments showed that the proposed method estimated knee kinematic angles with RMSE of 0.24 deg, and knee position with RMSE of 0.09 mm in in-plane, and 4.28 mm in out-plane. In the future, we will perform further validation of the proposed method through a large amount of computer synthesized images, real phantom images and subjects' data.



(a) Pose 1. (b) Pose 2.

Fig. 6. Subject experiments.

Table 5. Knee kinematic angles [deg].

	f/e	i/e	v/v
Pose 1	69.26	-0.38	1.12
Pose 2	108.72	-1.07	-0.87

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