32nd Annual International Conference of the IEEE EMBS
Buenos Aires, Argentina, August 31 - September 4, 2010

A Comparison of the 3D Kinematic Measurements Obtained by Single-Plane 2D-3D Image Registration and RSA

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Abstract— **3D computed tomography (CT) to single-plane 2D fluoroscopy registration is an emerging technology for many clinical applications such as kinematic analysis of human joints and image-guided surgery. However, previous registration approaches have suffered from the inaccuracy of determining precise motion parameters for out-of-plane movements. In this paper we compare kinematic measurements obtained by a new 2D-3D registration algorithm with measurements provided by the gold standard Roentgen Stereo Analysis (RSA). In particular, we are interested in the out-of-plane translation and rotations which are difficult to measure precisely using a single plane approach. Our experimental results show that the standard deviation of the error for out-of-plane translation is 0.42 mm which compares favourably to RSA. It is also evident that our approach produces very similar flexion/extension, abduction/adduction and external knee rotation angles when compared to RSA.**

I. Introduction

Understanding the motion pattern (kinematics) of joints whether normal, disease-effected, or following a surgery, is an integral part of developing effective musculoskeletal treatment. Until recently the most accurate, and therefore the clinical standard approach for 3D modelling of joint kinematics, implant performance and implant bearing wear has been roentgen stereophotogrammetry or roentgen stereo analysis (RSA) [3]. This approach involves implanting tantalum beads in the bones and then taking X-rays projected through the joint in two imaging planes to generate a 3D spatial model. Dynamic RSA is now capable of capturing these X-ray images at rates of up to 250 frames per second that allows the kinematics of the joint to be modelled.

The major limitation of RSA, however, is the need to implant tantalum beads under general anaesthetic. Therefore, studies of pre-operative kinematics or healthy joints are rare. Tashman et al. [4] proposed an alternative approach to register 3D CT data of a bone with two different simultaneous fluoroscopy frames and then combining the information to obtain 3D modelling or kinematic performance. This method is non-invasive but otherwise similar to RSA. The main limitation of this approach is, like RSA, the requirement for a double dose of radiation and the limited field of view provided by two different fluoroscopes operating concurrently. More recently, single-plane fluoroscopy based schemes have been proposed in the literature [5]-[8]. These methods use much less radiation for the same purpose and allow more natural activities or movement of joints. However, the main limitation of this approach has been the inaccuracy in measuring six degrees of freedom or movement because of a single view as opposed to dual-plane based schemes [4]. Although in-plane rotation and translations are easier to measure, determining out-of-plane movement (which results from the bone moving towards or away from the x-ray source) is often quite challenging. Large out-of-plane movements frequently result in very small changes in scale or shape in the projection of a bone, thereby making it very difficult to evaluate precisely. Fregly et al. [5] and Dennis et al. [6] have reported precisions for in-plane translation registration error of 0.42 mm and 0.46 mm. However, the reported precision for out-of-plane translation was 5.6 and 3.03 mm, respectively.

The authors have recently developed a 2D-3D registration algorithm which uses a new similarity measure and a fast gradient-based algorithm [7]. The aim of this paper is to compare the kinematic measurements produced by this new algorithm with those produced by RSA. To perform this comparison, RSA and fluoroscopy images were captured simultaneously while cadaveric knees were passively flexed between 0 to 90 degrees.

The rest of the paper is organised as follows. In section II, we describe the new algorithm and the experimental procedure used to obtain the kinematic measurements. The experimental results are presented in section III and some conclusions from these results are discussed in section IV.

II. 2D-3D Registration Algorithm

In this section, a brief description of the new registration algorithm [7] is described for the application of registering 3D CT data to 2D single plane fluoroscopy frames. However this new technique can be applied to any 2D-3D registration problem or any arbitrary human joints.

Image registration is the process of spatially aligning one image to another. This involves two core components – a similarity measure and an optimization technique. The optimization technique determines the transformation parameters that, when applied to one of the images, will

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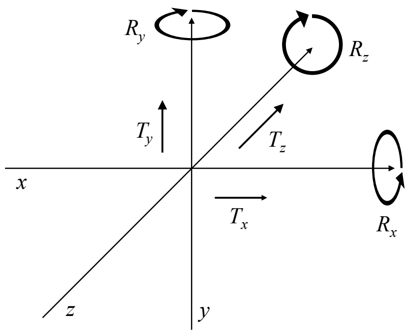

Figure 1. The 6 motion parameters to describe a 3D rigid-body motion.

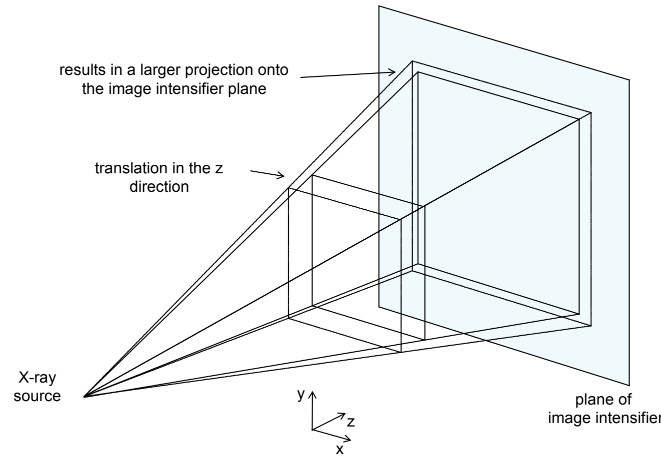

Figure 2. As an object moves closer to the X-ray source it will produce a larger image at the image intensifier of the fluoroscopy unit.

result in a global maximum of the similarity measure. When the similarity measure is maximized, the difference between two images is minimized or, in another words, they are spatially aligned.

The 3D rigid-body motion of an object or bone in this context can be described by 6 motion parameters. These 6 parameters control translation in the *x* (anterior-posterior), *y* (proximal-distal) and *z* (medial-lateral) directions (denoted by T_x, T_y and T_z respectively) and rotation about the *x*, *y* and *z* axes (denoted by R_x, R_y and R_z respectively) as shown in Figure 1.

During every iteration of the registration algorithm, a 3D rigid-body geometric transform is applied to the CT volume to produce a change in the 3D position of the bone. A perspective transform is also applied to duplicate the conical spread of the X-rays during the capture of fluoroscopy frames. The 3D volume is then reduced to a 2D digitally reconstructed radiograph (DRR) by summing the voxel values of the transformed CT volume in the *z* direction.

The algorithm then calculates a value for a similarity measure to determine how well the bones in the DRR and fluoroscopy are aligned. A new mutual information based similarity measure called sum of conditional variances (SCV) is utilized which requires less computation and provides good accuracy [1,7]. The gradients of the similarity measure with respect to the 6 motion parameters are also calculated and these gradients are used to determine the direction in which to move the 3D volume for the next iteration.

To increase the range of initial displacements for which the algorithm will converge to the global maximum, a coarse-to-fine approach is adopted. This approach enables the algorithm to successively produce a more accurate registration result. A standard Gauss-Newton gradient based optimization algorithm [11] was used with gradients calculated using the method defined by Wang and Vemuri [2].

The X-ray beams in the fluoroscopy unit diverge from a common point as they pass through the knee and arrive at the image intensifier. Consequently, as an object moves closer to the X-ray source, it will produce a larger image at the image intensifier (see Figure 2). Hence relative translation in the *z* direction is estimated by a change in scale of the object in the fluoroscopy frame. However, this change in scale is usually difficult to measure precisely as a large translation in the *z* direction will result in only a very small scale change in the fluoroscopy frame. The effect of this conical spread can be modelled as a perspective transform applied on the 3D CT data.

In order to accurately determine the scale change due to out-of-plane translation (in this case in the *z* direction), a 400mm×400mm perspex calibration box was used. The front and back planes of the box have tantalum beads implanted on them in a regular grid pattern. The perspective transform parameter W_z can be calculated as follows:

$$W_z = \frac{(a/b - 1)}{d} \tag{1}$$

Here *d* is the distance between two parallel planes, *a* is the distance between two beads in the plane closer to the x-ray source (front) as projected in the fluoroscopy frame and *b* is the projected distance between two parallel beads in the other (back) plane. The beads are spaced equally in both the planes but their projection will differ due to the conical spread. For our fluoroscopy unit, we have measured the perspective transform parameter W_z to be 0.0009. That is, a movement of 1 pixel in the *z* direction will correspond to a scale change of 0.0009.

A. Kinematic Analysis

To evaluate the performance of the proposed algorithm, two cadaveric knees - 71 (female) and 109 (male) were utilized. Tantalum beads were inserted in the shaft and epicondyle section of each femur and tibia. Figure 3 shows an example DRR for knee 71 with the position of the tantalum beads clearly visible. These beads do not assist the proposed registration algorithm in any way. However, the beads are essential for kinematic analysis in RSA.

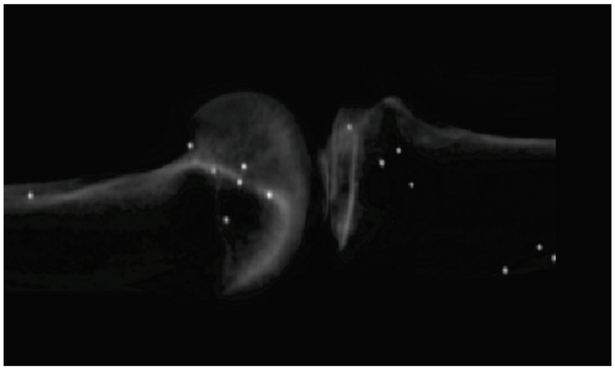

Figure 3. A DRR of cadaver knee 71 in the neutral position. The tantalum beads can be seen as white circles.

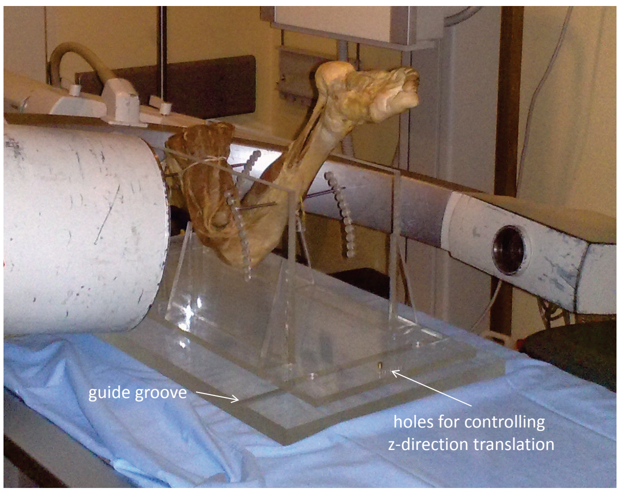

Figure 4. Experimental apparatus for the simultaneous capture of Flurosocopy and RSA images.

The anatomical coordinate system of the femur and the tibia were defined based on a neutral position where the cadaver knee is fully extended as shown in Figure 3. At this position, the proximal-distal axes of the segments coincide with the vertical or y axis, anterior-posterior axes with the x axis and medio-lateral axes with the z axis. This allows a consistent coordinate system for both the bones and the beads inserted into them. A singular-value decomposition method [9] was used to calculate the transformation matrices between the femur and tibia coordinate systems. Knee rotations angles – flexion/extension, abduction/adduction and internal/external rotation were expressed in terms of Cardan angles [10] and determined from a few specific beads. It is worth noting that only 3 non-colinear beads from each bone were used to perform the kinematic analysis. However, more beads are preferred for good accuracy. Knee abduction was defined as the tibial abduction relative to the femur and internal/external rotation as the tibial rotation relative to the femur.

A 230 mm Steinman pin was inserted in each lower limb specimen, 150 mm proximal and 150 mm distal to the lateral epicondyle of the femur in the coronal plane. A separate

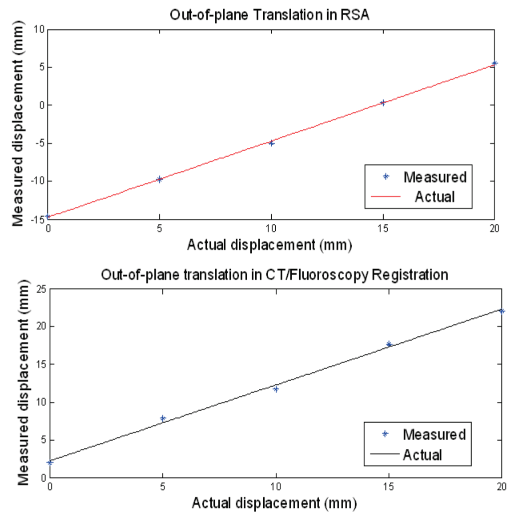

Figure 5. Out-of-plane translation accuracy of femur, knee 71

TABLE 1: STANDARD DEVIATION OF REGISTRATION ERROR FOR OUT-OF-PLANE TRANSLATION (mm)

Knee	Bone	RSA	CT/Fluoroscopy Registration
71	Femur	0.18	0.49
	Tibia	0.22	0.43
109	Femur	0.16	0.44
	Tibia	0.21	0.48
	Average	0.15	0.42

TABLE 2: COMPARISON OF REGISTRATION ERRORS

Registration Method	Out-of-plane Translation (mm)
Proposed	**0.42**
Fregly et al. [5]	5.6
Dennis et al. [6]	3.03

transparent Perspex cage was built to hold the knee in different positions and prevent the knee from moving while the images were captured as shown in Figure 4.

The knees were flexed between 0 and 90 degrees. For each position, a fluoroscopy frame was captured for 2D-3D registration. Two orthogonal X-rays were also captured using the calibrated grid specially designed for RSA analysis.

III. EXPERIMENTAL RESULTS

For our first experiment, each knee was placed in the neutral position (fully extended) inside the perspex cage. The cage is able to slide laterally on a base plate with excursions controlled by pin holes at 5 mm intervals (see Figure 4). The cage was moved towards the fluoroscopy X-ray source by 20 mm in increments of 5 mm. For all cases, the knee was kept still in the neutral position. The cage was moved in order to simulate out-of-plane or medio-lateral translation (denoted by T_z). For every position, two X-rays (for RSA processing)

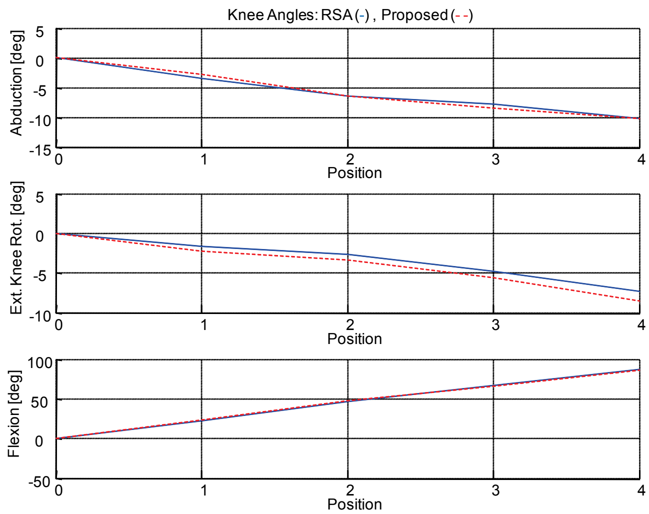

Figure 6. Kinematic analysis for knee 71.

and a fluoroscopy image was captured. We then apply the 2D-3D registration algorithm to register the CT data of the knee to each fluoroscopy frame and hence obtain the true 3D pose for each bone. Figure 5 shows the calculated T_z versus the actual displacement in RSA and the proposed method for the femur of knee 71. The precision of the RSA measurements agree with those reported in the literature which validates our experimental procedure. The precision of the new algorithm is very close to that of RSA. The individual standard deviations, as shown in Table 1, are less than 0.5 mm in all cases and the average standard deviation of error (calculated from all the measurements) was 0.42 mm, which is much smaller than the previously reported results of Fregly et al. [5] and Dennis et al. [6] as shown in Table 2.

Next, we perform kinematic analysis using the improved 2D-3D registration algorithm and compare the performance with that of the standard RSA method. In this case, each lower limb was placed prone into the Perspex frame. The Steinman pins lock into holes drilled on either side of the frame. Moving the pins to a different hole creates a range of knee flexion positions. We start with the neutral or fully extended position denoted by position '0' in Figure 6, which has a flexion of 0 degrees. Following that, the knees were flexed in increments of approximately 20 degrees to reach the 90 degrees flexed position denoted by position '4'. For each position, RSA and fluoroscopy data were captured simultaneously. Three beads were selected from each bone and different knee angles were calculated as shown in Figure 6. The same kinematic analysis was performed using the position of the same 3 beads calculated via RSA.

It can be seen here that all the curves produced by the proposed method and RSA have good agreement in shape. The flexion angles measured by both schemes show very good similarity with a mean error of -0.05 degrees and standard deviation of 0.87 degrees. The abduction angles are very close with a mean error of 0.03 and standard deviation of 0.42 degrees. External knee rotation (tibial) is also very similar in shape but with a mean error in this case of 0.68 and standard deviation of 0.45 degrees.

IV. CONCLUSION

In this paper, we have presented an improved 3D CT to 2D single-view fluoroscopy registration algorithm. It is shown here that the proposed scheme is able to measure out-of-plane movements more precisely than other methods in the literature. Moreover, kinematic measurements produced by this new scheme are very similar to that of standard RSA. The major advantages of this method are that it eliminates the need for implanting tantalum beads and the use of a double dose of radiation as used in RSA or dual-plane fluoroscopy based schemes. Therefore, it will enable comparative studies of the kinematics of healthy knees with those of injured or arthritic knees pre- and post-surgery.

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