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Technical note

An interpolation technique to enable accurate three-dimensional joint kinematic analyses using asynchronous biplane fluoroscopy

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ABSTRACT

Biplane 2D-3D model-based registration and radiostereometric analysis (RSA) approaches have been commonly used for measuring three-dimensional, in vivo joint kinematics. However, in clinical biplane systems, the x-ray images are acquired asynchronously, which introduces registration errors. The present study introduces an interpolation technique to reduce image registration error by generating synchronous fluoroscopy image estimates. A phantom study and cadaveric shoulder study were used to evaluate the level of improvement in image registration that could be obtained as a result of using our interpolation technique. Our phantom study results show that the interpolated bead tracking technique was in better agreement with the true bead positions than when asynchronous images were used alone. The overall RMS error of glenohumeral kinematics for interpolated biplane registration was reduced by 1.27 mm, 0.40 mm, and 0.47 mm in anterior-posterior, superior-inferior, and medial-lateral translation, respectively; and 0.47°, 0.67°, and 0.19° in ab-adduction, internal-external rotation and flexion-extension, respectively, compared to asynchronous registration. The interpolated biplane registration results were consistent with previously reported studies using custom synchronous biplane fluoroscopy technology. This approach will be particularly useful for improving the kinematic accuracy of high velocity activities when using clinical biplane fluoroscopes or two independent c-arms, which are available at a number of institutions.

1. Introduction

The notion of registering 3D bone volumes to fluoroscopic images in order to quantify 3D joint kinematics in vivo has been studied for several decades [1]. Biplane fluoroscopy is a highly accurate way to measure 3D joint kinematics, using two common techniques of bead tracking (fluoroscopic radiostereometric analysis (RSA)) or 2D-3D model-based registration [2–13]. When imaging a moving object, the accuracy of the estimated 3D bone pose using these techniques is very sensitive to the synchronicity of image acquisition between the two planes.

Custom-built biplane fluoroscopy systems have commonly been used for conducting 3D joint kinematic analyses [2,3,6,7,11]; however, these systems are not available at most institutions. On the other hand, clinical biplane systems, which are FDA-approved for clinical use and more widely available, are limited in their utility due to the fact that images are intentionally acquired asynchronously to reduce the effects of cross-scattering [14]. The magnitude of error introduced into conventional registration process due to asynchrony in image acquisition depends on the speed of movement and fluoroscopy frame rate. Thus, achieving accurate 3D kinematics using conventional 2D-3D registration techniques with asynchronous biplane images is challenging, especially for faster movements.

To overcome the limitations associated with asynchronous image acquisition, we propose an interpolation algorithm that generates simulated corresponding fluoroscopy images, thus producing “approximately-synchronous” image pairs.

The main goal of this study was to determine improvement in 2D-3D image registration that could be obtained as a result of using this novel approach. To evaluate the efficacy of our interpolation technique independent from the joint being studied, we first performed a phantom study. We also evaluated the effectiveness of our algorithm on reducing 2D-3D model-based registration error by performing a cadaveric shoulder study. A 3D interpolation method has recently been used to accurately quantify spine kine-

Abbreviations: Asynch, asynchronous; DRR, digitally reconstructed radiograph; FP, frontal plane; SP, sagittal plane; GH, glenohumeral.

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matics from a minimum data sample size [15]. However, to our knowledge, no study has addressed the limitations associated with asynchronous image acquisition of clinical biplane fluoroscopic systems for evaluating joint kinematics. Thus, this technique will allow researchers to use clinical biplane systems or two independent c-arms to acquire semi-synchronous biplane images while still achieving accurate descriptions of 3D kinematics.

2. Method

2.1. Asynchronous biplane registration

In asynchronous biplane registration, 2D projections of 3D bone volumes were registered to the offset biplane images under the assumption that they were acquired synchronously. Registration is performed by finding the optimal match between digitally reconstructed radiographs (DRR), to fluoroscopy images from both planes. The process is initialized by manually adjusting the bone position and orientation until a visual match between the projection of the bone model and fluoroscopy image is obtained. Then, the position is optimized automatically to maximize the normalized cross correlation between the grayscale values of the DRR and radiograph [16].

2.2. Interpolated biplane registration

In the proposed interpolation algorithm, the bone models are registered independently to each image plane first using single-plane registration (Fig. 1a, b and c). Pose interpolation is applied between successive frames to estimate the bone pose at the time point between each acquisition (Fig. 1b and c). To do so, the rigid body transformations are converted to kinematic parameters (3 translation and 3 rotations), using an XZ′Y″ Euler rotation sequence, and then interpolated using spline interpolation.

The interpolation technique requires kinematics data from at least 4 successive frames and is accomplished with a cubic spline using not-a-knot end conditions [17]. This allows the change in bone acceleration to be approximated during each time interval. For this study, the kinematic data was interpolated for the entire trial for each image plane. With the pose determined for the missing time point, we can then create a 2D projection of the 3D volume given the known position of the source and detector. A Matlab script (version 9.0.0.341360 (R2016a)) was developed to generate DRRs from the CT volumes using a standard ray casting approach [18–20]. This generates the missing image which coincides with the time point of the corresponding fluoroscopy image from image plane2 (Fig. 1b). The same process is repeated for image plane2 (Fig. 1c). The 3D bone models are then registered to each set of interpolated biplane images in order to determine the joint movement (Fig. 1d).

A similar algorithm was used to generate interpolated biplane images of the beads for bead tracking analysis. Knowing the 3D position of the beads from the CT volumes, an optimization algorithm was used to register the 3D bead cluster to the single plane fluoroscopy images by minimizing the distance between the projected landmarks and the beads in the image. Then, the kinematics were interpolated using spline interpolation in order to generate the missing time point data.

2.3. Image acquisition

A clinical flat-panel biplane fluoroscope (Siemens Artis Zee; Forchheim Germany) was used for all 2D imaging (Fig. 2a; Fig. 3a). Biplane fluoroscopic images of the shoulder were acquired at 15 frames/s for each source (30 frames/s for asynchronous biplane acquisition; *source 1:* 70 kVp, 320 mA, pulse width 3.6 ms, source-to-detector distances (SID): 105 cm; *source 2:* 82 kVp, 570 mA, pulse width 12 ms, SID: 120 cm; inter-beam angle: 60°). An oscilloscope was used to confirm that the offset between the pulsing of each x-ray source was constant. A custom Plexiglas calibration cube, with 64 stainless steel beads (3 mm diameter) placed 65 mm apart in a grid shape (machine tolerance of ±0.005 mm), was imaged to determine the orientation of the x-ray sources and detectors [8].

CT imaging of the shoulder (full scapula and humerus) was conducted on a clinical CT scanner (128-slice SOMATOM Definition Flash; Siemens Healthcare) with slice thickness: 0.75 mm; slice increment: 0.35 mm; kVp: 120; FOV: 200 mm; Kernel: B40s; and pixel image size: 512 × 512.

2.4. Phantom study

In order to evaluate the efficacy of our interpolation technique independent from the joint being studied, we performed a phantom study. Additionally, this provides a quantification of our interpolated bead tracking translational and rotational errors. Different approaches have been used for validation of bead tracking [21–24]. For example, a phantom with accurately known bead positions or comparison with an existing accurate RSA system may be used for validation of a new system. In this study, a Plexiglas cube phantom with two non-coplanar bead sets, comprised of three beads each, (3 mm diameter; positioning tolerance of ±0.005 mm) was suspended using a nylon cord allowing it to spin randomly throughout the field of view of the biplane fluoroscope (Fig. 2a). The phantom movements were binned into one of three separate speed categories of slow, moderate and fast by calculating the average speed across frames. The relative 6 DOF translations and rotations between two coordinate frames, assigned to 2 non-coplanar bead sets, were used to estimate bead tracking translational and rotational errors (Fig. 2b). Because the beads are rigidly fixed, frame-to-frame variations in these measures provides a direct estimate of the uncertainty in bead tracking. These errors were calculated for three different movement speeds of the phantom; slow (average angular velocity (AAV): ~87 °/s), moderate (AAV: ~179 °/s), and fast (AAV: ~332 °/s). Inter-bead distances between the six beads were also measured and compared to the known machined distances.

2.5. Cadaveric study

With approval from our institutional biospecimens committee, 1 intact fresh-frozen cadaver torso (age: 82 years) was obtained from our anatomical bequest program. One millimeter tantalum beads were implanted into the humerus and scapula of the right shoulder of the specimen. Five beads were implanted into the humerus, widely distributed throughout the humeral head. Six beads were implanted into the scapula, in the acromion, scapular spine, glenoid neck, and coracoid process. The cadaveric torso was fixed in a custom apparatus that allowed free movement of the humerus and scapula, and the glenohumeral (GH) joint was centered in the imaging volume of the biplane fluoroscope (imaging set-up is shown in Fig. 3a).

The shoulder was manually manipulated in 3 motion activities: (1) frontal-plane (FP) elevation (from neutral position of arm to max abduction); (2) sagittal-plane (SP) elevation (from max extension to max flexion); and (3) internal-external rotation (from max internal rotation to max external rotation about the long axis of the humerus). The average absolute linear velocity, angular velocity and angular acceleration of the bones were quantified from the kinematic analysis.