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A comparison of calibration methods for stereo fluoroscopic imaging systems ☆

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ABSTRACT

Stereo (biplane) fluoroscopic imaging systems are considered the most accurate and precise systems to study joint kinematics *in vivo*. Calibration of a biplane fluoroscopy system consists of three steps: (1) correction for spatial image distortion; (2) calculation of the focus position; and (3) calculation of the relative position and orientation of the two fluoroscopy systems with respect to each other. In this study we compared 6 methods for calibrating a biplane fluoroscopy system including a new method using a novel nested-optimization technique. To quantify bias and precision, an electronic digital caliper instrumented with two tantalum markers on radiolucent posts was imaged in three configurations, and for each configuration placed in ten static poses distributed throughout the viewing volume. Bias and precision were calculated as the mean and standard deviation of the displacement of the markers measured between the three caliper configurations.

The data demonstrated that it is essential to correct for image distortion when sub-millimeter accuracy is required. We recommend calibrating a stereo fluoroscopic imaging system using an accurately machined plate and a calibration cube, which improved accuracy 2–3 times compared to the other calibration methods. Once image distortion is properly corrected, the focus position should be determined using the Direct Linear Transformation (DLT) method for its increased speed and equivalent accuracy compared to the novel nested-optimization method. The DLT method also automatically provides the 3D fluoroscopy configuration. Using the recommended calibration methodology, bias and precision of 0.09 and 0.05 mm or better can be expected for measuring inter-marker distances.

1. Introduction

Single-plane or stereo (biplane) fluoroscopic imaging systems used to measure joint implant motion (Garling et al., 2007; Banks and Hodge, 1996) or *in vivo* joint motions (Li et al., 2008; Anderst et al., 2009; You et al., 2001; Bey et al., 2006; Torry et al., 2010) are considered the most accurate and precise systems to study joint kinematics *in vivo* without soft tissue artifacts (Garling et al., 2007; Banks and Hodge, 1996). A disadvantage of single-plane fluoroscopy is the low out-of-plane accuracy (Hirokawa et al., 2008; Prins et al., 2010), which is eliminated by using a biplane fluoroscopy system (Li et al., 2008; Anderst et al., 2009; You et al., 2001; Bey et al., 2006; Tashman and Anderst, 2003; Brainerd et al., 2010). However, this comes at the expense of a higher radiation dose, a potentially less practical experimental setup, as well as a more complex calibration procedure to determine the 3D configuration of the two fluoroscopy systems.

The purpose of this study was to determine the performance of a new calibration method which included a novel nested-optimization technique in comparison to established calibration methods in search for a cost-effective and most accurate way to calibrate a biplane fluoroscopy system. Therefore, we compared five different methods to calibrate a biplane fluoroscopy system. In addition, the effect of image distortion correction was quantified. The calibration methods were evaluated by measuring 3D inter-marker distances and comparing them with a reference measurement (Brainerd et al., 2010; Tashman and Anderst, 2003).

2. Methods

2.1. Experimental hardware

Two B.V. Pulsera C-arms (Philips Medical Systems, Best, The Netherlands) with synchronized control systems were placed at an angle of approximately 80° to form a biplane fluoroscopy system. This configuration was based on *in vivo* experiments performed with this system. The C-arms contained 30 cm image intensifiers with a

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