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A novel multi-planar radiography method for three dimensional pose reconstruction of the patellofemoral and tibiofemoral joints after arthroplasty

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ABSTRACT

Determining the 3D pose of the patella after total knee arthroplasty is challenging. The commonly used single-plane fluoroscopy is prone to large errors in the clinically relevant mediolateral direction. A conventional fixed bi-planar setup is limited in the minimum angular distance between the imaging planes necessary for visualizing the patellar component, and requires a highly flexible setup to adjust for the subject-specific geometries. As an alternative solution, this study investigated the use of a novel multi-planar imaging setup that consists of a C-arm tracked by an external optoelectric tracking system, to acquire calibrated radiographs from multiple orientations. To determine the accuracies, a knee prosthesis was implanted on artificial bones and imaged in simulated 'Supine' and 'Weightbearing' configurations. The results were compared with measures from a coordinate measuring machine as the ground-truth reference. The weightbearing configuration was the preferred imaging direction with RMS errors of 0.48 mm and 1.32° for mediolateral shift and tilt of the patella, respectively, the two most clinically relevant measures. The 'imaging accuracies' of the system, defined as the accuracies in 3D reconstruction of a cylindrical ball bearing phantom (so as to avoid the influence of the shape and orientation of the imaging object), showed an order of magnitude (11.5 times) reduction in the out-of-plane RMS errors in comparison to single-plane fluoroscopy. With this new method, complete 3D pose of the patellofemoral and tibiofemoral joints during quasi-static activities can be determined with a many-fold (up to 8 times) (3.4 mm) improvement in the out-of-plane accuracies compared to a conventional single-plane fluoroscopy setup.

1. Introduction

Measurements of the positions and orientations (pose) of the prosthesis components after knee arthroplasty are essential for investigating postoperative complications such as anterior knee pain, abnormal kinematics, particularly patellar maltracking (Baldini et al., 2007), and to compare patients with different prosthesis designs. However, each of the current measurement techniques has limitations with respect to measuring patellofemoral kinematics.

Although single-plane fluoroscopy has been used to measure tibiofemoral kinematics and patellar flexion in normal knees and after knee arthroplasty (Banks and Hodge, 1996; Mahfouz et al., 2003; Komistek et al., 2003), its accuracy for measuring the clinically relevant medial–lateral shift and tilt of the patella is recognized as inadequate. Abnormal postoperative patellar tracking has been defined as more than 5 mm mediolateral shift or more than 5° mediolateral tilt (Shih et al., 2004). The recommended ideal accuracy of an imaging system is one order of magnitude smaller than the measurement of interest (Bey et al., 2008), thus ± 0.5 mm for translations and $\pm 0.5°$ for rotations. In single-plane fluoroscopy, acceptable levels of accuracy can be obtained for all degrees of freedom except for the translations along the axis orthogonal to the image plane with reported RMS errors of up to 3.9 mm (Fregly et al., 2005). Although more advanced registration algorithms have been suggested (Hoff et al., 1998; Kaptein et al., 2003; Yamazaki et al., 2004; Hirokawa et al., 2008), out-of-plane inaccuracy remains a limitation of single-plane fluoroscopy.

Conventional bi-planar fluoroscopy cannot generally be used to measure patellofemoral kinematics after knee arthroplasty, although this method has been used to accurately measure the kinematics of the natural tibiofemoral (TF) and PF joints (Asano et al., 2001; Valstar et al., 2001; You et al., 2001; Kaptein et al., 2003; Varadarajan et al., 2008; Suggs et al., 2009). The challenge with

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