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Short communication

Accuracy of a contour-based biplane fluoroscopy technique for tracking knee joint kinematics of different speeds

J. Erik Giphart [a,*], Christopher A. Zirker [a], Casey A. Myers [a], W. Wesley Pennington [a], Robert F. LaPrade [b]

[a] Department of BioMedical Engineering, Steadman Philippon Research Institute, 181 West Meadow Drive, Suite 1000, Vail, Colorado 81657, USA
[b] The Steadman Clinic, Vail, CO, USA

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ABSTRACT

While measuring knee motion in all six degrees of freedom is important for understanding and treating orthopaedic knee pathologies, traditional motion capture techniques lack the required accuracy. A variety of model-based biplane fluoroscopy techniques have been developed with sub-millimeter accuracy. However, no studies have statistically evaluated the consistency of the accuracy across motions of varying intensity or between degrees of freedom. Therefore, this study evaluated the bias and precision of a contour-based tracking technique by comparing it to a marker-based method (gold standard) during three movements with increasing intensity. Six cadaveric knees with implanted tantalum markers were used to simulate knee extension, walking and drop landings, while motion was recorded by a custom biplane fluoroscopy system. The 3D geometries of the bones were reconstructed from CT scans and anatomical coordinate systems were assigned. The position and orientation of the bone and marker models were determined for an average of 27 frames for each trial and knee joint kinematics were compared. The average bias and precision was $0.01\pm0.65^{\circ}$ for rotations and 0.01 ± 0.59 mm for joint translations. Rotational precision was affected by motion ($p=0.04$) and depended on the axis of rotation ($p=0.02$). However, the difference in average precision among motions or axes was small ($\leq 0.13^{\circ}$) and not likely of consequence for kinematic measurements. No other differences were found. The contour-based technique demonstrated sub-millimeter and sub-degree accuracy, indicating it is a highly accurate tool for measuring complex three dimensional knee movements of any intensity.

1. Introduction

While the knee may generally be considered a hinge joint, it is a complex joint with motion occurring in all six degrees of freedom. These complex motions must be measured accurately to address clinical needs, because many knee pathologies result in motions occurring outside of flexion/extension (Lafortune et al., 1992). Motion capture techniques using optical markers placed on the skin have been reported to provide insufficient accuracy for measuring most degrees of freedom of the knee (Ramsey and Wretenberg, 1999; Reinschmidt et al., 1997a, b).

Biplane fluoroscopy using implanted radiopaque markers was developed to track *in vivo* knee joint kinematics with greatly improved accuracy over other motion capture techniques (You et al., 2001). While this marker-based method is highly accurate, surgical implantation of markers especially limits the recruitment of non-surgical patients. A variety of model-based tracking techniques have been developed with sub-millimeter accuracy, which instead use anatomical features to determine kinematics (Anderst et al., 2009; Bey et al., 2008; Li et al., 2008). However, no studies have statistically evaluated the consistency of the bias and precision of the measurement technique across motions with increasing degrees of velocity and impact, or between the different degrees of freedom. The purpose of this study was to determine if contour-based tracking of the knee was equally accurate across a range of motions of varying velocity and impact, and if bias and precision varied between degrees of freedom. Our hypothesis was that bias and precision would be independent of motion and degree of freedom.

2. Methods

2.1. Specimen preparation and motion simulation

Six non-paired, fresh–frozen cadaveric knees were prepared for marker-based tracking by implanting five 1.6 mm tantalum beads into the subchondral bone of both the distal femur and proximal tibia through small incisions. No soft tissue was removed and the incisions were closed. Three *in vivo* knee motions of increasing speed and impact were simulated: knee extension, the stance phase of walking and a drop landing. For knee extension, the femur was rigidly mounted in a specimen holder (Pacific Research Laboratories Inc., Vashon, Washington; Fig. 1) and was extended from 90° of flexion to full extension over a 2 s period by a pulley system. For the simulated stance phase of walking, the specimens were slowly swung

* Corresponding author. Tel.: +1 970 479 5848; fax: +1 970 479 9753.
E-mail address: erik.giphart@sprivail.org (J.E. Giphart).
URL: http://www.sprivail.org (J.E. Giphart).

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through the capture volume of the biplane fluoroscopy system. For the simulated drop landing, the specimens were dropped from a 40 cm height, while the distal tibia was rigidly fixed in a plastic cap attached to a tube that was free to slide over a post.

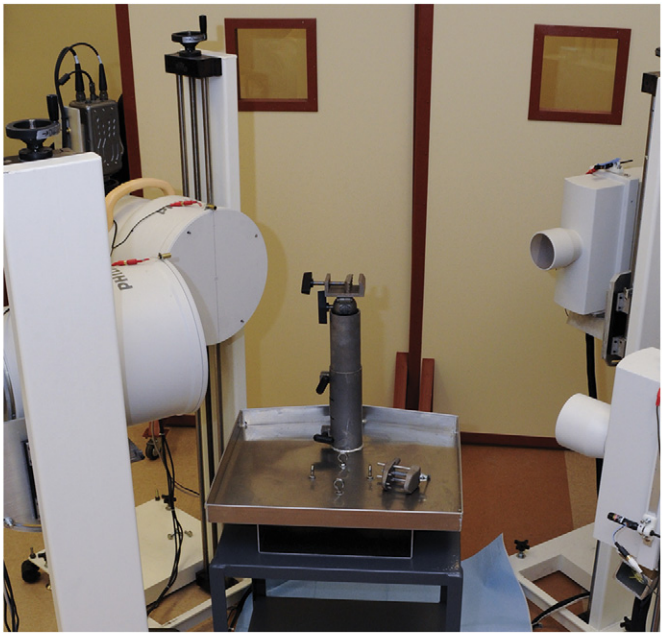

Fig. 1. Photo of the biplane fluoroscopy system with the specimen holder positioned as used for the knee extensions. The two fluoroscopy systems were placed at a 70° angle of each other to create the 3D viewing area in which the specimens were imaged.

2.2. Data collection

For each motion, images were recorded using a custom biplane fluoroscopy system (Fig. 1) constructed from two BV Pulsera *C*-arms (30 cm image intensifiers; Philips Medical Systems, Best, The Netherlands) which were synchronized and modified under appropriate FDA guidelines and State Radiation Safety Regulations. For this study, the gantry was configured with an inter-beam angle of 70° and a source-to-image distance of 1.5 m. Images were recorded using two digital cameras (resolution: 1024×1024 pixels; Phantom V5.1, Vision Research, Wayne, NJ) interfaced with the image intensifiers. The biplane fluoroscopy system was calibrated prior to the start of data collection (Kaptein et al., 2011). For the knee extension motion, data was recorded at 100 Hz with a 9 ms shutter speed with the X-ray generators operated in ''continuous'' mode (72 kVp, 20 mA). For the landing and walking motions, data was recorded at 500 Hz with a 0.5 ms shutter speed with the X-ray generators operated in ''radiographic'' mode (60 kVp, 60 mA). Both settings are customary at our institution for imaging the knee (Myers et al., 2011; Torry et al., 2011). CT scans (voxel size: approximately $0.7 \times 0.7 \times 0.5$ mm^3) of all specimens were obtained at 120 kVp and 200 mA using a bone reconstruction technique (Aquilion 64, Toshiba America Medical Systems, Tustin, CA).

2.3. Data analysis

The 3D geometries of the femur, tibia and fibula were extracted from the CT data (Mimics, Materialize, Inc., Plymouth, MI). Marker models of the bead configurations were created in Model-Based RSA (Medis Specials, Leiden, The Netherlands) (Garling et al., 2005). Custom software written in MATLAB (The Mathworks, Natick, MA) was used to assign anatomical coordinate systems to the bones (Grood and Suntay, 1983) and to transform the bones to positions suitable for 3D tracking. Determination of the 3D bone and marker model positions and orientations from the biplane fluoroscopy data were also performed using Model-Based RSA (Fig. 2) (Kaptein et al., 2003). For the bones, edges were automatically detected in the fluoroscopic images using a Canny edge-detection filter (Canny, 1986) and manually assigned as contours of the femur and tibia/fibula. A fully-automatic optimization algorithm (a combined downhill simplex and simulated annealing algorithm; Press et al., 1994) was

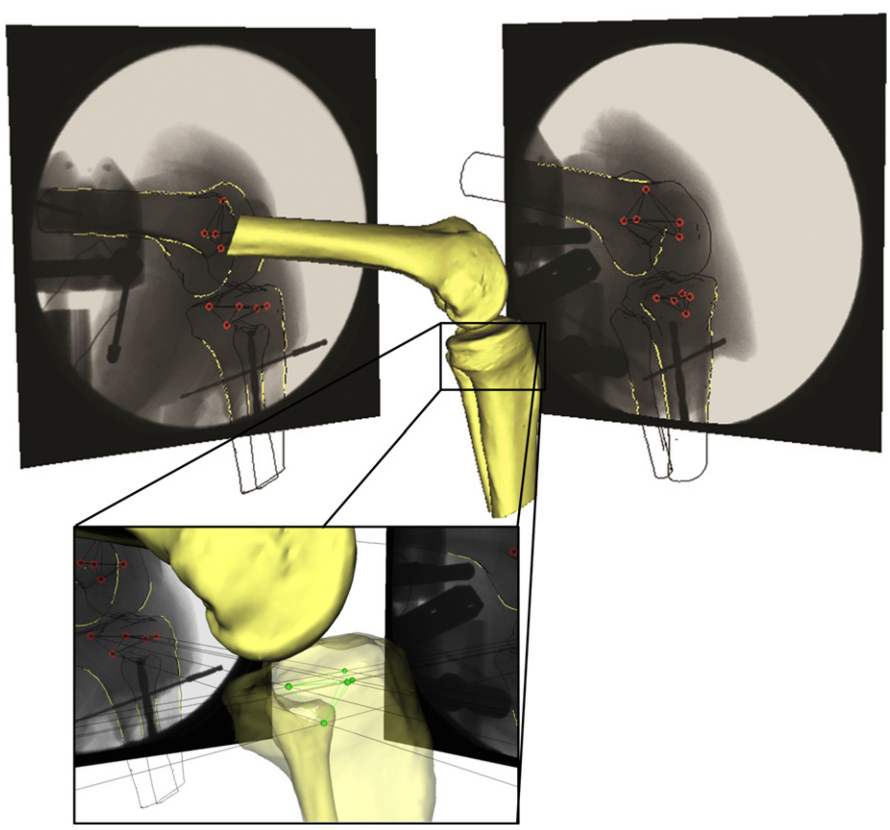

Fig. 2. The position and orientation of the 3D bone models of the femur and tibia/fibula reconstructed from CT data were manipulated in 3D space such that contours from the projections of the bone models (black lines) optimally matched the bone contours identified in the fluoroscopy images (light lines). The markers were automatically identified in the fluoroscopy images (circles) and the position and orientation of the marker models were manipulated such that the marker positions optimally matched the projection lines (inset).

used to find the position and orientation of each bone model that minimized the distance between the contours projected from the model and the contours detected in the fluoroscopic images (Kaptein et al., 2004). The markers in the femur and tibia were automatically detected in the images, and the same fully-automatic optimization algorithm was used to find the position and orientation of each marker model that minimized the distance between the projection lines of the detected markers and their corresponding marker location from the marker models (Fig. 2 inset). A reference frame was used to determine the transformation between the bone and marker models and their corresponding anatomical coordinate systems such that knee kinematics could be calculated based on the bone and marker models independently. Knee joint kinematics (Grood and Suntay, 1983) were calculated using the custom software written in MATLAB for each tracked frame.

2.4. Parameter extraction and statistical analysis

For each motion, bias and precision (ASTM, 1996) were determined by calculating the mean (bias) and standard deviation (precision) of the difference in joint kinematics between the bone- and marker-model based method of tracking for between 25 and 30 frames per motion. A two-way ANOVA compared the bias and precision measurements with independent factors of motion (knee extension, walking, and drop landing) and degree of freedom (the three axes of rotation and translation, respectively). Bias and precision for rotation and translation were analyzed separately. If significant main effects were found, Bonferroni-corrected post-hoc comparisons were performed. Statistical significance was defined as $p<0.05$.

3. Results

A comparison between the kinematics measured using the marker and bone models for one specimen is shown in Fig. 3. For all three motions and all degrees of freedom, the mean bias and precision were sub-millimeter and sub-degree (Tables 1 and 2). The overall average bias and precision was $0.01\pm0.65^{\circ}$ for rotations and 0.1 ± 0.59 mm for translations.

Only the precision of rotation measurements was affected by motion ($p=0.04$) and depended on the axis of rotation ($p=0.02$).

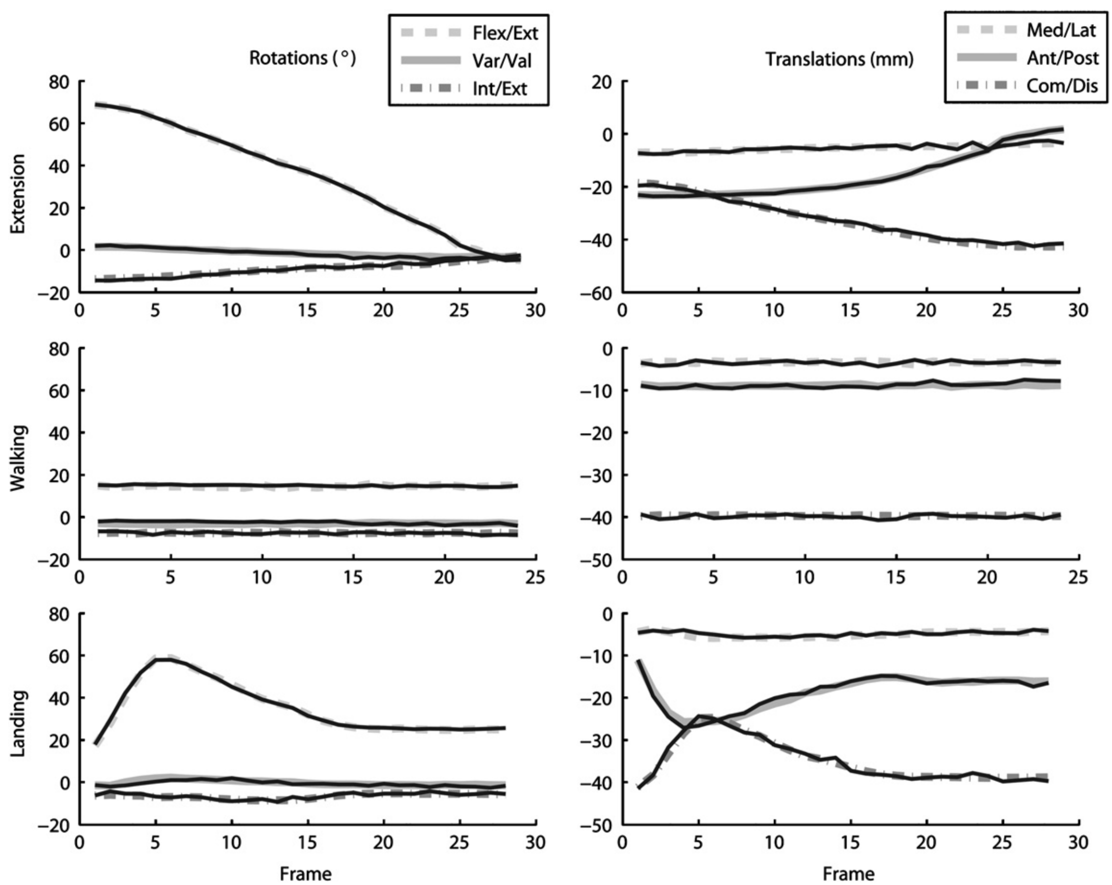

Fig. 3. Three dimensional kinematics based on the marker models (thick grey lines) and bone models (thin black lines) for each degree of freedom and each motion for one trial of one specimen. Rotations and translations are determined based on the definition described by Grood and Suntay (1983).

Table 1
Bias and precision results for each degree of freedom of knee kinematics during the three motions. Values shown are the mean and standard deviation across the six knee specimens.

Degree of freedom	Extension		Walking		Landing	
	Bias	Precision	Bias	Precision	Bias	Precision
Flex/Ext (°)	0.03 ± 0.26	0.43 ± 0.15	0.00 ± 0.36	0.73 ± 0.10	-0.07 ± 0.23	0.67 ± 0.17
Var/Val (°)	-0.03 ± 0.20	0.61 ± 0.13	0.07 ± 0.23	0.63 ± 0.20	-0.02 ± 0.34	0.57 ± 0.12
Int/Ext (°)	-0.05 ± 0.21	0.69 ± 0.17	0.17 ± 0.49	0.76 ± 0.15	0.00 ± 0.20	0.75 ± 0.14
Med/Lat (mm)	0.27 ± 0.15	0.71 ± 0.11	0.09 ± 0.18	0.51 ± 0.19	0.12 ± 0.21	0.51 ± 0.08
Ant/Post (mm)	-0.02 ± 0.32	0.49 ± 0.15	0.24 ± 0.26	0.73 ± 0.25	0.03 ± 0.28	0.71 ± 0.13
Com/Dis (mm)	0.08 ± 0.24	0.60 ± 0.19	0.07 ± 0.17	0.57 ± 0.33	0.00 ± 0.03	0.46 ± 0.17

Table 2
Mean bias and precision measurements across all three motions for each degree of freedom of the knee. Values shown are the mean and standard deviation of the six test specimens.

Degree of freedom	Bias	Precision
Flex/Ext (°)	-0.01 ± 0.27	0.61 ± 0.19
Var/Val (°)	0.01 ± 0.25	0.60 ± 0.15
Ext/Int (°)	0.04 ± 0.32	0.73 ± 0.15
Med/Lat (mm)	0.16 ± 0.19	0.58 ± 0.16
Ant/Post (mm)	0.09 ± 0.29	0.64 ± 0.21
Com/Dis (mm)	0.05 ± 0.16	0.54 ± 0.23

The knee extension trials had greater precision ($0.58 \pm 0.18^\circ$) compared to walking ($0.71 \pm 0.16^\circ$) trials ($p = 0.03$). Measurement of internal/external rotation ($0.73 \pm 0.15^\circ$) was less precise than varus/valgus ($0.60 \pm 0.15^\circ$, $p = 0.03$) rotations and approached significance with the flexion/extension ($0.61 \pm 0.19^\circ$, $p = 0.06$). No other significant differences were found.

4. Discussion

The contour-based tracking technique described here was able to produce sub-millimeter and sub-degree accuracy in measuring the translations and rotations of the knee during increasingly dynamic motions when compared to marker-based tracking. Furthermore, bias and precision for translations as well as bias for rotations were independent of motion. However, rotation precision was significantly affected by both motion and axis of rotation. Therefore, our hypothesis was only partially confirmed. It must be noted, however, that the differences in rotation precision were small ($\leq 0.13^\circ$), and for most applications, this decrease in accuracy is sufficiently small to allow for accurate 3D testing of *in vivo* subjects.

Knee internal/external rotation was measured with less precision compared to the other rotations, because changes in flexion/extension and varus/valgus rotations both resulted in a change in location of the diaphysis of the bones in each image, while changes in internal/external rotation primarily only changed the shape of the contours. In addition, the radius of rotation was the shortest for internal/external rotation, thus minimizing the changes in the radiographs.

The accuracy of the biplane fluoroscopy tracking technique used in this study was similar to that of other validated model-based techniques. Li et al. (2008) reported biases of 0.2° and 0.2 mm with precisions of 0.6° and 0.2 mm. Their technique demonstrated similar bias and slight better precision in determining joint position, although their findings are limited in scope because they tested two specimens with inconsistent results. Anderst et al. (2009) tested three subjects while running on a treadmill and found greater mean biases for all degrees of freedom; however, the reported biases were not significantly different from zero. Mean precisions were all within 0.9° and 0.7 mm, but appeared to demonstrate greater dependence on the degree of freedom measured compared to the precisions presented here. However, this was not statistically tested.

In conclusion, the contour-based tracking technique used in this study produced measurements of sub-millimeter and sub-degree accuracy for all six degrees of freedom of the knee during all three motions of increasing impact and velocity.

Conflict of interest statement

The authors have no conflicts of interest to declare.

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Appendix A. Supplementary information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.jbiomech.2012.08.045.

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