Title

Error Analysis of Methods for Determining Tibiofemoral Kinematics in the Native Knee and After Total Knee Replacement: An in vivo Study Using Single-Plane Fluoroscopy During Weight-Bearing Deep Knee Bend

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Error Analysis of Methods for Determining Tibiofemoral Kinematics in the Native Knee and After Total Knee Replacement: An *in vivo* Study Using Single-Plane Fluoroscopy During Weight-Bearing Deep Knee Bend

By

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THESIS

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Abstract

Background:

One of the primary goals of total knee replacement is to restore native knee function. Tibiofemoral kinematics provides an objective measure of knee function and have been used to characterize and compare knee function among native (i.e., healthy), replaced, osteoarthritic, and anterior cruciate ligament (ACL) deficient knees. Tibiofemoral kinematics specifically refers to the relative rigid body motions of the tibia with respect to the femur in all six degrees of freedom. Quantification of clinically meaningful tibiofemoral kinematics requires a joint coordinate system where motions are free from kinematic crosstalk errors.

One common method to determine tibiofemoral kinematics is to capture single-plane fluoroscopic images of a patient activity and determine the relative position and orientation of the tibia with respect to the femur. This method involves the use of 3D model-to-2D image registration in which projections of 3D models of the native knee (or replaced knee) are fitted to the silhouette of their respective components in the image. The most common software used to perform this registration is JointTrack, of which there are two different versions (JointTrack Manual and JointTrack Auto).

Because the precisions of the two different JointTrack programs are unknown, the first objective was to determine the overall precision of both programs in determining the AP positions of the femoral condyles for an example set of TKR components. The rationale behind using the AP Positions as the primary dependent variable is that it is one of the most common variables used to determine tibiofemoral kinematics in the literature and uses a method (lowest point) that has been validated by many research groups. Furthermore, the TKR knee was analyzed because JointTrack was specifically designed to perform image registration with the replaced knee.

While the AP positions of the femoral condyles provide information about tibiofemoral kinematics in primarily one degree of freedom (internal tibial rotation), there are still relative motions in four degrees of freedom other than flexion that need to be determined. As previously stated, quantification of clinically meaningful tibiofemoral kinematics requires a joint coordinate system (JCS) where motions are free from kinematic crosstalk errors. For the JCS to be free of kinematic crosstalk errors, two key requirements are that the body-fixed flexion-extension (F-E) and internal-external rotation (I-E) axes must coincide with the functional axes and that the femoral and tibial Cartesian coordinate system origins must lie on the functional axes. However, the International Society of Biomechanics (ISB) recommends the joint coordinate system (JCS) described by Grood and Suntay, where the axes are not functional and is therefore subject to kinematic crosstalk errors. However, these errors are unknown.

Therefore, the second objective of this study was to determine whether a JCS constructed using functional body-fixed axes (termed FUNC JCS) reduced kinematic crosstalk errors compared to the ISB JCS. As these JCSs were constructed for the native knee, this investigation was done in the native knee using JointTrack Manual per the information gathered from the first chapter of this thesis (Appendix A).

Methods:

For the first study on JointTrack precision, fluoroscopic images of 16 patients who performed a weighted deep knee bend following TKR were analyzed. JointTrack Manual and JointTrack Auto were used to perform 3D model-to-2D image registration and determine the absolute positions and orientations of the femoral and tibial components in each image. The AP positions of the femoral condyles were determined using the lowest point method. Precision was found by performing image registration 3 times for each patient and computing the variability in the AP positions measured for each trial. Intraclass correlation coefficients (ICCs) were also determined for both JointTrack programs. As the native knee requires the use of JointTrack Manual (due to degraded image and 3D model quality), further analysis was performed to inform the methods of the second study (Appendix A).

In the second study, fluoroscopic images of native knees in 13 subjects performing a deep knee bend were analyzed. JointTrack Manual was used to perform 3D model-to-2D image registration and determine the absolute positions and orientations of the femoral and tibial components in each image. Relative rigid body motions of the tibia with respect to the femur in all six degrees of freedom were calculated for both the ISB JCS and the FUNC JCS using a Cardan angle sequence and corresponding transformation matrix.

Results:

Overall precision for the JointTrack Manual program was 3 times worse than the JointTrack Auto program for both medial and lateral AP positions of the femoral condyle (0.97 mm and 0.91 mm versus 0.34 mm and 0.38 mm, respectively; $p < 0.0001$ for both). ICC values for the Auto program indicated good to excellent agreement (range: 0.82 – 0.98); whereas ICC values for the Manual program indicated only moderate to good agreement (range: 0.58 – 0.82). Precision using JointTrack Manual was significantly improved for determining the medial and lateral AP positions when performing three trials and taking the average of the three trials (0.58 and 0.70 mm, respectively; $p = 0.0001$ for medial and $p = 0.0288$ for lateral).

Results for the second study show that tibiofemoral kinematics using the FUNC JCS fell within the physiological range of motion in all five degrees of freedom excluding flexion-extension. Internal rotation of the tibia with respect to the femur averaged 13° for the FUNC JCS versus 10° for the ISB JCS and motions in the other four degrees of freedom (collectively termed off-axis motions) were minimal as expected based on biomechanical constraints. In contrast, off-axis motions for the ISB JCS were significantly greater; maximum valgus rotation was 4°, maximum anterior translation was 9 mm, and maximum distraction translation was 25 mm, which is not physiologic.

Discussion:

It is not surprising that JointTrack Auto has better precision and reproducibility as indicated by higher interobserver ICCs than JointTrack Manual for measuring the tibiofemoral kinematics of the TKR knee. JointTrack Manual requires considerably more operator intervention and considerably more time to perform image registration than JointTrack Auto. Therefore, the use of Auto over Manual is strongly recommended. However, if JointTrack Manual must be used, which is necessary for 3D models developed from image segmentation, then it is recommended to perform Manual image registration 3 times and take the average of the 3 trials for better precision.

For the second study, the FUNC JCS achieved clinically meaningful kinematics by significantly reducing kinematic crosstalk errors compared to the ISB JCS and is the more suitable coordinate system. Moving forward, the ISB is well advised to update their recommendation, which was published 20 years ago, so that the updated recommendation reflects the latest knowledge.

Preface

One of the primary ways to evaluate whether total knee replacement (TKR) restores knee function is to compare the kinematics of the tibiofemoral joint between the healthy knee and the TKR knee. Accordingly, this research is presented in the form of two independent chapters, the first evaluating the precision of two computer programs for performing 3D model-to-2D image registration as a stepping stone to determining tibiofemoral kinematics and the second providing an analysis of tibiofemoral kinematics in the native knee. Each chapter has been submitted for publication in a peer-reviewed scientific journal. As a result, there is some redundancy in the introduction and methods between the two chapters.

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Chapter 1: Significantly Better Precision with New Automated Versus Manual Image Registration Software in Processing Images from Single-Plane Fluoroscopy to Determine Tibiofemoral Kinematics

ABSTRACT

Background: One common method to determine tibiofemoral kinematics following total knee replacement (TKR) is to capture single-plane fluoroscopic images of a patient activity and determine the anterior-posterior (AP) positions of the femoral condyles. JointTrack is widely used to analyze single-plane fluoroscopic images, however the precisions in determining the AP positions following image registration using the two publicly available versions have never been quantified. The objectives were to determine the overall precision of both JointTrack programs, determine whether precision depended on the flexion angle, and determine the reproducibility of results achieved with both programs.

Methods: Fluoroscopic images of 16 patients who performed a weighted deep knee bend following TKR were recorded and analyzed. JointTrack Manual and JointTrack Auto were used to perform 3D model-to-2D image registration and determine the absolute positions and orientations of the femoral and tibial components in each image. The AP positions of the femoral condyles were determined using the lowest point method. Precision was found by performing image registration 3 times for each patient and computing the variability in the AP positions measured for each trial. Intraclass correlation coefficients were also determined for both JointTrack programs.

Results: Precision for the JointTrack Manual program was 3 times worse than the JointTrack Auto program for both medial and lateral AP positions of the femoral condyle (0.97 mm and 0.91 mm versus 0.34 mm and 0.38 mm, respectively; $p < 0.0001$ for both). For the Auto program, flexion angle did not affect precision. ICC values for the Auto program indicated good to excellent agreement (range: 0.82 – 0.98); whereas ICC values for the Manual program indicated only moderate to good agreement (range: 0.58 – 0.82).

Conclusion: JointTrack Auto has better precision and reproducibility than JointTrack Manual and is also more efficient to use. Therefore, the use of Auto over Manual is strongly recommended.

INTRODUCTION

To determine tibiofemoral kinematics following total knee replacement (TKR), a common method is to have patients perform activities under surveillance by single-plane fluoroscopy. The method calls for performing 3D model-to-2D image registration [1–3] and subsequently processing images to determine tibiofemoral kinematics by finding the anterior-posterior (AP) positions of each femoral condyle as a function of flexion [4,5]. Although two methods exist for finding AP positions, the lowest point method is more accurate than the flexion-facet center method [6].

As for any dependent variable stemming from a measurement, knowing the accuracy of the measurement is of high importance. To determine accuracy, two error metrics must be quantified [7]. One is the systematic error (or bias) defined as the mean error and the other is the random error (or precision) defined as the standard deviation of the error. Although determining the bias requires that the true value of the dependent variable be known, the precision can be determined by quantifying the repeatability, which involves computing the standard deviation over a number of trials. In analyzing fluoroscopic images of patients, it is not possible to determine the bias since true values of the AP positions are unknown, but it is possible to determine the precision. In addition to quantifying random error, another important use of precision is for sample size determination in a power analysis.

There are a number of error sources which affect the precision of the AP positions and these sources are traced primarily to 3D model-to-2D image registration. Since registration involves best-fitting a projection of a CAD model to the silhouette of the component in an image, sources of error in the image per se include warping, noise, resolution, and ghosting (i.e., motion artifact). Other sources are size mismatch between the CAD model and component imaged [8], the pose of the components [9], and the ability of the software used to achieve a best fit through optimization. In practice, errors due to warping are minimized by using a calibration device [2,3] and errors due to ghosting are minimized by having patients move slowly or by using a high sampling rate. While it is unnecessary and impractical to quantify error due to each source, the precision due to all sources can be readily quantified by repeatably registering a CAD model onto an image in independent trials and computing the variability in the AP positions determined for each trial [10].

To perform the registration, arguably the most commonly used software is JointTrack developed by Banks and coworkers at the University of Florida. Two different programs are currently available for use in the public domain. JointTrack Manual is the earlier program released for public domain use in 2006. This program requires time consuming and careful initial adjustment of the components in six degrees of freedom to closely match the silhouettes in the images prior to optimization and also final manual adjustment in the medial-lateral direction to correct for out-of-plane errors [11]. JointTrack Auto is the newer program released to the public domain in April 2022 and requires only coarse adjustment of the components in six degrees of freedom and no final manual adjustment to correct for out-of-plane errors. Hence, the Auto program is considerably more efficient than the Manual program. Although the Manual program has been available more than 15 years, the precision achieved with this program never has been evaluated to the knowledge of the authors. Likewise, the precision of the newer Auto program also is unknown.

The objectives of this study were threefold. One was to determine the overall precision of both programs in determining the AP positions of the femoral condyles for an example set of components. Because registration is affected by the pose, which changes with varying flexion, a second objective was to determine whether precision depends on the flexion angle. A final objective was to determine the reproducibility of results achieved with both programs. If our results showed that the precision of the Auto program was significantly better than that of the Manual program, then this would justify the use of Auto over Manual particularly considering the increased efficiency of Auto.

METHODS

Subjects

Fluoroscopic images of 16 patients who performed a weighted deep knee bend following unrestricted kinematic alignment (KA) TKR were recorded and analyzed. Acquisition of the images was approved by the Institutional Review Board (IRB# 1385598-6) at the University of California, Davis in Sacramento, CA. All patients underwent informed consent prior to their participation in the study. Patients were randomly selected from a patient series operated on by a single surgeon who performed unrestricted KA TKR with caliper verification [12]. All of the patients had an asymmetric stainless steel baseplate mated with a medially conforming insert and a flat, lateral articular surface with retention of the PCL (GMK Sphere, Medacta, Castel San Pietro, Switzerland).

Data Collection

A static single-plane fluoroscopic (OEC 9900 Elite, General Electric, Boston, MA) image of the knee was obtained with all noise reduction functions disabled and the automatic brightness and contrast settings were enabled to optimize image quality. Patients performed a weighted deep knee bend on a platform with handrails and staggered their stance so that the knee being imaged was not obscured by the contralateral limb. Fluoroscopic images were obtained at 15 frames per second using an oblique sagittal view of approximately 15° anterior. The oblique view enhanced the distinguishing features of the silhouettes of both the femoral component and tibial baseplate promoting more accurate 3D model-to-2D image registration.

Data Processing

Fluoroscopic images at 0°, 30°, 60°, 90°, and maximum flexion (MF) were selected for analysis. A pixel-wise, adaptive low-pass Wiener filter in Matlab (Matlab R2014b, Math-works, Natick, MA) corrected for distortion and filtered out noise. Each image and the corresponding size computer-aided design (CAD) models of the femoral and tibial components were imported into open-source software. One program was JointTrack Manual (version 2.3.0) and the other was the newer JointTrack Auto. Both programs determined the absolute position and orientation of the femoral and tibial components in a laboratory coordinate system using 3D model-to-2D image registration.

For the JointTrack Manual program (https://sourceforge.net/projects/jointtrack), image registration started with loading a calibration file setting the x-ray source-to-image distance. The position and orientation of the femoral and tibial components were found beginning with a precise manual adjustment of the CAD models in six degrees of freedom until they closely matched the silhouettes of the components in the images [1,2]. An automated optimization routine determined the final CAD model positions and orientations for both components using a Simulated Annealing algorithm [1,3]. The femoral component was translated out-of-plane (medial–lateral) until visually centered on the tibial component to limit translation errors intrinsic to single-plane fluoroscopy [11,13].

For the JointTrack Auto program (https://github.com/BRIO-lab/Joint-Track-Machine-Learning), registration again began with loading an x-ray calibration file. The position and orientation of the femoral and tibial components were found beginning with a course manual adjustment of the CAD models in six degrees of freedom until they roughly matched the silhouettes of the components in the images. To determine the final CAD model positions and orientations, the femoral component was optimized first. This optimization used a cost function that compared the dilated contour of the image with the dilated silhouette of the femoral component in a 3-stage minimization until the difference between the two sets of pixels was minimized. Default values for each of the three stages of optimization also were changed per recommendation from the developers of the software (Table 1.1) (A. Jensen, personal communication, May 10, 2022). The tibial component was then optimized using a cost function that performed the same minimization while also constraining the out-of-plane (medial-lateral) distance between the two components.

Following transformations to determine the relative position and orientation of the tibial baseplate with respect to the femoral component, the AP position of each femoral condyle with respect to the dwell point of the medial articular surface of the insert was determined in a multi-step process. First, a bounding box was drawn around the baseplate and the midline in the medial-lateral direction served as the reference to record the AP positions of the medial and lateral femoral condyles [14]. The AP position of each femoral condyle in the baseplate bounding box was indicated by the AP position of the lowest point of each femoral condyle on the plane of the tibial resection [1,2]. The AP positions in the baseplate bounding box were standardized to the AP dimension of the mid-sized tibial baseplate (50 mm for Size 4, Medacta GMK Sphere). Standardization involved multiplying each patient's AP position by the ratio of the AP dimension of the mid-sized baseplate to the AP dimension of their implanted baseplate. Next, the dwell point of the medial articular surface was determined and the AP positions in the baseplate bounding box were converted to AP positions with respect to the dwell point to determine the AP positions reported herein.

2.4 Statistical Analysis

The repeatability was computed to quantify the precision of the femoral condyle AP positions for both JointTrack programs. For each program, overall precision was quantified for each of the medial and lateral compartments at each of the 5 flexion angles by computing the pooled variance of 3 trials on 16 subjects for a single observer and taking the square root. The data were then checked for normality in 8 data sets using the Shapiro-Wilk test. The 8 data sets were the extremes of the repeatability (i.e., lowest and highest) for each program and each compartment. Seven of the 8 data sets were found to be normal, so 95% confidence limits were computed for each repeatability value.

To determine whether the precision depended on the flexion angle, Bartlett's test was used to test whether the precision was equal at all flexion angles for each program and each compartment. When significance was detected, an F-test was used to determine which pairs of flexion angles had different precisions.

In addition, the repeatability and reproducibility of the AP positions determined with each program were assessed by calculating the intraobserver and interobserver intraclass correlation coefficients (ICCs) using two-factor analysis of variance (ANOVA) with random effects [15]. The same image registration was performed independently by three observers using both programs for all 16 patients repeated 3 times at each of the 5 flexion angles and the resultant femoral condylar AP positions were determined at each flexion angle. For the ANOVA, the first factor had three levels (observers 1 to 3), and the second factor had sixteen levels (16 patients). Eight ANOVAs were performed (medial/lateral femoral condyles, 2 programs, and 2 flexion angles where extremes of precision occurred). ICC values > 0.9 indicate excellent agreement, 0.75–0.90 indicate good agreement, 0.5–0.75 indicate moderate agreement, and 0.25–0.5 indicate fair agreement [16].

RESULTS

Precision was about 3 times worse for both the medial and lateral AP positions using JointTrack Manual (0.97 mm and 0.91 mm, respectively) compared to JointTrack Auto (0.34 mm and 0.38 mm, respectively) (Table 1.2). F-tests comparing the precision for JointTrack Manual and JointTrack Auto indicated significant differences between the two programs for both the medial and lateral AP positions ($p < 0.0001$ and $p < 0.0001$, respectively).

For both programs, precision was similar at all flexion angles except for the lateral AP position using JointTrack Manual (Table 1.3, Figure 1.1). For this case, the precision of 1.21 mm at 0° flexion was significantly different than the precision of 0.63 mm at 30° flexion ($p = 0.0159$) and the precision of 0.68 mm at 120° flexion ($p = 0.0302$). The precision of 0.63 mm at 30° flexion was also significantly different than the precision of 1.12 mm at 90° flexion ($p = 0.0322$).

The intraobserver and interobserver ICC values were better (i.e., greater) for the JointTrack Auto program compared to the JointTrack Manual program (Table 1.4). For repeatability (i.e., intraobserver), ICC values for the Auto program indicated good to excellent agreement ranging from 0.82 – 0.98. In contrast for the Manual program, ICC values ranged from 0.56 – 0.82 indicating moderate to good agreement.

For reproducibility (i.e., interobserver), ICC values for the Auto program indicated generally excellent agreement with only one value falling slightly below 0.90 (Table 1.4). However, one value for the Manual program fell below 0.60 indicating moderate agreement and there were no values above 0.90 indicating excellent agreement.

DISCUSSION

This main purpose of this study was to determine the precision in using 3D-model-to-2D image registration to measure the AP positions of the femoral condyles. The three objectives were to 1) determine the overall precision of image registration using JointTrack Auto and JointTrack Manual; 2) determine whether precision of the image registration depended on the flexion angle; and 3) determine the reproducibility achieved using both programs. The key findings were that the precision was significantly better using JointTrack Auto compared to JointTrack Manual; precision did not depend on the flexion angle; and reproducibility was better using JointTrack Auto.

The most desirable method for measuring the AP positions of the femoral condyles using image registration is the one that produces the most repeatable and reproducible results without introducing complexity into the method. As JointTrack is the most commonly used software to perform image registration, it is necessary to quantify and compare the two publicly available versions to see which is more desirable. In terms of complexity, JointTrack Auto is the easier program to operate as user intervention is minimal. In contrast, for the Manual program, careful positioning of the implants is required as well as a final out-of-plane adjustment. Because this out-of-plane adjustment occurs in the plane of the image and because images are taken at an oblique angle to the sagittal plane of the knee, out-of-plane adjustments of the components may result in slight changes in the measured AP position.

In terms of repeatability and reproducibility, the Auto program proved to be better than the Manual program. Precisions of both programs were less than 1 mm, but the precision of Auto was three times better than Manual in both the medial and lateral compartments (Table 1.2, Figure 1.1). Likewise, ICC values indicated excellent agreement in 3 of the 4 cases for Auto (good agreement in the 4th case) while ICC values for the manual software indicated good agreement in 2 of the 4 cases (moderate agreement in the other 2 cases).

Another important consideration regarding which program to use for fluoroscopic image analysis is efficiency. The developers of JointTrack reported that registration success for the Manual program, defined as the percentage difference between the final registered position and the actual position, dropped from around 90% when the initial guess was 4 mm from the in-plane solution and 4° from the rotation solution to 50% when the initial guess was within 16 mm and 16°, respectively [3]. Successful registrations require the operator to spend up to 30 minutes using the Manual program for one patient to optimize the two implants on five different images (for each flexion angle). However, this same process might take the same operator 10 minutes on the Auto program, due to the lack of significant operator intervention. The significant difference in time while achieving better repeatability and reproducibility and less complex operation justifies the use of the Auto over the Manual program.

The fact that the Auto program has significantly lower error than the Manual program may affect the perception of previous literature. JointTrack Manual was publicly available in 2006, with the Auto program just becoming available in April 2022, indicating 15+ years of studies involving the use of the Manual program for analysis of tibiofemoral kinematics. While the precision for determining the AP positions of the condyles was significantly worse for the Manual program compared to the Auto program, it was still less than 1 mm in both compartments. That overall precision achieved may be small enough to justify acceptance of results reported using the Manual software.

Quantifying the precisions of both JointTrack programs is also useful in determining sample size for power analysis. In a hypothetical situation where the true AP positions of the femoral condyles are known, it would be helpful to know the sample size necessary to detect errors up to 1 mm using both programs. Given a power of 0.95, a significance of 0.05, and the precisions of both programs, the required sample size for the Manual program becomes 14 subjects versus just 5 subjects for the Auto program. Thus, for equivalent power, using the Manual program would require 3 times as many patients than using the Auto program.

For both JointTrack programs, there was little relationship between precision and flexion angle. The lack of relationship between precision and flexion angle is surprising, considering the varying amounts of detail in the image silhouettes at each flexion angle (Figure 1.2). One reason that this may have occurred was that patients were imaged at an oblique angle, which may have introduced sufficient detail into the silhouettes that image registration could still be successful for any flexion angle. This can be seen especially with the Auto program, whose repeatability can be attributed to its optimization algorithms more than operator ability.

Another surprising result was that ICC values for the Manual program in the lateral compartment were significantly higher than in the medial compartment. This may have happened due to the design of the implant, specifically the medially-conforming plastic insert associated with this set of components. The design of the GMK Sphere Medacta components closely follows a study concluding that the knee experiences axial rotation about the medial compartment, meaning that the AP position of the medial femoral condyles remains fixed whereas the lateral femoral condyle moves posteriorly as the knee is flexed [17]. Because different knees will experience varying amounts of internal axial rotation in flexion, the actual AP position in the lateral compartment will be significantly more variable than in the medial compartment, creating a subject variability bias when calculating the ICC values. This same trend occurred for the Auto program; however, it was not as apparent as the Manual program.

There are some limitations in the present study that merit discussion. First, this study involved the use of only one set of components (GMK Sphere, Medacta, Castel San Pietro, Switzerland), and the precision values computed herein may not apply to all TKR designs. Although other designs could affect the precisions of the two JointTrack programs, the effects would be systematic so that the overall comparisons of the two programs would yield similar conclusions.

Another limitation associated with any study involving single-plane fluoroscopy is the effect of image quality. The effects of image resolution and noise are difficult to quantify. Additionally, fluoroscopic images obtained in this study were collected at 15 frames per second, which is a lower framerate than many modern fluoroscopic imaging systems, meaning that motion blur could have affected our results. However, the purpose of this study was to report the precision given all sources of error and errors were determined under a worst-case analysis.

CONCLUSION

This study determined the precision of measuring the AP positions of the femoral condyles in the TKR knee using the JointTrack Manual and Auto programs and concluded that the Auto program has better repeatability and reproducibility. Given these results and the ease and efficiency of operation, the Auto program should be used over the Manual program.

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Table 1.1 Default values and recommended values for translations (xt, yt, zt) and rotations (xr, yr, zr) in the 3-stage optimization used in the JointTrack Auto program. The three stages are trunk, branch, and leaf. The zt range is greater than xt and yt because zt defines the out of plane direction and is prone to more error than the in-plane directions.

Default Values	**Translation Range (mm)**	**Rotation Range (°)**	**Dilation (Edge Thickness)**	**Budget (Iteration Count)**
Trunk	xt = yt = zt = 35	xr = yr = zr = 35	6	20000
Branch	xt = yt = 15, zt = 25	xr = yr = zr = 25	4	5000
Leaf	xt = yt = 3, zt = 15	xr = yr = zr = 3	1	5000
Recommended Values				
Trunk	xt = yt = zt = 50	xr = yr = zr = 45	6	15000
Branch	xt = yt = zt = 35	xr = yr = zr = 30	3	15000
Leaf	xt = yt = 50, zt = 250	xr = yr = zr = 3	1	10000

Table 1.2 Overall precision in each compartment for the two JointTrack programs.

	Overall Precision, Medial Compartment	**Overall Precision, Lateral Compartment**
JointTrack Manual	0.97 mm	0.91 mm
JointTrack Auto	0.34 mm	0.38 mm
F test p-value	<0.0001	<0.0001

Table 1.3 Bartlett's Test for the two JointTrack programs for each compartment. For significant p-values, all pairs of flexion angles were checked for significant differences.

Program/Compartment	**Manual/Medial**	**Manual/Lateral**	**Auto/Medial**	**Auto/Lateral**
Bartlett's Test p-value	0.0688	**0.0306**	0.6065	0.0827
Significant Pairs	N/A	0-30 (p = 0.0159) 0-120 (p = 0.0302) 30-90 (p = 0.0322)	N/A	N/A

Table 1.4 ICC values for the two JointTrack programs.

Program	**Manual**	**Manual**	**Manual**	**Manual**	**Auto**	**Auto**	**Auto**	**Auto**
Medial/Lateral	Medial	Medial	Lateral	Lateral	Medial	Medial	Lateral	Lateral
Precision Extreme	Best	Worst	Best	Worst	Best	Worst	Best	Worst
Flexion Angle (deg)	30	90	30	0	60	90	30	60
Intraobserver ICC	0.563	0.682	0.825	0.806	0.923	0.825	0.977	0.985
Interobserver ICC	0.538	0.671	0.818	0.794	0.919	0.823	0.977	0.985

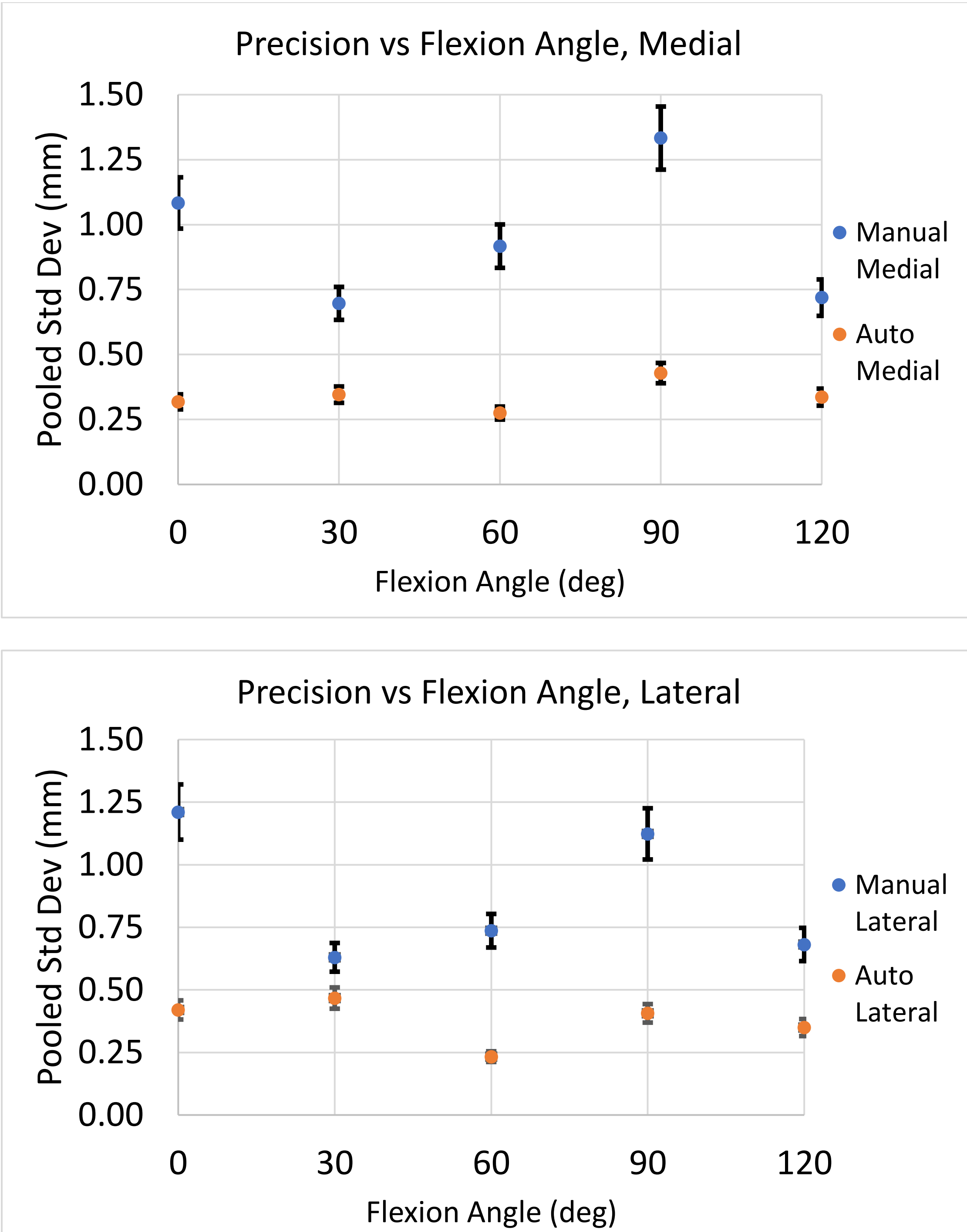


Figure 1.1 Precision of the two JointTrack programs in measuring the AP positions of the medial and lateral femoral condyles at each flexion angle.

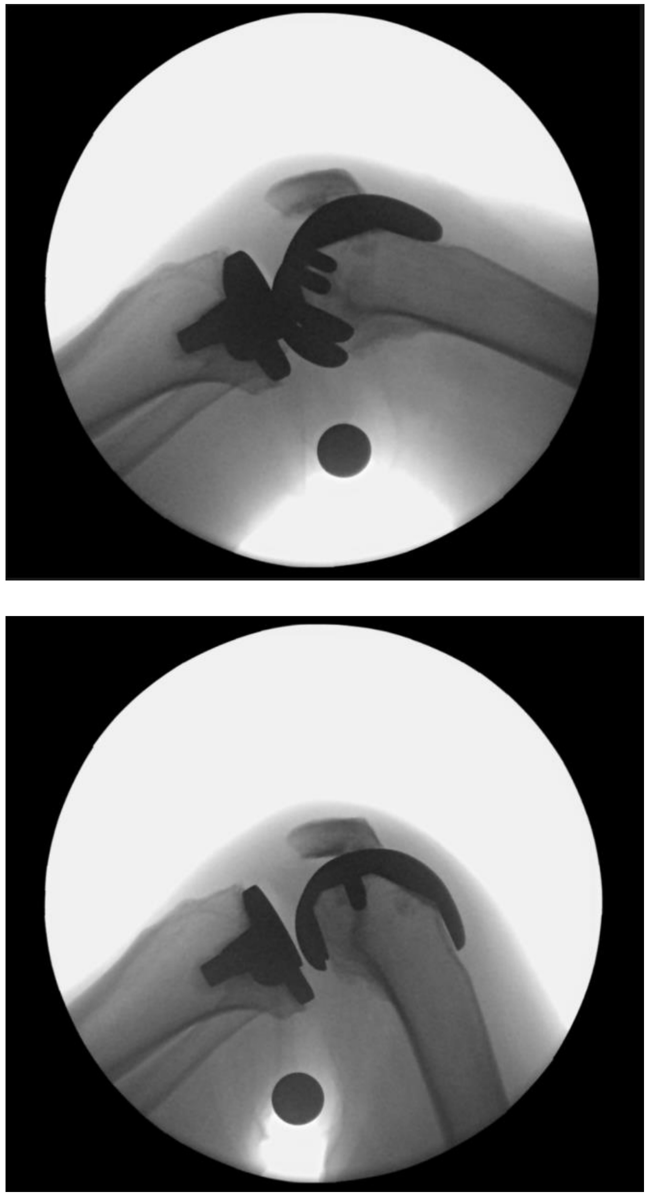


Figure 1.2 Two images for the same patient. The silhouette for the image on the left contains significantly more features for both components (especially the femoral component) than the image on the right.

APPENDIX A: JointTrack Manual Multiple Trial Analysis

Methods: From the 16 patients, a random set of 10 patients was selected for analysis. For these 10 patients, the AP positions of the medial and lateral femoral condyles at each of the 5 flexion angles were measured for 3 sets of 3 trials each. For each set, the AP positions of the 3 trials were averaged. Overall precision was quantified for each of the medial and lateral compartments by computing the pooled variance of the 3 sets for all 10 patients and then taking the square root. F tests comparing the pooled variance between 3 sets of 3 trials and 1 set of 3 trials (the original study) were performed determine whether taking the average of multiple trials improved the precision of JointTrack Manual.

Results: JointTrack Manual Precision improved when taking the average of 3 trials for 3 sets for both the medial and lateral compartments (0.58 mm and 0.70 mm, respectively) compared to just 1 set of 3 trials from the original study (0.98 mm and 0.91 mm, respectively) (Figure A1). F tests comparing the overall precisions of 3 sets and 1 set indicated significant improvement in precision for both the medial and lateral compartments ($p = 0.0001$ and $p = 0.0288$, respectively). Looking specifically at each flexion angle, precision improved when using 3 sets for every flexion angle in the medial compartment and improved when using 3 sets for all but one flexion angle in the lateral compartment (Figure A2).

Discussion: While the original study shows that JointTrack Auto has better repeatability and reproducibility than JointTrack Manual, it is important to note that this conclusion applies specifically to the TKR knee. When studying tibiofemoral kinematics for the native knee using single-plane fluoroscopy, it is advised to use JointTrack Manual because the image quality of the native knee does not contain enough contrast for JointTrack Auto to perform registration accurately. This investigation shows that the precision of JointTrack Manual improves significantly when taking the average of 3 trials as opposed to using a single trial for analysis, and that the average of 3 trials on JointTrack Manual is almost comparable to the precision achieved using JointTrack Auto.

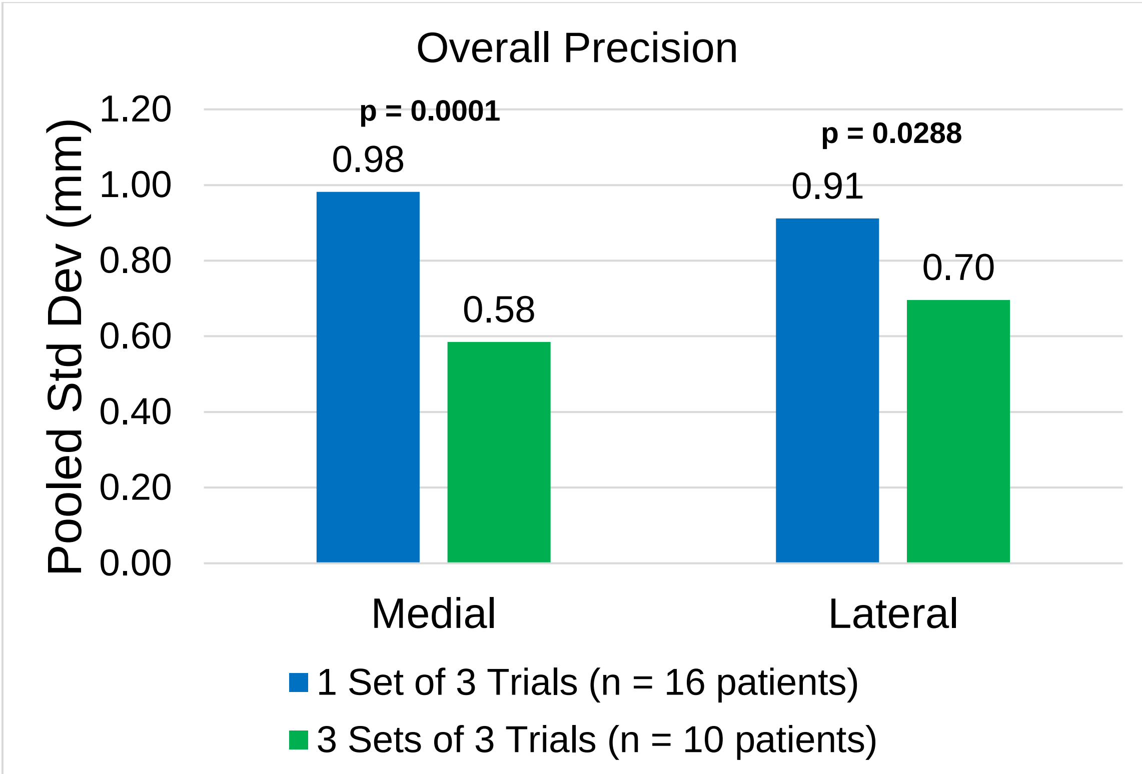
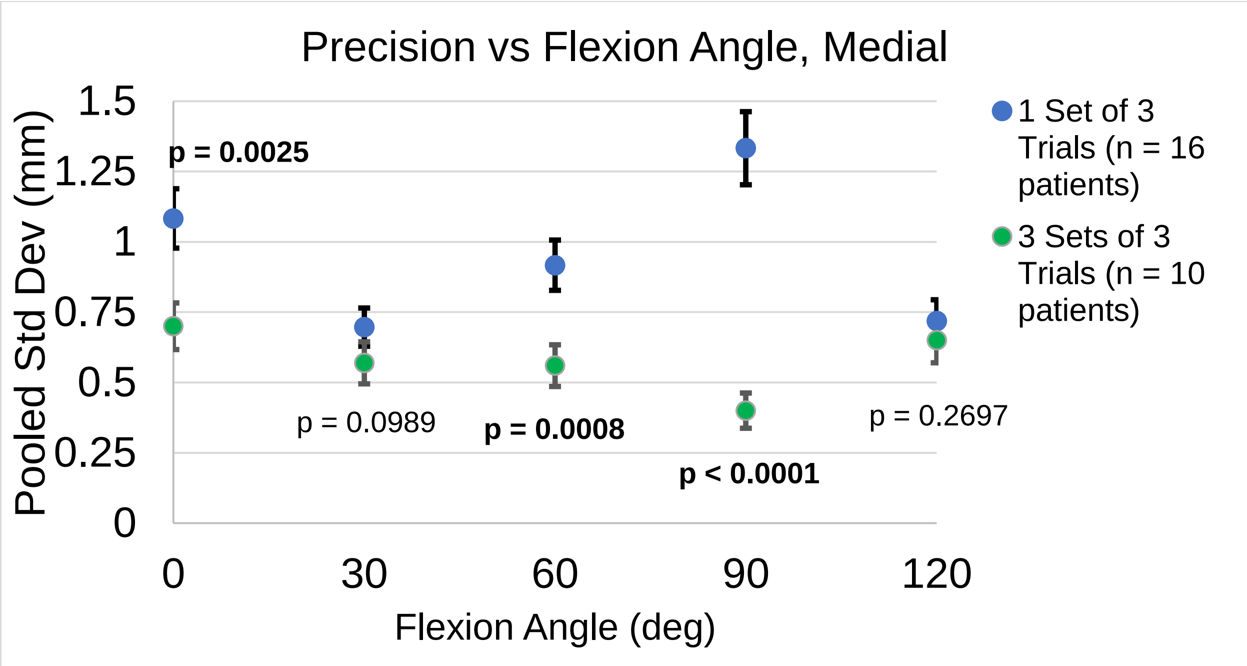


Figure A1 Bar chart comparing the precisions of JointTrack Manual when using 3 sets of 3 trials (Green) versus using just 1 set of 3 trials (Blue).



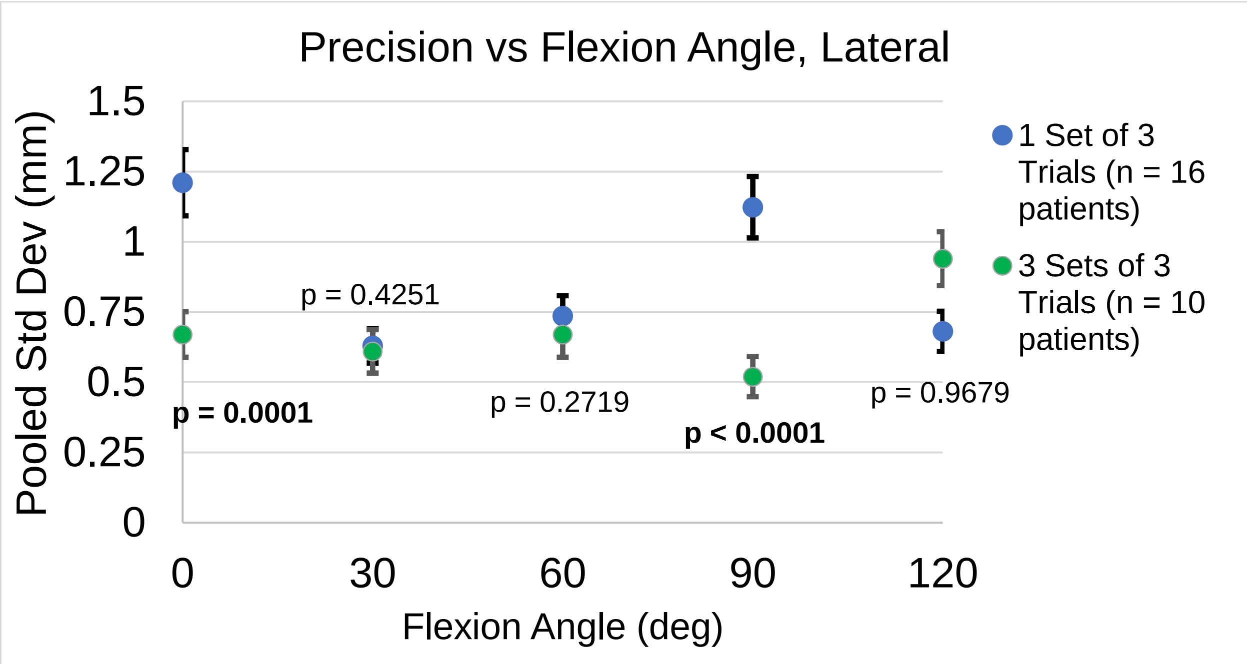


Figure A2 Precision of JointTrack Manual when using 3 sets of 3 trials (green) versus 1 set of 3 trials (blue) in measuring the AP positions of the medial and lateral femoral condyles at each flexion angle.

Chapter 2: Joint Coordinate System Using Functional Axes Achieves Clinically Meaningful Kinematics of the Tibiofemoral Joint as Compared to the International Society of Biomechanics (ISB) Recommendation

ABSTRACT

Quantification of clinically meaningful tibiofemoral motions requires a joint coordinate system where motions are free from kinematic crosstalk errors. The objectives were to 1) use a joint coordinate system (JCS) with literature-backed functional axes (FUNC JCS) and a coordinate system recommended by the International Society of Biomechanics (ISB JCS) to determine tibiofemoral kinematics of the native (i.e., healthy) knee during a deep knee bend, 2) determine the variability associated with each JCS, and 3) determine whether the FUNC JCS significantly reduces kinematic crosstalk errors compared to ISB JCS. Based on a kinematic model consisting of chain of three cylindric joints, the FUNC JCS included body-fixed functional flexion-extension (F-E) and internal-external (I-E) tibial rotation axes. In contrast, the ISB JCS included body-fixed F-E and I-E axes defined using anatomic landmarks. Single-plane fluoroscopic images of native knees in 13 subjects performing a deep knee bend were analyzed to show that tibiofemoral kinematics using the FUNC JCS fell within the physiological range of motion in all six degrees of freedom. Internal rotation of the tibia with respect to the femur averaged 13° for the FUNC JCS versus 10° for the ISB JCS and motions in the other four degrees of freedom (collectively termed off-axis motions) were minimal as expected based on biomechanical constraints. In contrast, off-axis motions for the ISB JCS were significantly greater; maximum valgus rotation was 4°, maximum anterior translation was 9 mm, and maximum distraction translation was 25 mm which is not physiologic. The variability in the off-axis motion was significantly greater with the ISB JCS than the FUNC JCS ($p < 0.0002$). Hence, the FUNC JCS achieved clinically meaningful kinematics by significantly reducing kinematic crosstalk errors compared to the ISB JCS and is the more suitable coordinate system.

INTRODUCTION

Tibiofemoral kinematics refers to the relative rigid body motions between the tibia and the femur. Quantification of in vivo tibiofemoral kinematics is critical to assess joint function in healthy, osteoarthritic, and anterior cruciate ligament deficient knees and for the development and validation of total knee replacements and surgical protocols. One method for quantifying these motions is to use a joint coordinate system such as that of Grood and Suntay which is based on a kinematic model consisting of a chain of three cylindric joints (Figure 2.1) [1].

For the joint coordinate system of Grood and Suntay to yield clinically meaningful motions free from kinematic crosstalk errors, two key requirements are that the body-fixed flexion-extension (F-E) and internal-external rotation (I-E) axes must coincide with the functional axes and that the femoral and tibial Cartesian coordinate system origins must lie on the functional axes [2]. As an example of how significant kinematic crosstalk error can be, Most et al. demonstrated that using a non-functional F-E axis to measure internal tibial rotation yielded mean kinematic crosstalk errors up to 9° at 90° of flexion [3].

Although the International Society of Biomechanics (ISB) recommends using the joint coordinate system (JCS) developed by Grood and Suntay [4], the recommended placement of axes and the locations of the Cartesian coordinate systems origins do not satisfy the requirements above to yield clinically meaningful motions. Specifically, for the ISB JCS placement of the axes relies on anatomical landmarks, which do not represent points that lie on the functional axes. The femoral F-E axis passes through the most distal point of the trochlear groove while the tibial I-E axis is the tibial mechanical axis. Further, the femoral and tibial Cartesian coordinate system origins coincide and lie on the F-E axis which is not the functional axis. Given these limitations, the resulting motions will be subject to kinematic crosstalk errors but the magnitude of these errors is unknown.

To quantify kinematic crosstalk errors in the ISB JCS and to determine clinically meaningful relative rigid body motions, a JCS which meets the two key requirements above must be used [2]. Regarding the functional axes requirement, the functional F-E axis is body-fixed to the femur during weight-bearing flexion and is closely approximated by a line connecting the centers of circles best fit to the posterior femoral condyles from about 15-110° of flexion [5]. As a result, the functional body-fixed F-E axis is positioned well superior and posterior to the body-fixed F-E axis in the ISB JCS (Figure 2.2).

Likewise, the functional I-E axis is body-fixed to the tibia, is approximately parallel to the tibial mechanical axis, and intersects the medial tibial plateau in compression [6], a finding corroborated by others in weight-bearing flexion [5,7-10]. As a result, the functional body-fixed I-E axis is positioned well medial to the body-fixed I-E axis in the ISB JCS (Figure 2.2).

The specific objectives of this study were to 1) determine tibiofemoral kinematics during a dynamic deep knee bend using the ISB JCS and a second JCS using literature-backed definitions for the functional body-fixed axes (termed FUNC JCS), 2) determine the variability associated with each JCS, and 3) based on differences between the ISB and FUNC JCSs, determine whether the FUNC JCS significantly reduces kinematic crosstalk errors.

METHODS

Patient Imaging

This study was approved by the Institutional Review Board at the University of California, Davis (IRB# 954288) and all patients imaged gave informed consent. Total knee arthroplasty patients (n=13) with posterior cruciate-retaining components (Persona CR, Zimmer-Biomet, Warsaw, IN) implanted with kinematic alignment total knee arthroplasty and a native contralateral limb with no skeletal abnormalities or prior surgery were identified (Table 2.1). Details of the inclusion and exclusion criteria and participant recruitment were previously reported [10]. All patients received a clinical knee examination by an experienced knee surgeon to determine the passive flexion and extension of the native knee. Single-plane fluoroscopy (OEC 9900 Elite, General Electric, Boston, MA) was performed at 15 frames per second during a dynamic deep knee bend from full extension to maximum flexion. Stationary magnetic resonance imaging (MRI) scans of the contralateral native knee were taken with a 3T MRI (TIM Trio, Siemens, Munich, Germany) with dedicated knee surface coil and 1 mm thick sagittal plane slices (0.8 × 0.8 × 1.0 mm voxel size) at full extension as previously described [10]. MRI images of the native knee were segmented to create patient-specific three-dimensional (3D) bone models sans articular cartilage of the distal femur and proximal tibia using Mimics v20.0 (Materialise, Belgium).

3-D Tibiofemoral Kinematics

The process for defining both the ISB and FUNC joint coordinate systems progressed in multiple steps. In the 1st step, the body-fixed F-E axes for the ISB and FUNC joint coordinate systems were determined (Figure 2.3). In the 2nd step, the 0° flexion reference was defined using the femoral and tibial mechanical axes in the sagittal plane (Figure 2.4). In the 3rd step, the body-fixed I-E axes of the ISB JCS (Figure 2.5) and the FUNC JCS were determined (Figure 2.6). Once the steps were completed, the body-fixed F-E axis of the ISB JCS was anterior and inferior to that of the FUNC JCS and the origins of the ISB and FUNC femoral Cartesian coordinate systems were at the midpoints of the body-fixed F-E axes (Figure 2.2). The body-fixed I-E axis of the ISB JCS was approximately centered in the tibial plateau, while the I-E axis for the FUNC JCS was approximately centered in the medial compartment of the tibia. The origin of the ISB tibial Cartesian coordinate system coincided with that of the ISB femoral Cartesian coordinate system whereas the origin of the FUNC tibial Cartesian coordinate system was inferior to that of the FUNC femoral Cartesian coordinate system being positioned on I-E functional axis where it intersected the tibial plateau medially (Figure 2.2).

Fluoroscopic images were processed to determine relative rigid body motions of the native knee (Figure 2.7) as previously described [10]. Briefly, single-plane fluoroscopic images were taken during active deep knee bend and images were chosen for analysis in 30° increments from 0◦ to approximately 120◦ of flexion (5 images total/patient). A 3D model-to-2D image registration technique [15] was used to register 3D bone models to 2D fluoroscopic images at each flexion angle from 0◦ to maximum flexion. Due to large out-of-plane errors in the M-L direction inherent to single-plane registration [15], the M-L position of the femur on the tibia was adjusted manually. This step was necessary to avoid reconstruction of physiologically impossible poses [16, 17].

Euler angles and linear displacements were determined for the femur and tibia in a laboratory coordinate system using open-source JointTrack Manual v2.3.0. Bone models were aligned into the ISB and FUNC JCSs (Figure 2.2) using Geomagic Control v2015 (3D Systems, Cary, NC). Relative rigid body motions of the tibia with respect to the femur were calculated using a Cardan angle sequence and corresponding transformation matrix [18] in MATLAB vR2021a (Mathworks, Natick, MA). Results follow clinical terminology and include three rotations ([+ Flexion, - Extension] (F-E), [+ Internal, - External] (I-E), [+ Varus, - Valgus] (V-V)) and three translations ([+ Anterior, - Posterior] (A-P), [+ Compression, - Distraction] (C-D), and [+ Medial, - Lateral] (M-L)). As F-E rotation is the main degree of freedom of the knee, relative rigid body motions were plotted for each JCS evaluated against the flexion angle (mean ± standard deviation).

Statistical Analysis

All analyses were performed using n=13 matched samples per JCS on JMP PRO v16 (SAS Institute, Cary, NC). To quantify kinematic crosstalk errors associated with the ISB JCS, four of the six rigid body motions were analyzed. F-E rotation and I-E rotation are expected to occur in the native knee during weight-bearing activities [5-10, 19]. However, due to biomechanical constraints, the three translations and varus-valgus rotation (collectively termed off-axis motions) should be minimal, if not 0 [8, 20, 21]. Multiple linear regression analyses were performed for three of the four off-axis motions to determine the effect of the two independent variables (JCS and flexion angle) on the means. Because AP translation was curvilinear with flexion angle, paired t-tests comparing the means of the two coordinate systems were conducted at each flexion angle. For the standard deviations, F-tests were conducted to compare the ISB and FUNC JCSs for every degree of freedom except F-E rotation.

RESULTS

Results for the FUNC JCS revealed that motion primarily occurred about the F-E and I-E rotation axes. Absolute mean V-V rotations were less than 1.1º across the full range of flexion (Figure 2.8A) and absolute mean translations were below 1.5 mm for A-P, 1 mm for C-D, and 0.5 mm for M-L (Figure 2.9).

For the ISB JCS, greatest absolute mean V-V rotation occurred at 120º and was 3.9º (4 times greater than the greatest absolute mean of 1º for FUNC JCS at 120º). Greatest absolute mean translations also occurred at 120º flexion and were 8.6 mm (approximately 6 times greater than the greatest absolute mean of 1.5 mm for FUNC JCS at 120º) anterior for A-P (Figure 2.9A), 25 mm (25 times greater than the absolute mean of 1 mm for FUNC JCS at 120º) distraction for C-D (Figure 2.9B), and 1.5 mm (3 times greater than the absolute mean of 0.5 mm for FUNC JCS at 30º) lateral for M-L (Figure 2.9C).

From the multiple regression analyses, the JCS effect was highly significant indicating that the FUNC JCS significantly reduced kinematic crosstalk errors inherent in the ISB JCS ($p = 0.0068$

for M-L and $p < 0.0001$ for C-D and V-V). The paired t-tests for A-P translation showed that the FUNC JCS reduced kinematic crosstalk errors in the ISB JCS at 30º, 60º, and 120º ($p = 0.0016$, $p = 0.0313$, and $p < 0.0001$, respectively).

The FUNC JCS reduced standard deviations of all five motions analyzed for variability. Overall standard deviations of the ISB JCS were reduced by factors of 1.9 in I-E rotation, 2.1 in V-V rotation, 3.5 in A-P translation, 2.2 in C-D translation, and 1.6 in M-L translation. The results of the F tests showed that standard deviations for the FUNC JCS were significantly lower in all five degrees of freedom ($p = 0.0002$ for M-L and $p < 0.0001$ for the other four motions).

DISCUSSION

Clinically meaningful tibiofemoral kinematics must be free from kinematic crosstalk errors. Our objectives were to 1) determine tibiofemoral kinematics during a weight bearing deep knee bend using the ISB JCS and a second JCS using functional body-fixed axes based on the literature (FUNC JCS), 2) determine the variability associated with each JCS, and 3) based on differences between the ISB and FUNC JCSs determine whether the FUNC JCS significantly reduces kinematic crosstalk errors.

Relative rigid body motions in all six degrees of freedom calculated using the FUNC JCS fell within the physiological range of motion for a native knee. The FUNC JCS internal rotations were within the 6◦ to 30◦ of internal rotation of the tibia on the femur that occurs clinically through 90° of knee flexion [22]. Mean internal rotations at 90° and 120° were 10° and 13°, which is consistent with other groups who measured tibial internal rotation using the lowest point method [7, 9, 10]. The remaining motions were minimal as expected based on biomechanical constraints in the native tibiofemoral joint. For V-V rotation and C-D translation, these motions are minimal as long as the tibial and femoral articular surfaces in both the medial and lateral compartments remain in contact. To the authors knowledge, femoral condylar liftoff has not been reported by any study of the native knee in deep knee bend [20, 21]. Likewise, A-P translation is minimal because of the conformity and constraint provided by the medial meniscus which is securely attached to the surrounding tissues via the coronary ligament. As a result, the femur pivots about an I-E axis passing approximately through the center of the medial compartment with minimal A-P translation [5, 8, 19, 23].

In contrast to the FUNC JCS, the ISB JCS produced non-physiological motions in all off-axis motions. The mean valgus rotation of 4° at 120° of flexion translates into a medial flexion gap of nearly 4 mm. With a strain at yield below 20% [24] and a length of 50 mm [25], this gap would manifest as a strain of 8% in the medial collateral ligament which may cause acute damage. Likewise, the 9 mm anterior tibial translation at 120° of flexion is non-physiologic since A-P translation is minimal due to the constraint in the medial compartment to medial femoral condyle linear displacement explained above. Lastly the 25 mm distraction at 120° of flexion arguably would disrupt every major ligament in the tibiofemoral joint. These non-physiologic motions are evidence of significant kinematic crosstalk errors in the ISB JCS introduced by the incorrect identification of anatomical landmarks, axes placement, and constraint on the tibial and femoral Cartesian coordinate system origins to coincide. In producing I-E rotation consistent with other studies and minimal off-axis motions otherwise, the FUNC JCS significantly reduced kinematic crosstalk errors compared to ISB JCS and yielded clinically meaningful tibiofemoral kinematics.

The FUNC JCS also reduced standard deviations compared to the ISB JCS in all five motions analyzed allowing for more accurate comparisons of kinematics across patients. The larger standard deviations in the ISB JCS kinematics may be partially attributed to the difficulty in correctly identifying anatomical landmarks on clinical images. Anatomical landmarks are areas, not points, and their correct identification is heavily dependent on the operator’s skill level. The precision with which anatomical landmarks are chosen determines the accuracy of the anatomical JCS axes used to calculate tibiofemoral kinematics. Intraobserver variability in landmark identification has been shown to alter the calculated I-E rotation of the knee by 5.8◦ and interobserver variability by 10.4° [26]. In contrast, the F-E axis for the FUNC JCS was constructed using software (Geomagic Control v2015, 3D Systems, Cary, NC) that located the center of best-fit circles to the posterior femoral condyles. This removal of a crucial subjective step may have reduced the variability found in the ISB JCS.

One methodological issue which merits discussion is the method of measuring tibiofemoral kinematics. Although this study relied on analysis of images derived from radiography, other methods such as those which use video-based analysis of skin-mounted markers are available and have been used extensively in gait analysis. Because a previous paper by the senior author discussed this alternative method and the attendant difficulties in using this method in detail, the interested reader is referred to that source [2]. The conclusion of that discussion was that improved methods are needed before tibiofemoral kinematics free from kinematic crosstalk errors can be reliably determined in gait studies involving video-based analysis of skin-mounted markers.

Another methodological issue which merits discussion is the definition of the ISB JCS [4]. In forming this coordinate system, the three criteria that were satisfied per the ISB recommendation were that the 1) the coordinate system follow the framework of Grood and Suntay [1], 2) body-fixed axes be defined based on bony landmarks which are either palpable or identifiable from x-rays, and 3) the origins for the femur-fixed and tibia-fixed Cartesian coordinate systems coincide. While these criteria were met in the present study, it should be recognized that other coordinate systems could have been defined which also meet these criteria. For example, the transepicondylar axis could have been used as the body-fixed FE axis as has been done in some previous studies [3]. However, regardless of the specifics of the ISB JCS axes, satisfying the three criteria per the ISB recommendation would result in large kinematic crosstalk errors. Clearly, moving forward, the ISB is well advised to update their recommendation, which was published 20 years ago, so that the updated recommendation reflects the latest knowledge.

CONCLUSION

The results of this study are particularly exciting because the FUNC JCS is a step toward determining accurate, clinically meaningful tibiofemoral kinematics with minimal kinematic crosstalk errors. The functional joint coordinate system achieved clinically meaningful kinematics as compared to the ISB recommendation and is the more suitable coordinate system for evaluation of tibiofemoral joint function.

ACKNOWLEDGMENTS

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Table 2.1 Patient demographic data (n = 13)

Patient Data	Mean ± standard deviation (range)
Sex	5 females; 8 males
Age (years)	66 ± 7 (57 - 82)
BMI (kg/m^2)	28 ± 5 (22 - 39)
Passive Extension ($^\circ$)	0 ± 0 (0 - 0)
Passive Flexion ($^\circ$)	129 ± 6 (120 - 135)

Abbreviations: BMI, body mass index.

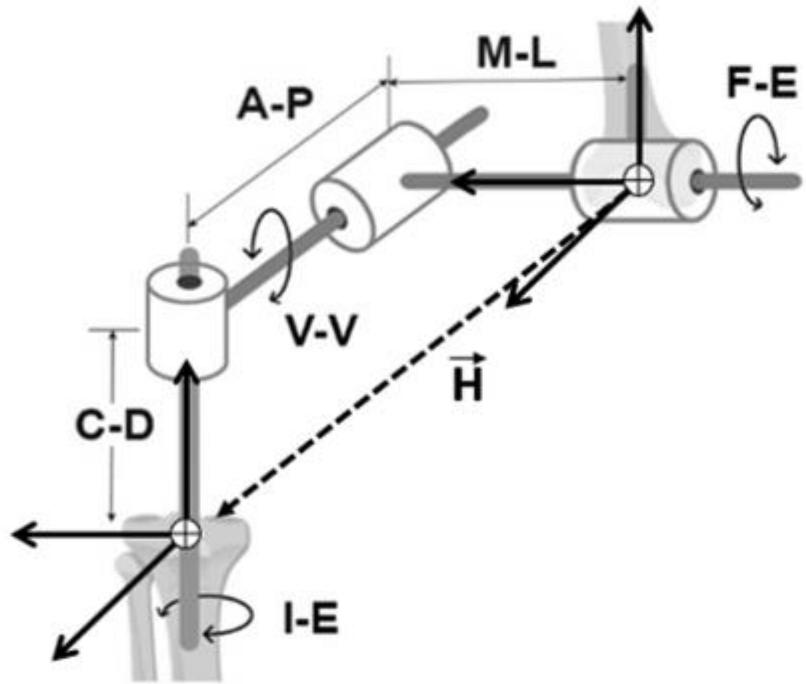

FIGURE 2.1: Kinematic model recommended by the ISB. The ISB recommends the kinematic model which embodies the joint coordinate system of Grood and Suntay [1]. This model is comprised of a chain of three cylindric joints which allow six degree-of-freedom motions. Two rotations (F-E and I-E) and translations (M-L and C-D) occur about and along the body-fixed F-E and I-E rotation axes. The other rotation (V-V) and translation (A-P) occur about and along the floating V-V rotation axis, which is mutually perpendicular to the body-fixed axes. Femur-fixed and tibia-fixed Cartesian coordinate systems are defined as shown and the vector H, which connects the origins, is used to determine either the joint or clinical translations. Per Grood and Suntay, clinical translations are the projections of H along the nonorthogonal axes of the cylindric joints and the joint translations are the components of H expressed in terms of the nonorthogonal unit vectors along each axis.

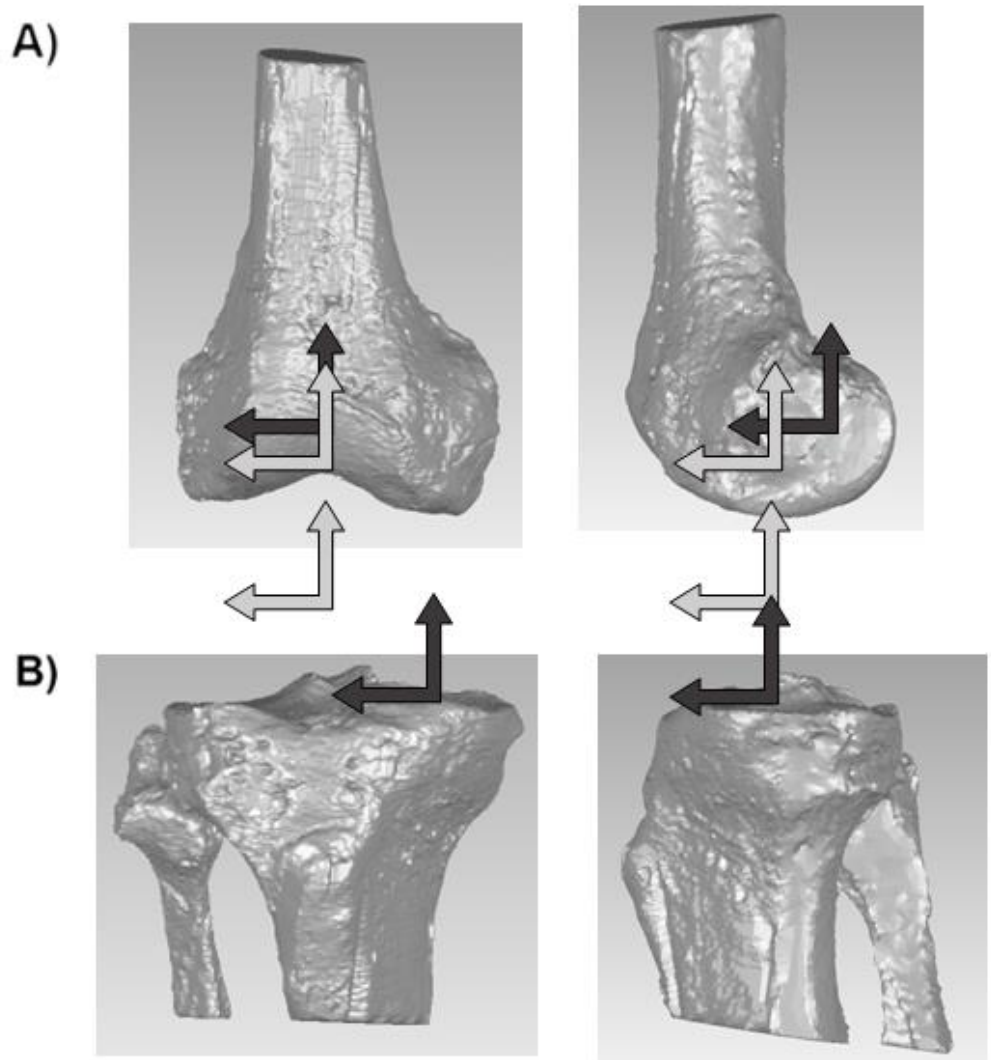

FIGURE 2.2: Comparison of body-fixed axes and origin locations for a right knee for the ISB (gray arrows) and FUNC (dark arrows) joint coordinate systems. A) Femur, B) Tibia

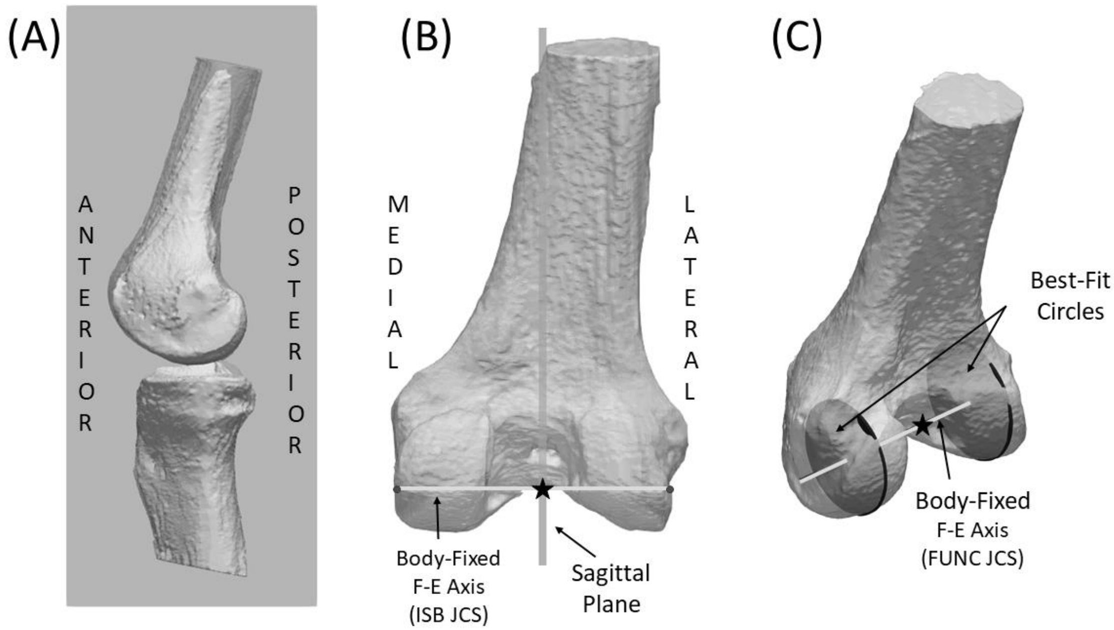

FIGURE 2.3: Process for defining the body-fixed F-E axes for the ISB and FUNC joint coordinate systems (JCS). (A) The sagittal plane (gray) was defined as the plane in which the posterior femoral condyles were superimposed. The same transformation to orient the femur in the sagittal plane was applied to the tibia. (B) The body-fixed F-E axis of the ISB JCS was perpendicular to the sagittal plane (vertical gray line) and passed through the most distal point of the trochlear groove. The origin of the femoral Cartesian coordinate system (black star) was the midpoint of the body-fixed F-E axis. (C) The body-fixed F-E axis of FUNC JCS was the line connecting the centers of best-fit circles of sagittal projections of the medial and lateral femoral condyles along an arc length of approximately 10º - 110º [5,8,11]. The origin of the femoral Cartesian coordinate system (black star) was the midpoint of the body-fixed F-E axis.

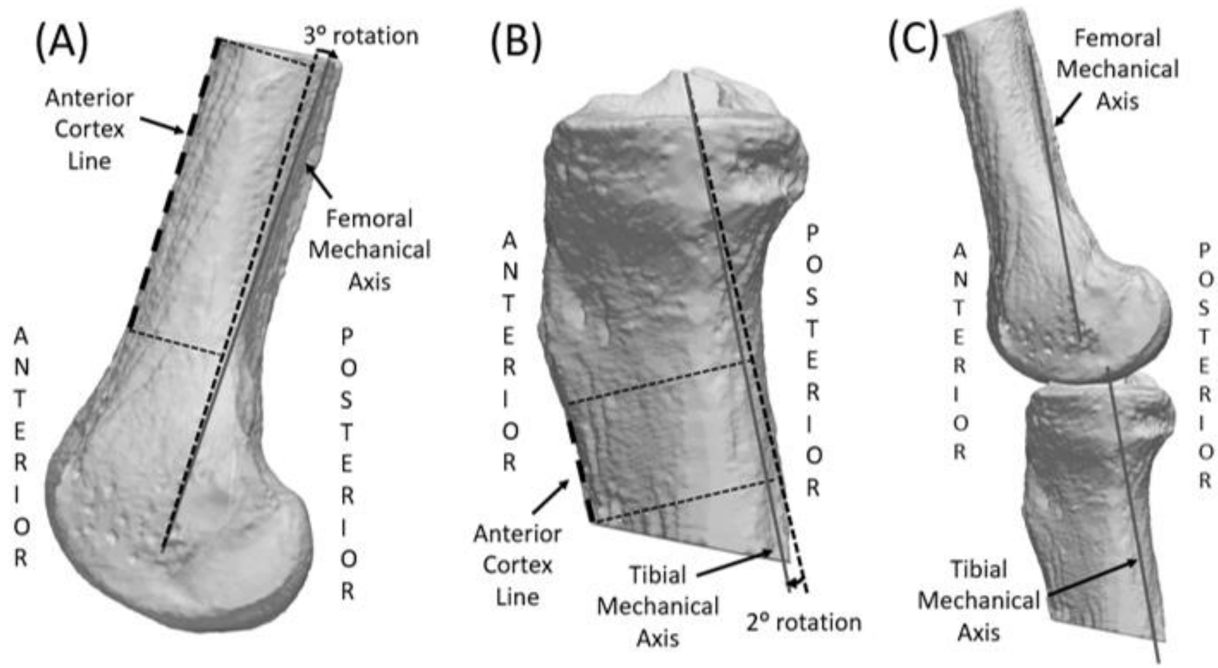

FIGURE 2.4: Process for defining the 0° reference using the femoral and tibial mechanical axes in the sagittal plane. (A) The femoral mechanical axis (solid) was the line that extended from the most distal point of the trochlear groove and was rotated 3° about that distal point from a line along the anterior cortex of the femur above the diaphysis (dashed) such that the proximal end of the line moved posterior [12]. (B) The tibial mechanical axis (solid) was the line that extended from the center of the tibial plateau and was rotated 2° from the line along the anterior cortex below the tibial tubercle (dashed) such that the distal point moved anterior [13]. (C) The 0° flexion reference was established as the relative rotation between the two bones when their respective mechanical axes were parallel in the sagittal plane.

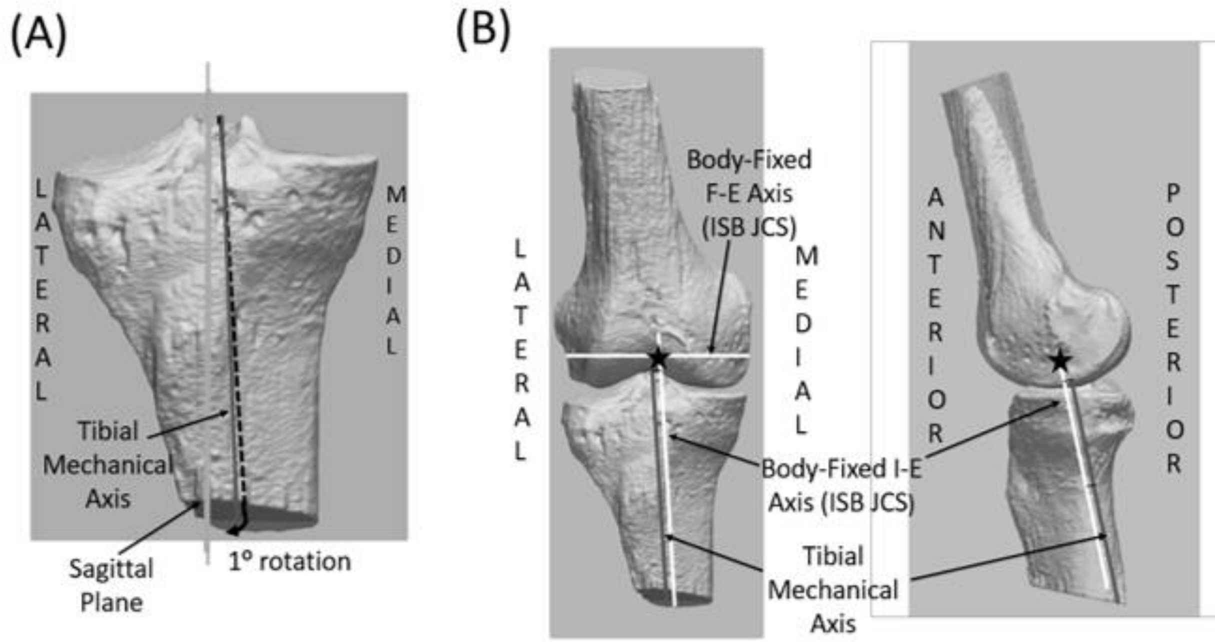

FIGURE 2.5: Process for finding the body-fixed I-E axis of the ISB JCS. (A) The coronal view (left) was perpendicular to the sagittal plane (right) and was the view in which the line (dashed) joining the midpoint of the tibia at the joint line to the point at the center of the shaft 10 cm below the joint line was longest. This line was the anatomic axis [14]. The mechanical axis of the tibia (solid dark gray) was the line rotated 1º from the anatomic axis such that the distal point moved laterally [14]. (B) Coronal (left) and sagittal (right) views of the body-fixed I-E axis of the ISB JCS, which was parallel to the tibial mechanical axis and passed through the origin of the femoral Cartesian coordinate system with the knee at the 0º flexion reference. The origin of the tibial Cartesian coordinate system for the ISB JCS coincided with the origin of the femoral Cartesian coordinate system (black star) [4].

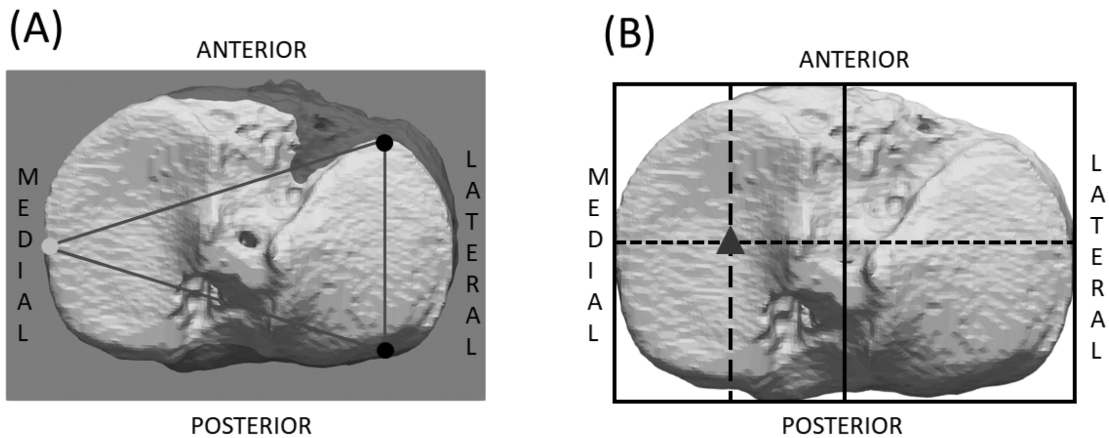

FIGURE 2.6: Process for finding the body-fixed I-E axis of the FUNC JCS. (A) The axial plane (gray background) was the plane connecting the end points of the major axis of the lateral tibial compartment (black dots) and the point on the medial edge of the tibia (white dot). (B) The origin of the tibial Cartesian coordinate system (dark gray triangle) was the center of a bounding box enclosing the medial compartment from the medial edge of the tibia to the center of the tibial plateau. The body-fixed I-E axis was perpendicular to the axial plane and passed through the tibial Cartesian coordinate system origin.

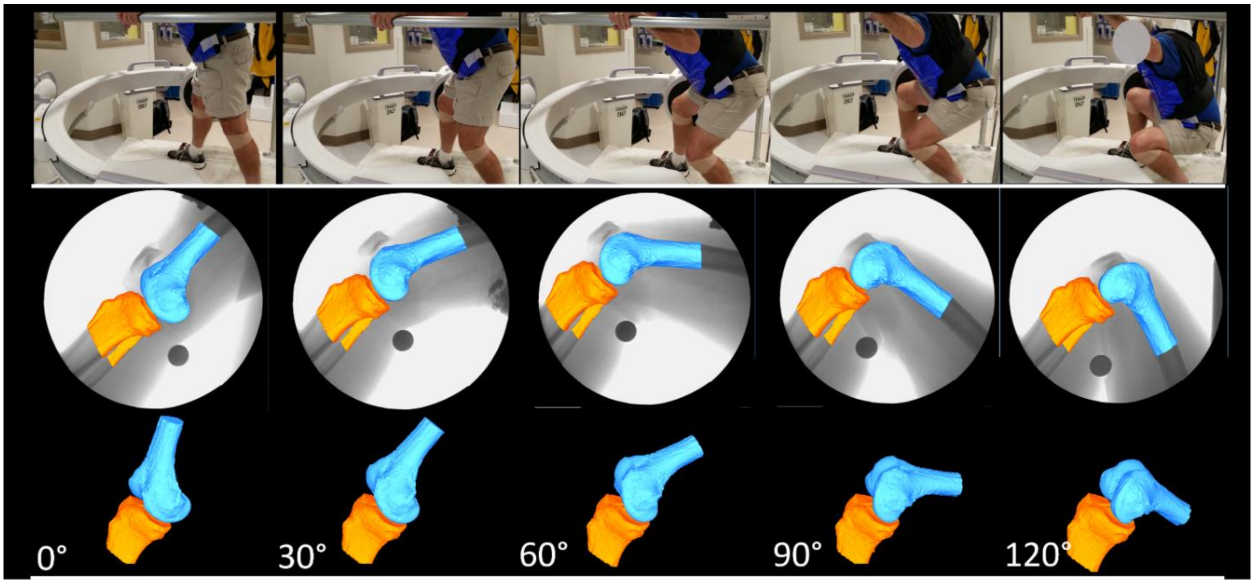

FIGURE 2.7: Single plane fluoroscopic images were taken during weight-bearing deep knee bend and used to register 3D bone models created from MRI images to compute the absolute position and orientation of the femur and tibia in their respective Cartesian coordinate systems. Using the kinematic model consisting of a chain of three cylindric joints [1], body-fixed F-E and I-E axes were assigned based on the ISB and FUNC definitions. Relative femoral and tibial 3D positions and orientations at specified flexion angles and tibiofemoral joint motions were calculated.

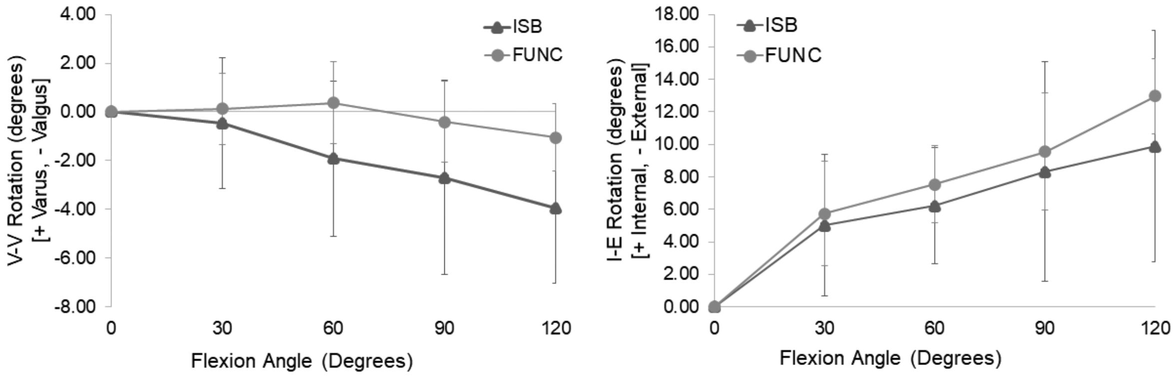

FIGURE 2.8: Rotations as a function of flexion angle for the two joint coordinate systems. The maximum absolute mean V-V rotation was limited to 1.1° with the FUNC JCS whereas the mean was 3.9° for the ISB JCS which is non-physiologic. The V-V rotation with the FUNC JCS satisfied the physiologic constraint (i.e., articular surfaces remain in contact). Internal rotation increased monotonically with flexion.

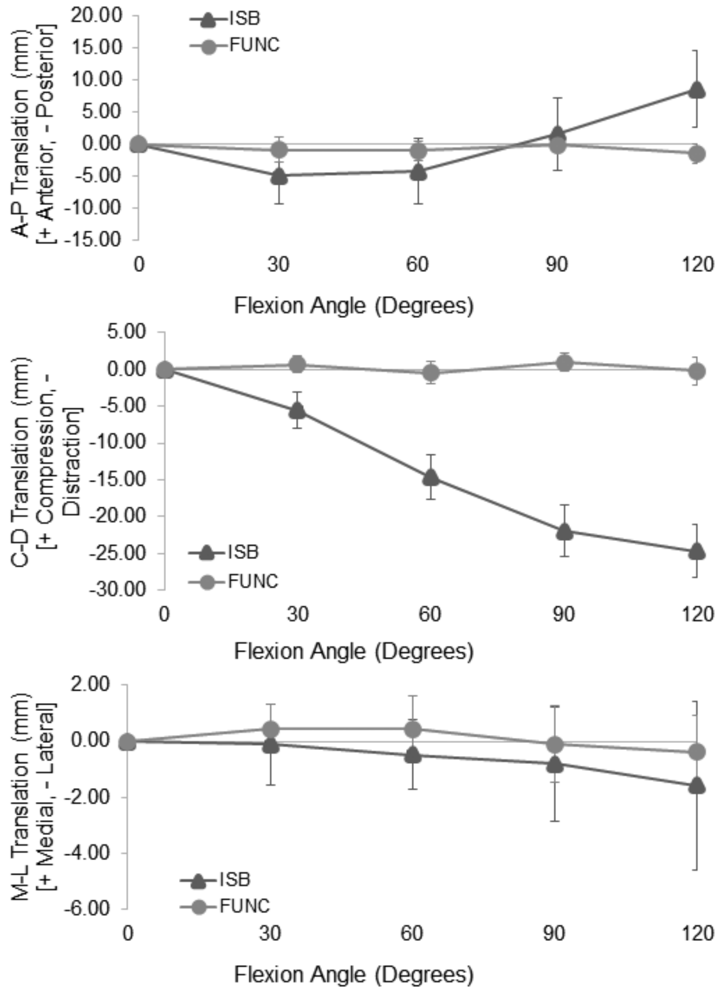

FIGURE 2.9: Translations as a function of flexion angle for the two joint coordinate systems. Patterns differed significantly between the ISB JCS and the FUNC JCS for all three translations. Magnitudes of C-D translations generated with ISB JCS were non-physiologic. The FUNC JCS resulted in clinically meaningful translations, which were near zero and hence largely free of kinematic crosstalk error for the entire range of flexion, in all three degrees of freedom.