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A COMPUTATIONAL ANALYSIS OF ERROR IN LOCATING THE ROTATIONAL AXES OF THE TIBIOFEMORAL JOINT WITH AN INSTRUMENTED SPATIAL LINKAGE

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INTRODUCTION

A method to measure the two kinematic axes of the tibiofemoral joint, the flexion-extension (F-E) axis and longitudinal rotation (LR) axis [1], was developed by Gatti [2]. This method used an instrumented spatial linkage (ISL), a series of six instrumented revolute joints that can measure motion between two rigid bodies. While Gatti's method demonstrated success in locating the F-E and LR axes, defining the axes and their errors using anatomically relevant coordinate systems would improve clinical relevance. While errors due to revolute joint transducer resolution were computed, errors due to nonlinearity and hysteresis in the transducers were not examined, and errors due to different applied tibiofemoral motions were not examined. Thus the objective was to computationally determine, using anatomically relevant coordinate systems, the errors in locating the F-E and LR axes due to nonlinearity and hysteresis in the revolute joint transducers for three different simulations of applied tibiofemoral motion.

METHODS

A virtual tibiofemoral joint, consisting of two perpendicular and non-intersecting axes [1], was created to simulate tibiofemoral kinematics. Two coordinate systems were created (Figure 1). The origin of the femoral anatomic coordinate system, $\mathbf{F_a}$, was created coincident with the global coordinate system, with $\hat{\mathbf{i}}_\mathbf{F}$ oriented anteriorly, $\hat{\mathbf{j}}_\mathbf{F}$ oriented medially, and $\hat{\mathbf{k}}_\mathbf{F}$ oriented proximally. The origin of the tibial anatomic coordinate system, $\mathbf{T_a}$, was defined at full extension to lie on the femoral anatomic coordinate system z-axis and 25 mm distal to the origin $\mathbf{F_a}$ (approximately the radius of the femoral condyles [3]), with the tibial coordinate system at the same orientation as the femoral coordinate system at full extension. The baseline F-E axis was created to pass through the femoral origin, perpendicular to the sagittal ($\hat{\mathbf{i}}_\mathbf{F}\hat{\mathbf{k}}_\mathbf{F}$) plane. The baseline LR axis was created to pass 2.5 mm anterior to the tibial origin [1], perpendicular to the transverse ($\hat{\mathbf{i}}_\mathbf{T}\hat{\mathbf{j}}_\mathbf{T}$) plane.

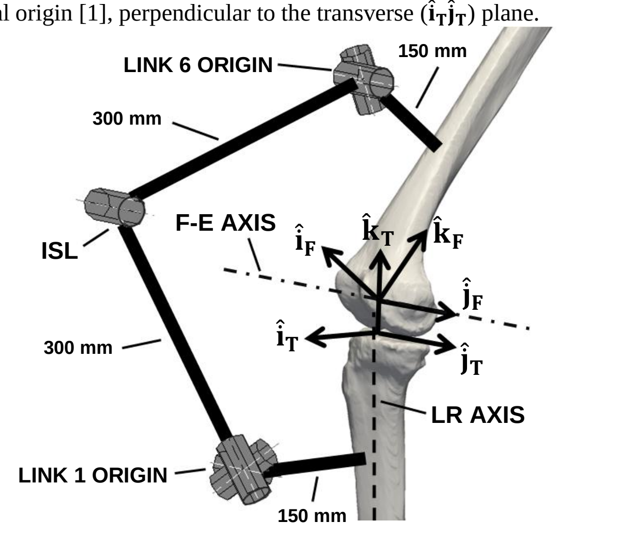

FIGURE 1. VIRTUAL TIBIOFEMORAL JOINT AND ISL.

To describe the F-E and LR axes with respect to anatomic references, each axis was described by two orientations and two positions, or 8 variables total. For the F-E axis, varus-valgus (V-V) and internal-external (I-E) orientations were defined as the projection angles of the axis on the $\hat{\mathbf{j}}_\mathbf{F}\hat{\mathbf{k}}_\mathbf{F}$-plane and the $\hat{\mathbf{i}}_\mathbf{F}\hat{\mathbf{j}}_\mathbf{F}$-plane respectively. The point where the axis intersects the $\hat{\mathbf{i}}_\mathbf{F}\hat{\mathbf{k}}_\mathbf{F}$-plane in the $\hat{\mathbf{i}}_\mathbf{F}$ and $\hat{\mathbf{k}}_\mathbf{F}$ directions describes the anterior-posterior (A-P) position and proximal-distal (P-D) position respectively. Likewise, for the LR axis, V-V and F-E orientations were defined as the projection angles of the axis on the $\hat{\mathbf{j}}_\mathbf{T}\hat{\mathbf{k}}_\mathbf{T}$-plane and the $\hat{\mathbf{i}}_\mathbf{T}\hat{\mathbf{k}}_\mathbf{T}$-plane respectively. The point where the axis crosses the $\hat{\mathbf{i}}_\mathbf{T}\hat{\mathbf{j}}_\mathbf{T}$-plane in the $\hat{\mathbf{i}}_\mathbf{T}$ and $\hat{\mathbf{j}}_\mathbf{T}$ directions describes the A-P position and medial-lateral (M-L) position respectively. In the virtual model, only the A-P position of the LR axis was nonzero.

A virtual ISL was created to measure motions across the virtual tibiofemoral joint. The coordinate system of ISL link 1 was defined as fixed to the virtual tibial anatomic coordinate system, with its origin placed on the $\hat{\mathbf{i}}_\mathbf{T}\hat{\mathbf{k}}_\mathbf{T}$-plane, 150 mm anterior to the tibial origin. Likewise, the coordinate system of ISL link 6 was defined as fixed to the femoral anatomic coordinate system, with its origin placed on the $\hat{\mathbf{i}}_\mathbf{F}\hat{\mathbf{k}}_\mathbf{F}$-plane, 150 mm anterior to the femoral origin. The neutral configuration of the ISL (i.e. with the tibiofemoral joint at full extension) was defined such that the angle between the two nonzero-length ISL links was 60°, and the origins of the first and last links were equidistant proximally and distally from the origin $\mathbf{F_a}$.

To simulate flexion, the tibial anatomic coordinate system was rotated about $\hat{\mathbf{j}}_\mathbf{F}$. To simulate I-E rotation, the tibial anatomic coordinate system was subsequently rotated about the virtual LR axis.

Three tibiofemoral motion simulations were created. In one simulation, sequential discrete flexion angles of 6° increments and sequential discrete I-E rotation angles of 5° increments were applied to the model. Each I-E rotation cycle began at 0°, and at odd-numbered flexion increments internal rotation was applied first to -20° followed by external rotation to 20° [5], followed by internal rotation back to 0°. At even-numbered flexion increments, the opposite pattern was applied. Flexion was applied from 0° to 120°, resulting in 357 total positions. To study the effect of randomized discrete motion, a second simulation randomly applied 21 discrete flexion angles between 0° and 120°. At each flexion angle, 17 random and discrete I-E rotations between -20° and 20° were applied, resulting in 357 total positions. To simulate continuous recording of applied motion, a third motion simulation was created with positions every 0.1° of flexion from 0° to 120°, resulting in 1201 total positions. Throughout flexion, I-E rotation was applied at a constant rate through 6 cycles, each representing I-E rotation from 0°, to -20°, to 20°, and back to 0°.

Using the virtual model, the ISL revolute joint angles throughout tibiofemoral motion were computed from the inverse kinematics of the ISL [4] using `MATLAB 7.6.0`. To simulate errors in the ISL, random revolute joint errors representing the linearity error (i.e. nonlinearity) and hysteresis error of the transducers were added to the simulated ISL revolute joint angles. To simulate linearity error, random errors were added with $\mu = 0$ and a standard deviation equal to one third the maximum linearity error of the transducer, or 0.25% full scale range. Three transducers had a full scale range of ±60° while three had a full scale range of ±30°. To simulate hysteresis error, the difference between the current and previous revolute angle was calculated at each position; if the change was positive, the maximum hysteresis error (0.1% full scale range) was subtracted from the nominal revolute joint angle; conversely, if the change was negative, the maximum hysteresis error was added to the nominal revolute joint angle. These two types of error were examined together.

New F-E and LR axes were determined using the erroneous data and the axis-finding method described by Gatti [2]. The errors in determining the axes were calculated by subtracting the positions and orientations of the baseline F-E and LR axes from the positions and orientations of the axes located with erroneous data. For each of the three types of applied motion, new revolute joint errors were calculated for 200 iterations to statistically determine the bias, precision and root-mean-squared (RMS) errors of each of the 8 positions and orientations. In the case of randomized discrete motion, the tibiofemoral positions were also randomized in each iteration.

RESULTS

The errors in the LR axis variables were much greater than the errors in the F-E axis variables (Figure 2). The LR axis variable with the highest error was the M-L position for all three types of motion. For the M-L position, continuous motion gave the lowest RMSE. The F-E axis variable with the highest RMSE was the A-P position for all three types of motion. Although the greatest RMSE for the A-P position occurred for the continuous motion, this error was an order of magnitude less than the error for the M-L position for the LR axis.

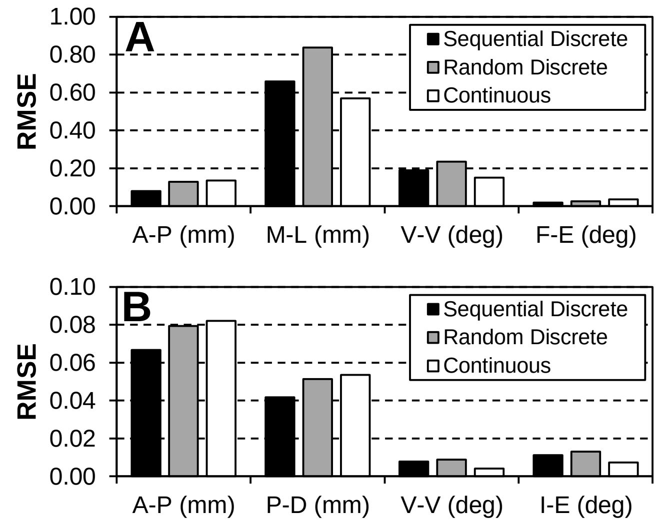

FIGURE 2. RMS ERRORS OF THE (A) LR AXIS AND (B) F-E AXIS FOR THE SPECIFIED MOTIONS.

DISCUSSION

Because no type of motion gave consistently the lowest RMS errors in the 8 positions and orientations studied, the preferred motion depends on the goal of the measurement. If the goal is to limit the largest error, then of the three motion types simulated, continuous motion is preferred because it gave the lowest error in the M-L position for the LR axis. Alternatively if the goal is to minimize the error in the most variables, then sequential discrete motion is preferred because it minimized the RMSE in 4 of the 8 variables studied.

Error sources not considered in this analysis that could further affect error include temperature variation of the revolute joint transducers, the resolution of the analog-to-digital converter connected to the ISL, errors in ISL calibration, and compliance in the ISL links.

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