INTRODUCTION

In robotic testing of cadaveric knees, the reported values of measured and applied motions and loads are dependent on the defined joint coordinate system (JCS) that describes the three-dimensional translations and rotations of the tibia with respect to the femur. The International Society of Biomechanics standard for describing tibiofemoral kinematics is reported by Grood and Suntay [1], relying on the locations of anatomical landmarks to define the axes about which flexion/extension, varus/valgus and internal/external rotations occur. While calculating coordinate systems (CSs) based on anatomical landmarks allows for specimen-specific descriptions of motion, the method is not ideal for comparing kinematics of many specimens, as the representation of kinematic responses will vary with uncertainty in locating the anatomical landmarks. This variability is evident when observing the range of off-axis translations and rotations during passive flexion. Grood and Suntay recognized this issue and recommended a method for translating the tibia and femur CSs to reduce off-axis translations during passive flexion. However, off-axis rotations were not considered and no detailed methodology exists to describe how to perform the necessary transformations [1].

The tibiofemoral joint is not truly a hinge joint, and some off-axis motion is expected, choosing a JCS that will minimize these motions might better regularize the manner in which tibiofemoral kinematics are measured, allowing for a more standardized representation that allows for tibiofemoral kinematic responses to be compared amongst specimens. Many have recognized a need for a more consistent JCS for describing tibiofemoral kinematics [1-3], but no established method has been adopted by the scientific community.

METHODS

Anatomical landmarks from six legs were digitized to define the tibiofemoral JCS reported by Grood and Suntay [1]. The JCS kinematics are reported as three translations (medial ($M$), posterior ($P$), superior ($S$)) and three rotations (flexion ($F$), valgus ($V$) and internal rotation ($I$)).

Each knee was rigidly secured to a custom testing apparatus and mounted to the Universal Musculoskeletal Simulator (UMS) [4] controlled with simVITRO™ software programmed using LabVIEW software (National Instruments, Austin TX). The system is capable of manipulating in six degrees of freedom (DOF) with six-axis force-torque control applied to the tibia CS. Each knee was positioned on the UMS at a neutral position and offsets were applied so that all JCS translations and rotations were zero. Each knee underwent a passive flexion profile ramping from 0-90 degrees flexion. A constant 50N compression load was applied and all other off-axis loads were set to zero.

The representation of the JCS was optimized ($JCS_{opt}(M_{opt}, P_{opt}, S_{opt}, F_{opt}, V_{opt}, I_{opt})$) such that the tibia CS remained the same, but an offset transformation was applied to femur CS ($f_{offset}(X,Y,Z,R,P,W)$) to minimize off-axis motions during passive flexion. Eq. 1 displays the transformation chain equation.

$$T_{fem_{opt},tib}(JCS_{opt}) = T_{fem_{opt},fem}(f_{offset}) \cdot T_{fem_{tib},tib}(JCS)$$

Tibiofemoral kinematics were considered at each 15 degree flexion increment during the passive flexion profile and optimization was performed in two parts using the LabVIEW NI_Gmath.lvlib: Constrained Nonlinear Optimization.vi. The rotational femur offsets ($R, P, W$) were initially set to zero and translational offsets were optimized by minimizing the cost function in Eq. 2 subject constraints ($|X,Y,Z| < 30 \text{ mm}$), where $i$ represents each flexion angle considered.
\[ f(X, Y, Z) = \sum_{i=1}^{N} \left( |M_{Opt}(i)| + |P_{Opt}(i)| + |S_{Opt}(i)| \right) \]  

(2)

With the translational offsets calculated, the rotational offsets were optimized by minimizing the cost function in Eq. 3, subject to constraints \((R, P, W < 29 \text{ degrees})\).

\[ f(R, P, W) = \sum_{i=1}^{N} \left( |F_{Opt}(i) - F(i)| + |V_{Opt}(i)| + |I_{Opt}(i)| \right) \]  

(3)

With the optimized femur CS, offsets were reapplied at the neutral position and the knee underwent the passive flexion profile with measured motions represented based on the optimized JCS.

RESULTS AND DISCUSSION

The optimized femur CS position differed from the original position by 5 to 34 mm and the resultant orientation differed by 1 to 18 degrees for the six specimens. Table 1 displays the femur CS offsets for all specimens.

**Table 1:** Femur CS Offsets

<table>
<thead>
<tr>
<th>Spec. #</th>
<th>Femur CS Offsets</th>
<th>X (mm)</th>
<th>Y (mm)</th>
<th>Z (mm)</th>
<th>R (°)</th>
<th>P (°)</th>
<th>W (°)</th>
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<td>oks_001</td>
<td>1.0</td>
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<tr>
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<tr>
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<td>-0.4</td>
<td>8.8</td>
<td>3.6</td>
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</tr>
</tbody>
</table>

Note: The X offset optimized to 1.0 mm for all specimens due to the optimization requiring a non-zero initial estimate. The default value was 1 mm and the X offset, being aligned with the medial direction, likely did not vary from the initial estimate. In the future, the initial estimate should be set closer to zero.

Figure 1 displays an example of the off-axis translations and rotations with motions represented based on the anatomical and optimized JCSs for specimen oks-001. Off-axis motions decreased substantially with the optimized JCS. However, there are still some, which supports the notion that the tibiofemoral joint is not a true hinge.

Figure 2 displays the ranges (averages and standard deviations) of off-axis motions for the six specimens undergoing passive flexion calculated based on both JCS representations. The average motions decreased when represented with the optimized JCS for all DOF. In addition, the standard deviations decreased for all DOF, indicating that as a JCS better aligns with the mechanical axes of the tibiofemoral joint, off-axis motions will converge to values within a threshold, allowing for kinematics to be compared across specimens.

A JCS optimized for minimal off-axis translations and rotations during passive flexion can facilitate a better baseline for comparing kinematics across specimens. The results in Figure 2 provides adequate evidence that our proposed methodology for optimizing the location of the femur CS decreases the off-axis motions of all knee specimens to a comparable amount during passive flexion.

REFERENCES


ACKNOWLEDGMENTS

Specimens for this study were funded by Open Knee(s) Project, NIGMS, NIH (R01GM104139, PI: Erdemir). Assistance from Ahmet Erdemir is appreciated.