INTRODUCTION:
Three-dimensional (3-D) skeletal motion capture technology currently employs a combination of planar video fluoroscopy and computed tomography (CT) to probe knee joint motion with high accuracy [1-4]. In order to take advantage of recent advancements in this technology, it is important to establish reliable coordinate systems for the tibia and femur. Current techniques for establishing anatomical coordinate systems (ACSs) for the tibia and femur use ex vivo joint palpation or radiographic bony landmark identification, and rely heavily on single points that are prone to variability. Furthermore, these techniques require data from the hip and ankle joints, in addition to the knee joint, which is often impractical for studies utilizing CT and MRI scans [4-6]. The objective of this study was to develop a reliable method for defining ACSs from 3-D surface models of the human distal femur and proximal tibia.

METHODS:
CT Imaging: The distal femur and proximal tibia of 5 fresh frozen cadaver knees (3 right, 2 left; 3 male, 2 female, age 61 ± 14 years) were imaged on a CT scanner (400 mA, 80 kVp, 0.22x0.22x0.625 mm: LightSpeed; GE, Piscataway, NJ).

Segmentation Technique: The distal femur and proximal tibia were segmented from the CT images and reconstructed at 3 different threshold levels (226, 406, & 586 HU) using commercial software (Mimics 12.01; Materialise, Ann Arbor, MI). Manual gap filling ensured mask continuity for each image slice. Distinct 3-D bone models were generated for each specimen’s femur and tibia at each threshold level.

ACS Determination: The 3-D bone surfaces of the tibial plateau, the femoral condyles, and the femoral shaft (Fig. 1), were isolated using geometric analysis software (Geomagic Studio; Geomagic, Durham, NC). The medial/lateral (M/L, x-) axis of the femoral coordinate system was defined by determining the best finite-cylindrical fit of the femoral shaft, then taking the cross product of its central axis with the M/L axis. Finally, the third (z-) axis of the femoral coordinate system was defined by the cross product of the M/L axis with the A/P axis (Fig. 1). The tibial coordinate system was defined using the plane that was the best fit to the surface of the tibial plateau. Within the plane, a bounding box was defined by the length and width of the tibial plateau. Its normal vector was designated as the long (z-) axis, and the other two axes (x- and y-) were defined by bisecting the plane perpendicular to its edges (Fig. 1).

Figure 1: Left: isolated femoral shaft with corresponding finite cylinder fit. Middle: isolated femoral condyles with corresponding finite cylinder fit. Right: isolated tibial plateau with corresponding finite plane fit. Example femur and tibia coordinate systems are shown; M/L (x-) axis in red, A/P (y-) axis in green, third (z-) axis in blue.

Reliability: 3 independent observers applied the femur and tibia ACS determination protocol described above to each 3-D bone model generated at each threshold level. Additionally, each observer applied the femur and tibia ACS determination protocol twice more for each 3-D model generated from each specimen’s CT scan at one threshold level (226 HU).

Variability Analysis: For both the tibial and femoral ACSs, the variability of the origin was evaluated as the position difference from the mean origin. ACS x-, y-, and z-axis variability was evaluated as the angular difference from the mean origin. ACS x-, y-, and z-axis variability was evaluated as the angular difference from the mean origin. ACS x-, y-, and z-axis variability was evaluated as the angular difference from the mean origin. Individual observer variation (intra), and absolute variation independent of observer (inter). Means and 95% confidence levels were calculated for all evaluation measures described.

RESULTS:
The mean variability in the location of the origin of the tibial and femoral ACS was less than 1 mm for threshold, inter, and intra variability evaluations (Fig 2). The mean tibial and femoral angular x-, y-, and z-axis displacement was less than 1 degree for threshold, inter, and intra variability evaluations (Fig 2).

DISCUSSION:
This study has introduced a novel method for establishing ACSs from 3-D models generated from CT scans of the distal femur and proximal tibia. ACS variability was assessed based on translational and rotational displacements from the mean origin and mean x-, y-, and z-axis directions. Both femur and tibia ACS determination algorithms were insensitive to threshold segmentation, individual observer variation and absolute variation independent of observer. The larger tibial ACS y- and z-axes inter and intra variability is a consequence of the algorithms slightly higher sensitivity to the observer selected tibial plateau. Overall, this algorithm offers a reliable method for computing ACSs for the femur and tibia in order to create a joint coordinate system for describing rotational and translational 3D knee motion. To better assess the overall accuracy of the proposed algorithm, further inquiry is required to evaluate the consistency of this method across subjects based on common anatomical landmarks or surface registration. Ultimately, a computational method needs to be developed that automatically isolates the bone regions (Fig. 1) in order to eliminate all observer variability.

REFERENCES:

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