In Vivo Method for Tracking 3D Kinematics of the Healthy and Anterior Crucial Ligament Transected Goat Knee Joint: A Preliminary Study

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Abstract*—The objective of this paper is to introduce a novel method for tracking 3D kinematics of the healthy and anterior crucial ligament (ACL) transected goat knee. Sham and ACL transection surgeries were performed on two goats (1 sham, 1 ACL transection) with tantalum bone markers inserted into the tibia and femur. Goat gait was captured using a high-speed, biplanar fluoroscopy system and bone markers were digitized to extract their 3D coordinates during the entire goat gait cycle. A method for defining a clinically relavent anatomical coordinate system was developed based bone features present on 3D bone models from computed tomography (CT) scans of the two goat knees. The defined anatomical coordinate system was linked, rotoscoped, and animated to extract meaningful rotational and translational gait kinematics. Rotational range of motion measurements were calculated with the largest range of motion in flexion/extension (FE), followed by internal/external (IE) rotation, and then ab/adduction (AB/ADD). The magnitude of anterior/posterior (AP) translation was determined showing slightly elevated translation in the ACL transected goat knee. These data indicate the ability to and repeatability of tracking 3D kinematics *in vivo*.

I. Introduction

ACL injury has reached epidemic levels. In the United States, it is estimated that between 100,000 to 200,000 people sustain an ACL injury each year [1]. Injury to the ACL is thought to change the inherent mechanics of the knee, disrupting cartilage metabolism. It is generally accepted that these changes in knee joint mechanics have been linked to increased incidence of articular cartilage degeneration (osteoarthritis); however, the precise mechanism is poorly understood [2]. Developing an *in vivo* method for accurately tracking 3D bone kinematics during relative movements of articular surfaces during natural and load bearing-movements in both healthy and injured knees may be useful for exploring the relationship between joint motion and osteoarthritis. The goal of this paper is to introduce a novel method for tracking 3D kinematics of the healthy and ACL transected goat knee joints.

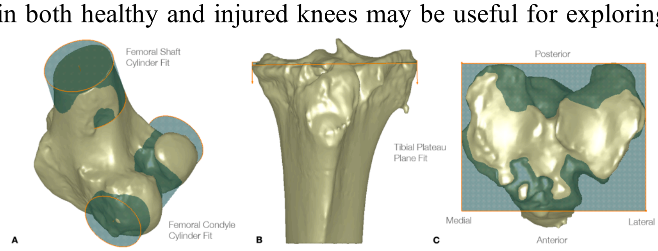

Fig. 1: Femoral shaft and condyle cylinder fit. (B) Anterior view of tibial plateau plane fit. (C) Top view of tibial plateau plane fit.

II. Methods

A. Surgical Technique

One pigmy goat (53.1 kg) received transection to remove the ACL, while one pigmy goat (64.2 kg) received sham surgery that was identical to the first surgery without ACL transection. In conjunction with the transection and sham surgeries, each goat was implanted with spherical tantalum bone markers. A total of twelve bone markers were embedded in the distal femur and proximal tibia (six markers per bone) of each goat. Tantalum spherical beads were chosen because of their biocompatibility and high radio-density for optimum visualization during fluoroscopic motion capture.

B. Fluoroscope Motion Capture

The knee joints of one sham and one ACL transected goat were imaged using a high-speed, biplanar video fluoroscopy system based on two C-arm (OEC 9400) fluoroscope assemblies. Each C-arm assembly is retrofitted with an x-ray source opposite a 12-inch image intensifier optically coupled to a digital high-speed video camera (Photron Fastcam-X 1025pci, 250 frames/s). Source-image distance is 66 cm.

Each goat was walked on a standard treadmill and video sequences were recorded synchronously with both video cameras at shutter speeds of 0.001 seconds to reduce motion blur. X-ray source voltage and current were independently set to provide optimal image contrast (camera one: 100 kVp 3.2 mA, camera two: 110 kVp 3.0 mA) for visualizing radiopaque bone markers. Gait was captured for 4 to 5 walking strides (one stride is defined as the period between goat hoof lift offs).

A calibration cube/lattice containing 64 radiopaque markers with known 3D coordinates was imaged using the biplanar video fluoroscopy system at the end of each recorded gait period. The calibration cube provides a basis for determining

3D coordinates of digitized bone markers.

C. 3D Marker Digitization

A marker digitization software package (XrayProject; CTX Technology Development Project, Brown University, Providence, RI) was used to digitize the 2D location of each bone marker visualized on each goat's recorded video fluoroscopy sequence. The bone markers were digitized at each frame of both cameras' synchronous video sequences. The 3D coordinates of each bone marker at each frame are calculated from the combined cameras' digitized 2D locations and calibration cube images.

D. Anatomical Coordinate System Determination

The digitized 3D bone markers must be expressed in an anatomical meaningful coordinate system to produce clinically relevant knee kinematics. A novel, repeatable method for establishing an anatomically meaningful coordinate system using bone features from 3D bone models was developed.

3D bone models were created from CT scans (LightSpeed; GE, Piscataway, NJ) for the tibia and femur of each goat knee (80 kVp, 165 mA, slice thickness 0.625 mm, number of slices 193 for sham and 220 for ACL transected). A medical imaging software package (Mimics 9.11; Materialise Ann Arbor, MI) was used to produce 3D models by manual segmentation of bone in the axial, coronal, and sagital planes.

3D bone features were found using a 3D geometry analysis software package (Geomagic Studio 9; Geomagic, Durham, NC). The 3D bone features include the surface of the tibial plateau, the volume located between the most medial and most lateral femoral condyles, and the femoral shaft.

The coordinate systems of the femur and tibia were made orthogonal through the following procedure [Fig. 1]. The flexion/extension axis of the femur coordinate system was designated as the primary or first axis and was based on a best cylindrical fit of the volume located between the most medial and most lateral femoral condyles. The ab/adduction axis was designated the second axis. It was defined by taking the cross product of the femoral shaft vector, determined from a best cylindrical fit, with the flexion/extension axis. Finally, the third axis of the femur coordinate system was defined by crossing the flexion/extension axis with the ab/adduction axis.

The tibial coordinate system was defined using the plane that was best-fit to the tibial plateau. The plane was finite with its corners approximating the length and width of the tibial plateau. Its normal vector approximates the tibial shaft, and the other two axes were defined by bisecting the plane perpendicular to its edges.

E. 3D Joint Kinematic Data Processing

A 3D modeling and animation software package (Maya 8.5; Autodesk, San Rafael, CA) was used to link, rotoscope, and animate the digitized bone marker 3D coordinates to the 3D bone models and the anatomical axes. The resulting animation includes the 3D coordinates of the tibia and femur bone models with corresponding anatomical axes for each goat at each frame of the entire gait period captured during video fluoroscopy.

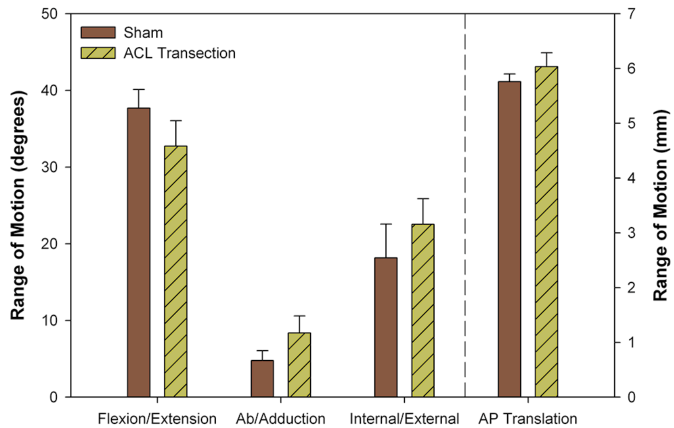

Fig. 2: Bar chart depicting mean range of motion (left y-axis in degrees, right y-axis in mm) between goat gait strides with standard deviation bars. FE, AB/ADD, IE rotation, and AP translation are shown.

The animated anatomical axes data generated in Maya were loaded into a motion analysis software package (Visual3D; C-Motion, Germantown, MD) for performing kinematic analysis on local reference frames. A joint coordinate system was defined from the tibia and femur anatomical axes using the method of Grood and Suntay [3]. The ordered sequence of rotations was FE (x-axis), AB/ADD, (y-axis), and IE rotation (z-axis). Additionally, AP translation of the femur relative to the tibia was determined. The average range of motion in each goat knee joint was determined as the difference between the maximum and minimum peaks of each rotation.

III. Results

The kinematic rotational and translational patterns were similar across both sham and ACL transected goat knee joints [Fig. 2]. The largest range of motion in the goat knee joint was FE (sham 37.7° ± 2.43°, ACL Transected 32.7° ± 3.30°), followed by IE rotation (sham 18.1° ± 4.41°, ACL Transected 22.5° ± 3.33°), and then AB/ADD (sham 4.76° ± 1.29°, ACL Transected 8.37° ± 2.21°). The AP translation magnitude of the femur relative to the tibia for the sham goat was approximately 5.76 mm ± 0.138 mm. The ACL transected goat's AP translation magnitude was slightly higher, approximately 6.03 mm ± 0.256 mm).

IV. Discussion

A novel method for tracking 3D kinematics of the healthy and ACL transected goat knee joints has been introduced. The relative rotational and translational motion of the goat knee joint was quantified by determining range of motion in a sham and ACL transected goat knee. Any differences observed in kinematics between the two subjects tested could be a result of ACL transection altering joint mechanics or possibly due in part to differences in the defined knee coordinate systems. Further studies need to be conducted to validate the robustness this method. Range of motion measurements [Fig. 2] are consistent with other quadruped kinematic studies by Frank *et al.*, which validate the proposed method and establishes a solid foundation on which to move forward [2, 4-5]. The results of this preliminary study indicate the ability to and repeatability of tracking 3D kinematics *in vivo*.

V. References

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