Laboratory 1: Rigid Body Kinematics
September 14/15, 2005
BIOEN 5201 – Introduction to Biomechanics
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Lab Quiz: A 10 point lab quiz will be given before class, accounting for 10% of the lab report grade. Be familiar with the entire protocol, however the “tips” section will not be tested.

Background:
After the second-world war, there were a large number of limbless ex-servicemen in the United States. The Government realized that a major effort was needed to develop improved prostheses, particularly lower-limb prostheses, to get these people walking again. As part of this large research project, the University of California at Berkeley was requested to perform comprehensive studies on normal and disordered locomotion. Out of this research came much of our present understanding of the biomechanical mechanisms used in walking and running.

Kinematics is the branch of physics which involves the description of motion, without examining the forces which produce the motion (dynamics or kinetics, on the other hand, involves an examination of both a description of motion and the forces which produce it). In bioengineering, body segments are considered to be rigid bodies for the purposes of describing the motion, allowing kinematics to become a useful tool in gait analysis. For example, traumatic brain injury introduces a varying mixture of spasticity and contractures that causes unpredictable errors in the patients’ gate. Kinematic analysis provides accurate definitions of the abnormalities in muscle action, enabling physicians to perform surgical release or transfer operations that can dramatically improve gate. Gate analysis can also assist to alleviate difficult and stiff movements caused by cerebral palsy.

Computational modeling is another application of kinematics in bioengineering. Kinematic data can be input to finite element preprocessors, guiding the motions of the model. This allows models to behave with correct anatomical movement and replicate experiments. Overall, kinematic analysis is a valuable tool in bioengineering and other industries. Calculating and applying kinematic data will be the focus of this laboratory.

Objective:
The objective of this laboratory is to use a 3D motion analysis system and 3D electromagnetic digitizer to measure the kinematics of a bovine knee joint under passive flexion. The student will learn how these measurement techniques work and how they can be combined with the equations of 3D rigid body kinematics to track the relative motion between two rigid bodies. The student will also learn how to decode a medium-size software program.

NOTE – there is only one set of digital cameras and framegrabbers. Thus, this experiment will be performed by one group at a time.

Equipment required:
2 Pulnix TM 1040 digital cameras, tripods and incandescent lights, lenses and extension tubes
Dual Athlon PC with 2 Bitflow Roadrunner Framegrabbers and DMAS motion analysis software
Polhemus electromagnetic digitizer
2 kinematic marker clusters and associated screws for attachment to femur and tibia
3D calibration frame
Extremity holder clamping system
Bovine knee
Drill press or cordless drill for mounting of kinematic marker clusters to femur/tibia
Philips screwdriver to attach kinematic marker clusters
CD-R for data backup
Freezer for specimen storage
Digital calipers
Plastic metric ruler

**Supplies required:**
Chux, gloves (non-sterile), dissection tools, 0.9% normal saline, cleanup supplies

**Experimental procedure:**

NOTE – DO NOT MOVE THE CAMERAS DURING TESTING! THEY ARE CALIBRATED BASED ON THEIR CURRENT LOCATIONS!

1. Attach kinematic markers to femur/tibia (TA before class)
2. Calibrate volume around knee with DLT using DMAS software (TA before class)
3. Mount knee in extremity holder at close to 0 degrees flexion.
4. Establish a neutral position for the knee at approximately 0 degrees flexion.
5. Record approximate distance between markers in femoral cluster, between markers in tibial cluster, and between the two clusters for later verification of results from the motion analysis system. (Use a tape measure and/or digital calipers)
6. Using the Polhemus digitizer, digitize coordinates necessary to establish an embedded coordinate system in the femur with respect to a coordinate system defined with the markers on the femoral kinematic marker cluster. Repeat for the tibia. The embedded coordinate systems should be set up to follow the conventions in the Grood-Suntay article. The TA will guide you through the digitization process.
7. Flex/extend knee between 90 and 0 degrees flexion and then back to 90 while recording both cameras at 5 Hz (1 cycle, approx 30 sec/cycle)
8. Determine the 3D coordinates of all markers on the femoral and tibial marker clusters using the DLT calibration in the DMAS software package.
9. Back up all data onto CD-R before leaving the laboratory. You should have:
   Data from the electromagnetic digitizer (anatomical coordinates used to define embedded coordinate systems in femur and tibia), coordinates of contrast markers composing the kinematic clusters, and coordinates used to define a reference system.

**Data analysis:** The objective of the data analysis is to determine the Grood-Suntay joint angles and translations during knee flexion/extension based on the transformation matrix between the
femoral embedded coordinate system and the tibial embedded coordinate system. You will be provided with a MATLAB program to perform the data analysis. Please see the instructions for the lab report for details on the procedure for analyzing the data and preparing your report.

The overall picture of the analysis is as follows:

1) Determine the 4x4 transformation matrix between a coordinate system embedded in the femur (fe) and a coordinate system defined using the femoral marker cluster (fm), \( T_{fe \rightarrow fm} \). Note that this transformation NEVER CHANGES during the test, as both coordinate systems are affixed to the same rigid body. This matrix is calculated from the digitized data.

2) Determine the 4x4 transformation matrix between a coordinate system defined using the tibial marker cluster (tm), \( T_{tm \rightarrow te} \), and a coordinate system embedded in the tibia (te). Note that this transformation NEVER CHANGES during the test, as both coordinate systems are affixed to the same rigid body. This matrix is calculated from the digitized data.

3) Determine the 4x4 transformation matrix between a coordinate system defined using the femoral marker cluster (fm) and a coordinate system defined using the tibial marker cluster (tm) as a function of time, \( T_{fm \rightarrow tm(t)} \) for both tests. This matrix is calculated from the recorded DMAS positional data.

Figure 1: Experimental setup. Bovine knee is mounted in holder, with kinematic marker clusters attached to femur (top) and tibia (bottom).
4) The overall transformation matrix between the embedded femoral and tibial coordinate systems is then:

\[
[T_{fe\rightarrow te}(t)] = [T_{tm\rightarrow te}] [T_{fm\rightarrow tm}(t)] [T_{fe\rightarrow fm}]
\]

5) Calculate the three Grood-Suntay joint flexion angles (flexion/extension, abduction/adduction, tibial rotation) and three translations (medial/lateral tibial displacement, anterior/posterior tibial displacement, joint distraction) as a function of time based on the overall transformation matrix for each of the experiments (see equations 16-20 of the Grood-Suntay JBME manuscript).

**Tips**

Use your ruler measurements between the approximate origins of the coordinate systems to verify the translations. The components of the rotation matrix can be verified by computing the appropriate dot products between the coordinate axes. This yields the cosine of the angle between the axis for a quick check that the angles are approximately right.

It will be easiest to verify the transformation matrices if you stick to the conventions described above and in the Grood-Suntay paper for orientation of your axes. For instance, the Grood-Suntay paper always defines the z-axis along the long direction of the bone, with positive in the proximal direction. The x-axis is always oriented medial-lateral, with the lateral direction as positive. The y-axis is always oriented anterior-posterior, with the anterior direction as positive.

When composing the transformation matrices, remember that you are looking for the transformation that rotates/translates one set of axes into another. Make sure that you define your displacement vectors appropriately (i.e, don’t get them backwards).