Target Outcome

- Measurements of six degree of freedom kinetics and kinematics of the tibiofemoral joint under quasi-static loading conditions
- Measurements of six degree of freedom kinetics and kinematics and contact pressures of the patellofemoral joint under quasi-static loading conditions

Prerequisites

Infrastructure

For more details see Infrastructure/ExperimentationMechanics.

Prerequisite Protocols

- Specifications/Specimens
- Specifications/SpecimenPreparation
- Specifications/ExperimentationAnatomicalImaging
- Specifications/PressureCalibration (for patellofemoral joint testing)

Related Protocols

- Specifications/Registration

Protocols

Tibiofemoral Joint Testing

Primary Conditions

- Joint laxity at 0°, 30°, 60°, and 90° flexion angles for three isolated degrees of freedom:
    1. internal-external rotation,
    2. varus-valgus, and
    3. anterior-posterior translation.
- Combined loading; permutations of internal-external rotation moments, varus-valgus moments, and anterior-posterior drawer forces.

Secondary Conditions

- Joint stretching at various flexion angles, to potentially identify gross mechanical properties of the ligaments

Measurements

- Joint and segment coordinate system transformation matrices
- Joint kinetics
    - Joint kinetics are calculated based on robot position and 6-axis load cell output.
    - reaction forces (anterior-posterior, compression-distraction, medial-lateral)
    - reaction moments (flexion-extension, internal-external rotation, varus-valgus)
    - provided in anatomical joint coordinate system
    - provided in a human-readable or openly accessible form with clear descriptions of data structures and file naming/storage conventions
- Joint kinematics
    - Joint kinematics are calculated in two different ways:
        - Based on Optotrak sensor output
        - Based on robot position output
    - translations (anterior-posterior, compression-distraction, medial-lateral)
    - rotations (flexion-extension, internal-external rotation, varus-valgus)
    - provided in anatomical joint coordinate system
    - provided in a human-readable or openly accessible form with clear descriptions of data structures and file naming/storage conventions

Equipment Use Modes

- Refer to Infrastructure/ExperimentationMechanics for details of the equipment utilized in this specification.
- Tibiofemoral joint testing will be done via the six degrees of freedom robot (Rotopod R-2000, PRSCO, Hampton, NH) with a rotary stage mounted to the top to yield a seventh degree of freedom for increased range of motion.
- An Optotrak motion tracking system (NDI, Ontario, Canada) will used to digitize the robotic system hardware and specimen anatomy, to create and control motions and loads in an anatomical knee joint coordinate system specific to the specimen (Grood and Suntay, 1983).
- A universal force sensor (UFS) will be attached to the robot platform, or may be attached to the frame surrounding the robot depending on the range of motion considerations of the particular loading condition. The tibia will be fixed to the UFS.
- The robot will be operated in real-time force feedback control so that loading trajectories can be applied to determine the five degrees of freedom kinematics of the joint. Flexion will be prescribed, as in position control.

Operating Procedure

Preparation:

The testing procedure assumes that the tibiofemoral joint is prepared according to specimen preparation specifications. See relevant section at Specifications/SpecimenPreparation

Robot-Specimen Assembly & Alignment:

The testing procedures require placement of the specimen on the robot and following the necessary set-up procedures. These are detailed in the Infrastructure/ExperimentationMechanics/simVITRO_setup_tutorial.pdf. Specific to this testing protocol:

- The tibia will be mounted pointing upwards, attached to the stationary frame through the load transducer.

Coordinate System Optimization:

- A kinetics based neutral position (minimal loading) will be established once the femur is set to 0° flexion angle by operating the robot in force control mode.
- The tibiofemoral joint will be moved under a passive flexion from 0° to 90° flexion with a 50 N compressive load. The femur coordinate system will then be optimized to minimize the change in joint translations and off-axis rotations throughout the cycle. This process is intended to objectively define a functional mechanical axis of the femur. Some limitations with this approach may exist in that the screw home mechanism, i.e. off-axis rotations, may be minimized.
- The kinetics based neutral position will re-established with the refined coordinate system.

Preconditioning:

- The specimen will be preconditioned by manually loading the knee and by applying the terminal loads of the laxity loading protocols once for 30° flexion.

Testing of Primary Conditions:

- Testing protocols were adapted from Borotikar (2009).
- The data will be collected and stored based on filing naming and data storage conventions utilized by the BioRobotics Core of the Cleveland Clinic, see Infrastructure/ExperimentationMechanics.
- Throughout all tests, a 20N axial compression will be included to maintain tibiofemoral joint contact.
- The actions during the timeline of testing will be:
    1. Apply AP laxity loading at 30° flexion (reproducibility test):
        - Anterior/posterior force of 0 to ±100 N in steps of 10 N. Ensure adequate wait time for each step to settle to the desired loading, e.g. ~5 sec.
        - Note that this loading condition will be repeated throughout testing to ensure there was no injury or damage to any of the structures in the joint. It will also quantify small changes in joint laxity that may occur during testing due to repetitive loading.
    2. Set flexion angle to 0°.
    3. Apply laxity loading:
        a. Internal-external rotation: 0 to ±5 Nm in steps of 1 Nm. Ensure adequate wait time for each step to settle to the desired loading, e.g. ~10 sec.

    b. Varus-valgus: 0 to ±10 Nm in steps of 2.5 Nm. Ensure adequate wait time for each step to settle to the desired loading, e.g. ~10 sec.
    c. Anterior-posterior translation: 0 to ±100 N in steps of 10 N. Ensure adequate wait time for each step to settle to the desired loading, e.g. ~10 sec.
4. Apply combined loading:
    . permutations of internal external rotation moments of -5, 0, 5 Nm, varus-valgus moments of -10, 0, 10 Nm, and anterior-posterior drawer force of -100, 100 N. Ensure adequate wait time for each step to settle to the desired loading, e.g. ~10 sec.
5. Set flexion angle to 30°.
6. Apply laxity loading.
7. Apply combined loading.
8. Apply AP laxity loading at 30° flexion (reproducibility test).
9. Set flexion angle to 60°.
10. Apply laxity loading.
11. Apply combined loading.
12. Set flexion angle to 90°.
13. Apply laxity loading.
14. Apply combined loading.
15. Apply AP laxity loading at 30° flexion (reproducibility test).

Patellofemoral Joint Testing

Primary Conditions

- Patellofemoral mechanics under quadriceps loading at tibiofemoral flexion angles of 0°, 15°, 30°, 45°, and 60°.

Secondary Conditions

- Patellofemoral mechanics under quadriceps loading at flexion angles of 0°, 15°, 30°, 45°, and 60° with perturbed tibiofemoral internal-external rotation (+/- 10°)
- Patellofemoral mechanics under quadriceps loading at flexion angles of 0°, 15°, 30°, 45°, and 60° with modified quadriceps line of action (+/- 5° varus/valgus).

Measurements

- Joint and segment coordinate system transformation matrices
- Joint kinematics
    - joint kinematics are calculated based on Optotrak sensor output
    - translations (anterior-posterior, compression-distraction, medial-lateral)
    - rotations (flexion-extension, internal-external rotation, varus-valgus)
    - provided in anatomical joint coordinate system

    - provided in a human-readable or openly accessible form with clear descriptions of data structures and file naming/storage conventions
- Contact pressures
    - contact pressures are calculated based on Tekscan sensor outputs
    - sensor location aligned with anatomical joint coordinate system
    - provided in a human-readable or openly accessible form with clear descriptions of data structures and file naming/storage conventions

Equipment Use Modes

- Refer to Infrastructure/ExperimentationMechanics for details of the equipment utilized in this specification. Specifications/SpecimenPreparation provides information on the state of the specimens before this testing starts.
- Tibiofemoral joint loading will achieved using the six degrees of freedom robot (Rotopod R2000, PRSCO, Hampton, NH) with a rotary stage mounted to the top to yield a seventh degree of freedom for increased range of motion.
- Quadriceps loading will be applied by a muscle actuator system.
    - A linear actuator will be used for this purpose, see (Infrastructure/ExperimentationMechanics).
    - A freeze clamp will be used to attach the actuator to the tendon (Specifications/SpecimenPreparation).
    - The line of action will be setup to approximate the sulcus defined (inferior-superior) direction of the trochlear groove and will be placed accordingly before testing.
        - The line of action of the actuator will be quantified in a known coordinate frame during robot initialization, see Specifications/Registration.
- Joint kinematics will be measured using an Optotrak motion tracking system (NDI Corp., Ontario, Canada), which utilizes infrared emitting diode (IRED) markers:
    - Triad marker clusters will be attached to each bone using the developed protocol.
    - Kinematics will be described using a standard joint coordinate system, much like the tibiofemoral joint.
- Pressure measurements will be accomplished using a pressure sensor (K-Scan sensor 5051, Tekscan Inc., MA) placed between the cartilage surfaces of the patella and femur
    - Measures contact pressure distribution, area, and total force.
    - Equivalencing and calibration will need to be performed before the testing, refer to Specifications/PressureCalibration.
    - Specimen preparation will be required to accommodate the sensor throughout the testing procedure. Details in Specifications/SpecimenPreparation.

Operating Procedure

Preparation:

The testing procedure assumes that the patellofemoral joint is prepared according to specimen preparation specifications. See relevant section at Specifications/SpecimenPreparation

Robot-Specimen Assembly & Alignment:

The testing procedures require placement of the specimen on the robot and following the necessary set-up procedures. These are detailed in the Infrastructure/ExperimentationMechanics/simVITRO_setup_tutorial.pdf. Specific to this testing protocol:

- Before assembly, ensure the pressure sensor is in place, see Specifications/SpecimenPreparation.
- The femur will be mounted pointing upwards, attached to the stationary frame; tibia will be attached to the moving frame through the load transducer.
- If necessary, quadriceps actuator will be repositioned to accommodate appropriate line of action.

Coordinate System Optimization (Tibiofemoral Joint):

- If the specimen is flipped in the robot for patellofemoral joint testing (femur pointing upwards), the coordinate system optimization for the tibiofemoral joint needs to be repeated.
- A kinetics based neutral position (minimal loading) will be established once the femur is set to 0° flexion angle by operating the robot in force control mode.
- The tibiofemoral joint will be moved under a passive flexion from 0° to 60° flexion with a 50 N compressive load. The femur coordinate system will then be optimized to minimize the change in joint translations and off-axis rotations throughout the cycle. This process is intended to objectively define a functional mechanical axis of the femur. Some limitations with this approach may exist in that the screw home mechanism, i.e. off-axis rotations, may be minimized.
- The kinetics based neutral position will re-established with the refined coordinate system.

Acquisition of Quadriceps Line of Action:

- The quadriceps line of action will be digitized at neutral joint state, using Optotrak probe. The order of digitization is inferior point, center point, and superior point.

Preconditioning:

- If desired, pre-conditioning of the patellofemoral joint should be performed by manually loading the knee. Our previous results indicated that patellofemoral joint kinematics were insensitive to the load magnitude. Nonetheless, pre-conditioning may have an effect.

Testing of Primary Conditions:

- The data (tibiofemoral and patellofemoral) will be collected and stored based on file naming and data storage conventions utilized by the BioRobotics Core of the Cleveland Clinic, see Infrastructure/ExperimentationMechanics.

- Tekscan pressure measurements output in the proprietary .fsx format. Pressure measurement file names will be specified as Specimen#_surgicalState_flexionAngle_quadLoad_Trial#.fsx.
    - specimen# = specimen identifying number as provided by the cadaveric supplier. Specimen demographics will be provided for each specimen.
    - surgicalState = This is the overall sate of the joint. This testing includes will be accomplished using a structurally intact joint. As such, it will be described as "intact." Details related to specimen preparation can be found in Specifications/SpecimenPreparation
    - flexionAngle = tibiofemoral flexion angle
    - quadLoad = specified quadriceps loading value
    - trial = trial number. This should correspond to the trial number in the kinematics file as well.
    - file naming conventions should allow for easy organizing of data with the robotic system data file structure conventions.
- Before trials, ensure the pressure sensor is in place, see Specifications/SpecimenPreparation.
- Before trials, collect data on the pressure sensor by:
    - Compressing the joint by hand on the superior side and saving data appropriately.
    - Compressing the joint by hand on the inferior side and saving data appropriately.
    - Compressing the joint by hand on the medial side and saving data appropriately.
    - Compressing the joint by hand on the lateral side and saving data appropriately.
- The actions during the timeline of testing will be:
    1. Set tibiofemoral joint kinematics
        - 0° flexion,
        - Minimize out of plane loads (representation of passive flexion); except a compressive load of 20 N
        - Lock tibiofemoral joint pose and orientation
    2. Apply incremental quadriceps loads of ~20, 100, 200, 300, 400, 500, and 600 N
        - To accommodate the necessity for manual acquisition of patellofemoral pressure maps, quadriceps loading states will be manually controlled.
            - At 20 N quadriceps load, verify patellofemoral contact patch is approximately centered on the sensor. If not, center the sensor using the sutures (see Specifications/SpecimenPreparation)
        - Once desired load is reached, data will be collected for approximately 5 seconds.
        - Record relative bone positions and patellofemoral contact pressures at each increment (follow file naming convention specified above).
        - Upon completion of quadriceps loading, specify zero force in the linear actuator and physically pull the quadriceps actuator to induce "slack" in the system (to facilite passive flexion)
    3. Passively (minimize out of plane loads) flex the knee to a tibiofemoral joint angle of 15°
        - Lock the tibiofemoral joint pose and orientation
    4. Apply incremental quadriceps loads and record bone positions and contact pressures (as at 0° flexion)

        - At 20 N quadriceps load, verify the pressure sensor is centered
        - Upon completion, induce slack in the tendon actuator
    5. Passively flex the knee to a tibiofemoral joint angle of 30°
        - Lock the tibiofemoral joint pose and orientation
    6. Apply incremental quadriceps loads and record bone positions and contact pressures (as at 0° flexion)
        - Verify the pressure sensor is centered
        - Upon completion, induce slack in the tendon actuator
    7. Passively flex the knee to a tibiofemoral joint angle of 45°
        - Lock the tibiofemoral joint pose and orientation
    8. Apply incremental quadriceps loads and record bone positions and contact pressures (as at 0° flexion)
        - Verify the pressure sensor is centered
        - Upon completion, induce slack in the tendon actuator
    9. Passively flex the knee to a tibiofemoral joint angle of 60°
        - Lock the tibiofemoral joint pose and orientation
    10. Apply incremental quadriceps loads and record bone positions and contact pressures (as at 0° flexion)
        - Verify the pressure center is centered
        - Verify pressure files are present and follow the above naming convention
        - Upon completion, induce slack in the tendon actuator and prepare to remove the specimen

Post-calibration of pressure sensor:

After completion of testing, remove the pressure sensor and calibrate again to ensure sensor is not damaged. Refer to Specifications/PressureCalibration.

Specimen Storage

After joint mechanics testing, the specimen should be stored according to storage specifications listed in the specimen preparation page, see Specifications/SpecimenPreparation.

Data Processing

Robotics testing system utilizes "right knee abstraction" for control and data collection. The data, including kinematics-kinetics information and coordinate transformation matrices need to be transformed back to "physical representation" for the left knees for their appropriate description in the physical space. Further details are available at the Infrastructure/ExperimentationMechanics pages, specifically in the file Infrastructure/ExperimentationMechanics/Knee Coordinate Systems.pdf

Data Storage

All joint testing files, including raw and processed kinematics-kinetics data, coordinate transformation matrices, contact pressure measurements, etc. should be uploaded to the in-house data management system (http://cobicore.lerner.ccf.org/midas, accessible only within the Cleveland Clinic network) for prospective organization (Open Knee(s) Community). Following organization, a documented version of the data will be disseminated at Open Knee(s) project site (https://simtk.org/home/openknee).

Data Dissemination

Joint mechanics data should be organized in the in-house data management system (http://cobicore.lerner.ccf.org/midas, accessible only within the Cleveland Clinic network) before dissemination. For each specimen, under joint mechanics folder, a dissemination subfolder should be created. Tibiofemoral and patellofemoral joint data should be organized in there as separate folders that contain subfolders for kinematics-kinetics and for patellofemoral joint only, contact pressures. Kinematics-kinetics folders should have a configuration folder that contains information on anatomical landmarks, registration marker locations, coordinate systems, etc. It should be noted that data on patella registration marker assembly is usually in the tibiofemoral joint kinematics-kinetics folder as the data are collected at the specimen preparation session immediately before tibiofemoral joint testing. This data should be augmented with a file indicating location of points on the patella registration marker assembly in CAD. This file can be found in the source code repository - https://simtk.org/websvn/wsvn/openknee/utl/PatFem_Registration/CAD_PT_DIMENSIONS.txt. A readme file should be added in empty experiment trial folders as a place holder. At the root of the dissemination folder, a readme file should be created to describe the folder structure and data content. These files were created for oks001 and can be used as templates.

For dissemination, the dissemination folder of the relevant specimen should be downloaded from the in-house data management system. The in-house data management system automatically compresses the folder. This file should be uncompressed in the local computer, the folder name should be changed to joint_mechanics-<specimen number>, e.g. joint_mechanics-oks001, and compressed again to create the file for dissemination, e.g. joint_mechanics-oks001.zip. This additional uncompress-compress cycle is anticipated to reduce the file size significantly. The file should be uploaded in the relevant specimen-specific package in the "Downloads" section (if not existing) of the Open Knee(s) project site (https://simtk.org/home/openknee). Appropriate documentation links should be provided, e.g. to the specimen preparation wiki page and to the joint mechanics experimentation specifications wiki page. For citation of the data, any relevant conference abstracts or peer-reviewed journal articles on joint mechanics testing should be listed. The release number should be incremented (see Roadmap for release numbering). It is anticipated that dissemination of joint mechanics data will follow the dissemination of anatomical image sets (see Specifications/ExperimentationAnatomicalImaging, therefore ensuring the existence of a specimen-specific package in the "Downloads" section. If not, a specimen-specific package should be created.

References

Borotikar, Bhushan, Subject specific computational models of the knee to predict anterior cruciate ligament injury, Doctoral Dissertation, Cleveland State University, December 2009.

Grood ES, Suntay WJ. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. J Biomech Eng. 1983 May;105(2):136-44. PubMed