FOURTH GRAND CHALLENGE COMPETITION TO PREDICT IN VIVO KNEE LOADS: DESCRIPTION OF AVAILABLE EXPERIMENTAL DATA

B.J. Fregly, Ph.D., University of Florida
Darryl D'Lima, M.D., Ph.D., Shiley Center at Scripps Clinic
Thor Besier, Ph.D., University of Auckland
David Lloyd, Ph.D., Griffith University
Scott Delp, Ph.D., Stanford University
Scott Banks, Ph.D., University of Florida
Marcus Pandy, Ph.D., University of Melbourne
Allison Hall, Ph.D., University of Florida

I. INTRODUCTION

Below we describe the experimental data being made available for the fourth "grand challenge" competition to be held at the 2013 ASME Summer Bioengineering Conference in Sunriver, Oregon (http://www.asmeconferences.org/SBC2013/). The goal of each year's competition is to advance the entire field of musculoskeletal modeling by critically evaluating muscle and contact force estimates at the knee during gait using data collected from a new patient with a force-measuring knee implant. Since muscle forces are the primary determinants of joint contact forces (Herzog *et al*., 2003), correctly predicted muscle forces should result in reasonable estimates of joint contact forces. This year's competitors are being given access to tibial contact force, motion capture, ground reaction, EMG, and CT data, including patient-specific implant-bone geometric models of the subject's pelvis, femur, patella, tibia, fibula, talus, calcaneus, midfoot, metatarsals, and phalanges. Tibial contact force data are being provided for a subset of trials to assist competitors with musculoskeletal model development but will be withheld for gait trials to permit quantitative evaluation of "blinded" muscle and contact force estimates.

The motivation for the competition, an overview of the instrumented knee implant design (called "eKnee") and accuracy, a description of collected experimental data, and logistics of the competition were presented in a special workshop at the 2009 ASME Summer Bioengineering Conference in Lake Tahoe, California. The presentation, entitled "Workshop on Grand Challenge Competition to Predict In Vivo Knee Loads," can be obtained from the Downloads page of the SimTK.org competition website (https://simtk.org/home/kneeloads). More recently, an overview of the grand challenge competition and a summary of knee contact force predictions generated by competitors to date were presented at the 2012 American Society of Biomechanics Conference in Gainesville, Florida. The presentation, entitled "Overview of the Annual Grand Challenge Competition to Predict In Vivo Knee Loads," can be downloaded from the SimTK.org competition website. Details of the instrumented implant design, experimental hardware (e.g., type of video motion system, force plates, and EMG system), surface maker placement, and EMG electrode placement can be found in these presentations.

Experimental data being released for the competition are described in section III of this document. Some data mentioned in the workshop presentation (e.g., eKnee data for the gait trials) will not be released until after abstract submission.

As described in the workshop presentations, a general overview of the competition is as follows:

- We provide the *in vivo* data (minus tibial contact force measurements for gait trials).
- Competitors predict muscle and contact forces in the knee during gait using a musculoskeletal model.
- Competitors submit a conference abstract along with an Excel data file containing their predicted medial and lateral tibial contact forces for the specified gait trials. The contact force predictions will be submitted by email to Allison Hall (allisonlhall@ufl.edu) by February 4th, 2013.
- We evaluate all tibial contact force predictions quantitatively using the *in vivo* measurements.
- Best predictions are presented in a special session at the conference.
- Tibial contact force measurements are released to competitors after abstract submission (deadline this year is January 11th, 2013).
- Competitors use the tibial contact force measurements to improve their models and submit un-blinded predictions of medial and lateral tibial contact forces in an Excel data file by email to Allison Hall (allisonlhall@ufl.edu) by June 12th, 2013.
- Winner is selected based on a modified ASME Summer Bioengineering Conference abstract scoring system described below.

The modified scoring system to be used for evaluating competition abstracts is outlined below:

- Significance (0-3 points)
- Technical content (0-5 points)
- Completeness (0-2 points)
- Accuracy (0-5 points - new)
- Novelty (0-5 points - new)
- Max 20 points

The two new categories added for the competition are Accuracy and Novelty. **Accuracy will be assessed by calculating root-mean-square and R^2 errors between predicted (blinded and un-blinded) and measured medial and lateral contact forces for two specific gait cycles in trial jw_ngait_tm_transition1 – gait cycle 1 (**start at 4.859 sec with heelstrike on force plate 2) **and gait cycle 2** (start at 18.752 sec with heelstrike on force plate 2). This walking trial was performed on an instrumented treadmill while the treadmill speed was ramped up from 0.8 m/sec up to 1.4 m/sec at a rate of 1.0 m/sec^2 and then ramped back down to 0.8 m/sec at the same rate. Gait cycle 1 occurs during the acceleration phase and gait cycle 2 occurs at the beginning of the deceleration phase.

Contact force predictions submitted for the competition should fulfill the following requirements:

- All contact force predictions should be submitted in a single Microsoft Excel file.
- Each gait cycle simulated (competition trials indicated above) should have its results reported in a separate worksheet.
- Each worksheet should contain data in the following three columns: 1) Percent of gait cycle (0 to 100), 2) Medial contact force (N), and 3) Lateral contact force (N).
- Predictions should be splined so that results are reported at 1% increments over the complete gait cycle.

The data file will be used by the competition organizers to quantify errors in estimated medial and lateral contact forces for the Accuracy score.
The research team has done its best to ensure that all data made available for the competition are error free. It is a large task to verify, organize, and synchronize the various types of data so that it can be used easily by the musculoskeletal modeling research community. Despite our best efforts, we realize that issues with the data may be discovered once researchers begin using it. **All data issues should be reported on the Public Forum associated with the SimTK.org competition project.** The forum can be accessed from the project overview page for the competition (https://simtk.org/home/kneeloads) by clicking on "Public Forums" at the left side of this page. The research team will use this forum to respond to posted enquiries so that all interested researchers will have a single place where a searchable list of questions and answers is maintained.

Institutional review board approval and subject informed consent were obtained for all de-identified competition data being released by the research team.

The research team encourages others to use the competition data and models for their own research, publications, and grant proposals. If you use any competition data or models in any publications, please cite the following journal article:

Fregly, B.J., Besier, T.F., Lloyd, D.G., Delp, S.L., Banks, S.A., Pandy, M.G., and D'Lima, D.D. (2012) Grand challenge competition to predict in vivo knee loads. *Journal of Orthopaedic Research* 30(4):503-513.

II. SUBJECT INFORMATION

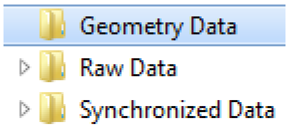
Subject: JW
Height: 168 cm
Weight: 66.7 kg
Instrumented knee side: Right
Shoes: Rockport flat bottom sneakers

III. AVAILABLE DATA

Below is a brief description of the experimental data available for the competition. OpenSim now possesses its own contact modeling capabilities, and some competitors may find these capabilities useful for developing their own contact models of the subject's implant components.

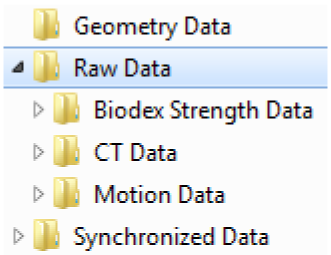
A. Geometry Data

The "Geometry Data" folder contains implant component and bone models for the subject's implanted leg. Implant component polygonal models are included for the femoral component, patellar button, tibial insert, and tibial tray. These models were generated from point cloud data obtained from the subject's implant components. Bone polygonal models are included for the pelvis, femur, patella, tibia, fibula, talus, calcaneus, midfoot, metatarsals, and phalanges. These models were generated from pre- and post-operative CT scan data collected from the subject.



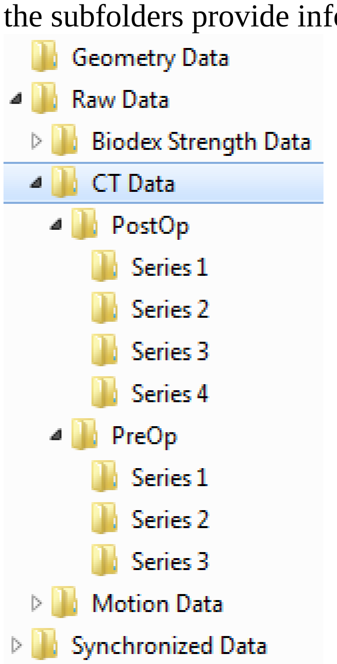
B. Raw Data

The "Raw Data" folder contains original unprocessed experimental data that falls into three categories: 1) CT Data, 2) Motion Data, and 3) Biodex Strength Data. Competitors who wish to start with raw unprocessed data rather than synchronized processed data will want to use the data contained in this folder.



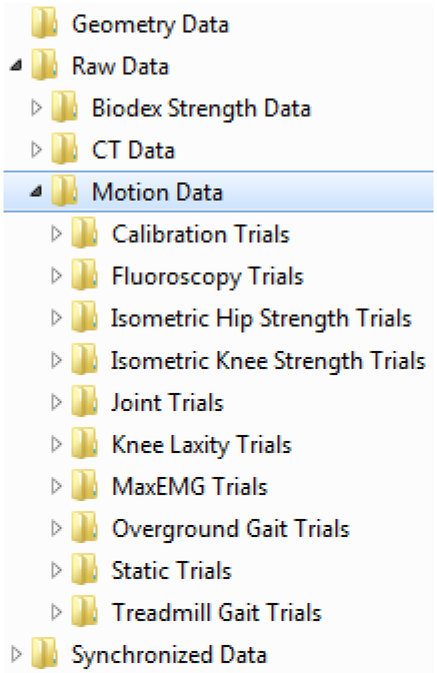
1. CT Data

The "CT Data" folder contains pre-operative and post-operative CT scan data of the knee region (pre-op) and entire leg (post-op – pelvis to toes) stored as separate series. README.txt files in the subfolders provide information on the contents of the pre- and post-operative CT scan data.



2. Motion Data

The "Motion Data" folder contains gait laboratory data for different types of movement trials, including: Calibration Trials (for testing initial muscle and contact force estimates), Overground Gait Trials (the subject's normal gait pattern plus bouncy, medial thrust, mild crouch, moderate crouch, and mtp (forefoot strike) gait patterns and walking with long and short walking poles in normal and wide pole placements to alter medial contact force), Treadmill Gait Trials (walking trials at several constant speeds and a trial of walking while accelerating and decelerating), Joint Trials (for calibrating lower extremity joint functional axes), Maximum EMG Trials (for normalizing muscle EMG signals), Static Trials (for creating segment coordinate systems), Isometric Strength Trials (for testing isometric joint strength), Fluoroscopy Trials (for measuring accurate knee joint kinematics during functional tasks), and Knee Laxity Trials (for testing ligament strength). Data from the Isometric Strength Trials, Fluoroscopy Trials, and Knee Laxity Trials will be released at a later date.



Below is a brief description of the individual trials contained within each of these trial categories:

Calibration Trials:

jw_1legstand – One-legged standing as motionless as possible on the implanted leg.

jw_2legsquat – Two-legged squat (down and up several times) with one foot on each force plate.

jw_calfrise – Calf rise (up and down several times with knees straight) with one foot on each force plate.

jw_chairrise – Chair rise (up and down several times) with arms folded across the chest and one foot on each force plate.

jw_loadlegext – Loaded open-chain leg extension (several cycles) with 10 lb ankle weights while sitting on a table.

jw_unloadlegext – Unloaded open-chain leg extension (several cycles) while sitting on a table.

jw_staticsit – Static trial with subject seated on a chair.

jw_staticmaxiso – Static trial with feet pointed forward and subject performing maximum isometric contraction of leg muscles (2 trials were collected).

Overground Gait Trials:

jw_bouncy_og – Six overground gait trials with clean force plate strikes using a bouncy gait pattern.

jw_medthrust – Eight overground gait trials with clean force plate strikes performed using a medial thrust gait pattern (Fregly *et al*., 2007).

jw_mildcrouch – Six overground gait trials with clean force plate strikes using a crouched gait pattern with a mild increase in knee flexion angle.

jw_moderatecrouch – Five overground gait trials with clean force plate strikes using a crouched gait pattern with a moderate increase in knee flexion angle.

jw_mtpgait – Six overground gait trials with clean force plate strikes using a forefoot strike gait pattern.

jw_ngait_og – Six overground gait trials with clean force plate strikes performed using the subject's normal gait pattern.

jw_wpgait_ln – Six overground gait trials with clean force plate strikes performed while walking with long hiking poles in a normal pole placement (Fregly *et al*., 2009).

jw_wpgait_lw – Six overground gait trials with clean force plate strikes performed while walking with long hiking poles in a wide pole placement (Fregly *et al*., 2009).

jw_wpgait_sn – Seven overground gait trials with clean force plate strikes performed while walking with short hiking poles in a normal pole placement (Fregly *et al*., 2009).

jw_wpgait_sn – Seven overground gait trials with clean force plate strikes performed while walking with short hiking poles in a wide pole placement (Fregly *et al*., 2009).

Treadmill Gait Trials:

jw_ngait_tm_ss – Treadmill trial performed using the subject's normal gait pattern at the subject's self-selected walking speed, 1.2 m/sec.

jw_ngait_tm_slow – Treadmill trial performed using the subject's normal gait pattern at a slow walking speed, 0.8 m/sec.

jw_ngait_tm_set – Treadmill trial performed using the subject's normal gait pattern at 1.0 m/sec.

jw_ngait_tm_fast – Treadmill trial performed using the subject's normal gait pattern at a fast walking speed, 1.4 m/sec.

jw_ngait_tm_transition – Treadmill trial performed using the subject's normal gait pattern while the treadmill accelerated and then decelerated from 0.8 m/sec to 1.4 m/sec at 1.0 m/sec^2.

Joint Trials:

jw_ankle_r and jw_ankle_l – Right and left ankle functional axis calibration trials performed using an unloaded ankle circumduction motion.

jw_knee_r and jw_knee_l – Right and left knee functional axis calibration trials performed using an unloaded knee flexion-extension motion.

jw_hip_Tr and jw_hip_Tl – Right and left hip joint center calibration trials performed using an unloaded T-shaped flexion-extension followed by abduction-adduction motion.

jw_hip_rstar and jw_hip_lstar – Right and left hip joint center calibration trials performed using an unloaded star-shaped flexion-extension and abduction-adduction motion.

MaxEMG Trials:

jw_mvc<muscle_group> - EMG measurements from isolated right leg muscle groups under maximum voluntary contraction conditions.

Static Trials:
jw_staticfor – Static trial with feet pointed forward.
jw_staticin – Static trial with feet pointed inward.
jw_staticout – Static trial with feet pointed outward.
jw_staticelbow – Static trial to capture the position of the medial and lateral elbow markers.
jw_wpgait_staticlong – Static trial with long hiking poles.
jw_wpgait_staticshort – Static trial with short hiking poles.

Isometric Hip Strength Trials:
jw_isomethip_abd – Standing isometric hip abduction.
jw_isomethip_add – Standing isometric hip adduction.
jw_isomethip_ext – Standing isometric hip extension.
jw_isomethip_flex – Standing isometric hip flexion.

Isometric Knee Strength Trials:
jw_isometknee_ext – Seated isometric knee extension.
jw_isometknee_flex – Seated isometric knee flexion.

Fluoroscopy Trials:
jw_chairrisef – Chair rise (up and down several times) with arms folded across the chest and one foot on each force plate. Fluoroscopic data were lost for these trials.
jw_squatf – Two-legged squat (down and up several times) with one foot on each force plate. Fluoroscopic data were recorded for this trial.
jw_stairupf – Stair ascent. Fluoroscopic data were recorded for this trial.
jw_stairdownf – Stair descent. Fluoroscopic data were recorded for this trial.
jw_stepupf – Stepping up on a box onto the implanted leg. Fluoroscopic data were recorded for this trial.
jw_lunge – Forward lunge onto the implanted leg. Fluoroscopic data were recorded for this trial.
jw_openfe – Unloaded open-chain leg extension while sitting on a table. Fluoroscopic data were recorded for this trial.
jw_twist – Standing twist on the implanted leg. Fluoroscopic data were recorded for this trial.

Knee Laxity Trials:
jw_apdrawf1 – Simulated anterior drawer test performed by applying a load to the tibia with a cable. Fluoroscopic data were recorded for this trial. The applied load was measured with a load cell.
jw_apdrawf2 – Simulated posterior drawer test performed by applying a load to the tibia with a cable. Fluoroscopic data were recorded for this trial. The applied load was measured with a load cell.
jw_varlaxf1 – Simulated varus laxity test performed by applying a load to the tibia with a cable. Fluoroscopic data were recorded for this trial. The applied load was measured with a load cell.
jw_vallaxf1 – Simulated valgus laxity test performed by applying a load to the tibia with a cable. Fluoroscopic data were recorded for this trial. The applied load was measured with a load cell.

jw_ierotf1 – Internal-external rotation moments applied to the tibia. Fluoroscopic data were recorded for this trial.

Within each group of motion trials, one or more of the following types of data are available:

eKnee Data (.csv files): Four uniaxial load cell measurements from the instrumented tibial prosthesis. Columns are time (sec), posterior-medial (PM) load cell (lbs), anterior-medial (AM) load cell (lbs), anterior-lateral (AL) load cell (lbs), posterior-lateral (PL) load cell (lbs), vertical ground reaction force synchronization signal (raw signal), and EMG synchronization signal (raw signal). Sampling frequency is 120 Hz. Medial and lateral contact force can be calculated from the load cell measurements using the following validated regression equations (Zhao *et al*., 2007):

$$c_1 = 0.9871$$
$$c_2 = 0.9683$$
$$c_3 = 0.0387$$
$$c_4 = 0.0211$$
$$F_{medial} = c_1 F_{AM} + c_2 F_{PM} + c_3 F_{AL} + c_4 F_{PL}$$
$$F_{lateral} = (1 - c_1) F_{AM} + (1 - c_2) F_{PM} + (1 - c_3) F_{AL} + (1 - c_4) F_{PL}$$

EMG Data (.csv files): Raw EMG measurements from 14 lower extremity muscles on the right (instrumented knee) side.

Movies (.avi files): De-identified movies for many of the trials.

Video Motion Data (.trc files for marker data, .csv files for ground reaction and EMG data, .c3d files for all video motion data): Three-dimensional marker position data (.trc files) for markers, along with corresponding ground reaction data (.csv or .c3d files) from 3 force plates. All file formats follow Motion Analysis Corporation conventions, with .trc files using units of mm and .csv files units of N (force), mm (center of pressure), N-mm (moment), and Volts (EMG data). Figure 1 shows surface marker placement and Figures 2 and 3 show the experimental set-up for the overground and treadmill trials, respectively. Details about marker placement are located in the document entitled “Marker Set Description” that can be downloaded from SimTK.org (https://simtk.org/home/kneeloads).

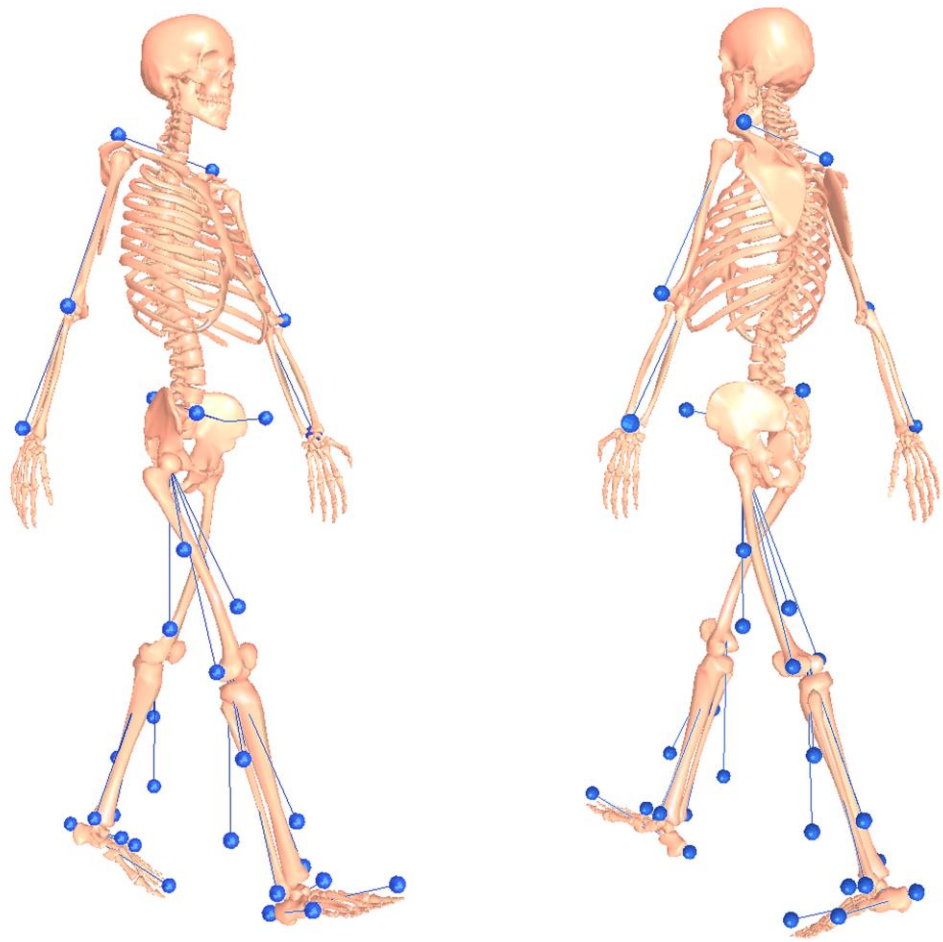


Figure 1. Surface marker placement during dynamic and static trials.

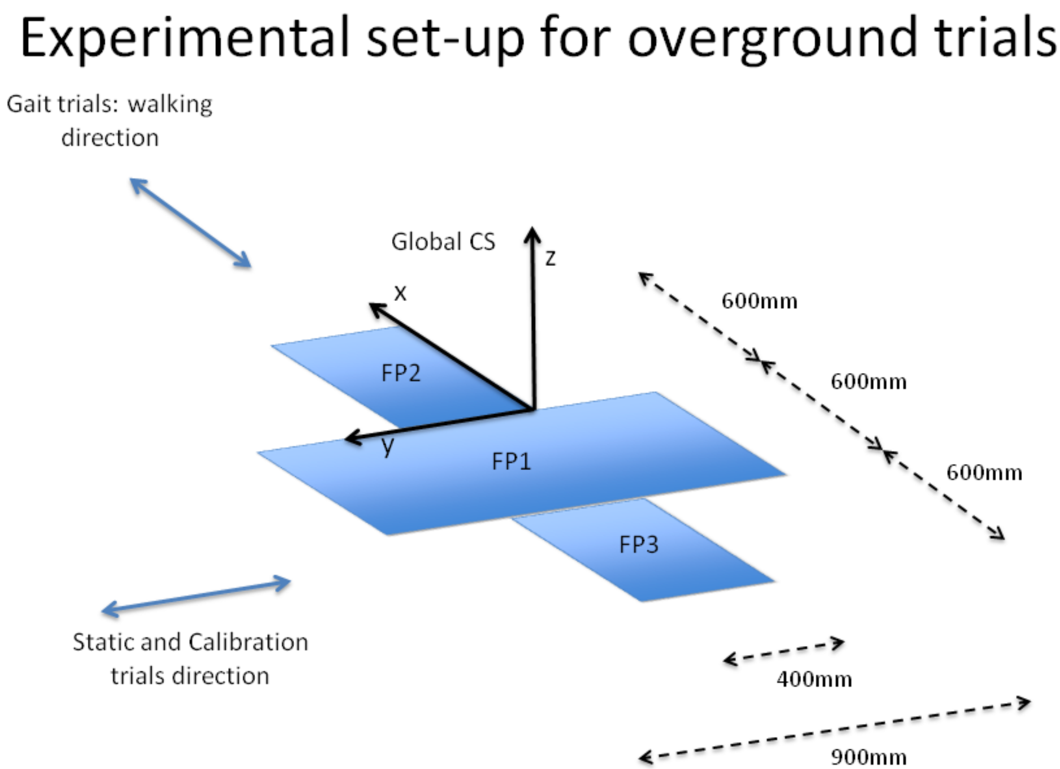
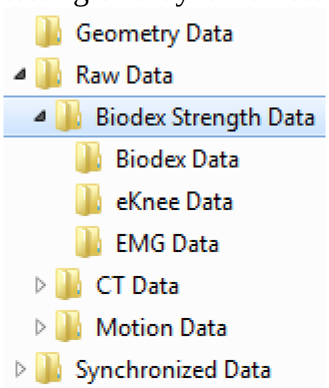


Figure 2. Experimental set-up for overground trials. Note that subjects walked in both the +X and –X directions during the gait trials.

Figure 3. Experimental set-up for treadmill trials. Note that subjects walked while holding on to the treadmill handrails.

3. Biodex Strength Data

The "Biodex Strength Data" folder contains data recorded while the subject performed strength testing on a dynamometer.



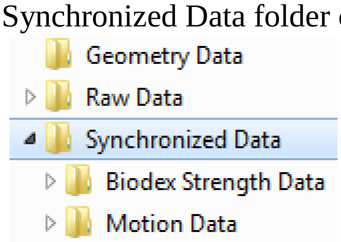
Below is a brief description of the individual trials contained within this category:

Biodex Strength Trials:
For all trials, the hip flexion angle was 80 degrees.

jw_isokin60 – Isokinetic knee flexion and extension with sub-maximal effort at 60 deg/sec from 0-110 degrees of knee flexion
jw _isokin90 – Isokinetic knee flexion and extension with sub-maximal effort at 90 deg/sec from 0-110 degrees of knee flexion
jw _isomet90 – Isometric knee flexion and extension with maximal effort at 90 degrees of knee flexion
jw _passknee30 – Passive knee flexion and extension at 30 deg/sec from 0-110 degrees of knee flexion

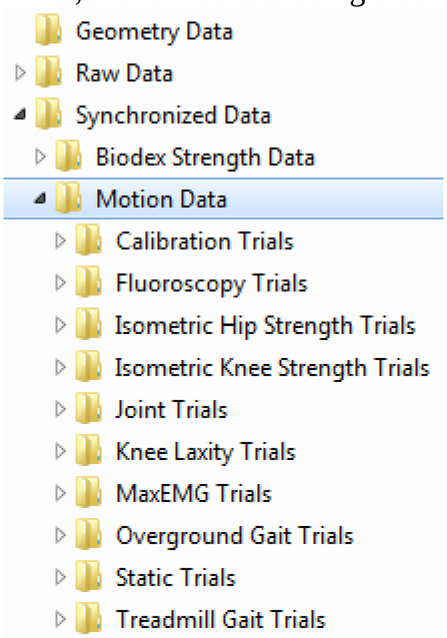
C. Synchronized Data

The "Synchronized Data" folder contains the same types of data as the "Raw Data" folder except that the data have been synchronized, resampled, and filtered. Resampling and filtering were performed as described in section 3 of the 2009 workshop presentation, while synchronization was performed using a common goniometer signal or ground reaction force signal. The Synchronized Data folder contains Motion and Biodex Strength Data.



1. Motion Data

For Motion Data, synchronization was performed between the video motion, ground reaction, EMG, and eKnee data using a common goniometer signal or a ground reaction force signal.



Categories of trials are the same as for the Raw Data folder. Types of data are also the same as for the Raw Data folder except that all files are saved as Excel .csv files or .trc files with a unique suffix that identifies the type of data:

eKnee Data: jw_<trial>_knee_forces.csv

EMG Data: jw_<trial>_emg.csv

Video Motion Data: jw_<trial>_trajectories.csv, jw_<trial>_grf.csv, jw_<trial>_new.trc

All movie files are saved within the Raw Data folder.

IV. DIFFERENCES FROM PREVIOUS COMPETITIONS

The data and models for the fourth competition differ from those of the previous competitions in the following ways:

1) Subject-specific geometric bone models are available for the subject's pelvis, femur, patella, tibia, fibula, talus, calcaneus, midfoot, metatarsals, and phalanges. Though the same subject was used for the first competition, the bone models released for that competition were not created from the subject's imaging data but rather were created from imaging data obtained from a subject of similar stature.
2) Additional overground gait patterns (mild crouch, moderate crouch, and four walking pole gait conditions) were performed by the subject for the fourth competition.

3) Treadmill gait trials were performed by the subject for the fourth competition.
4) Fluoroscopic data were collected for various motions and during knee laxity tests, though not during treadmill gait trials.

V. REFERENCES

Herzog, W., Longino, D., and Clark, A. (2003) The role of muscles in joint adaptation and degeneration. *Langenbeck's Archives Surgery* **388**, 305-315.

Fregly, B.J., Reinbolt, J.A., Rooney, K.L., Mitchell, K.H., and Chmielewski, T.L. (2007) Design of patient-specific gait modifications for knee osteoarthritis rehabilitation. *IEEE Transactions on Biomedical Engineering* **54**, 1687-1695.

Fregly, B.J., D'Lima, D.D., and Colwell, C.W. Jr. (2009) Effective gait patterns for offloading the medial compartment of the knee. *Journal of Orthopaedic Research* **27**, 1016-1021.

Fregly, B.J., Besier, T.F., Lloyd, D.G., Delp, S.L., Banks, S.A., Pandy, M.G., and D'Lima, D.D. (2011) Grand challenge competition to predict in vivo knee loads. *Journal of Orthopaedic Research* (conditionally accepted).

Mündermann, A., Asay, J.L., Mündermann, L., and Andriacchi, T.P. (2008) Implications of increased medio-lateral trunk sway for ambulatory mechanics. *Journal of Biomechanics* **41**, 165-70.

Zhao, D., Banks, S.A., D'Lima, D.D., Colwell, C.W., and Fregly, B.J. (2007) In vivo medial and lateral tibial loads during dynamic and high flexion activities. *Journal of Orthopaedic Research* **25**, 593-602.