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., Stanford University
David Lloyd, Ph.D., University of Western Australia
Marcus Pandy, Ph.D., University of Melbourne

I. INTRODUCTION

Below we describe the experimental data being made available for a unique "grand challenge" competition to be held at the 2010 ASME Summer Bioengineering Conference in Naples, Florida (http://www.asmeconferences.org/sbc2010/). The goal of the 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 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. Competitors will be given access to tibial contact force, motion capture, ground reaction, EMG, muscle strength, and CT data. Tibial contact force data will be 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, a summary of modeling results generated thus far, and logistics of the competition were presented in a special workshop at the 2009 ASME Summer Bioengineering Conference in Lake Tahoe, Florida. The presentation, entitled "Workshop on Grand Challenge Competition to Predict In Vivo Knee Loads," can be downloaded from
http://www.mae.ufl.edu/~fregly/competition/WorkshopPresentation.pdf
or from the SimTK.org project created for the competition (https://simtk.org/home/kneeloads). Details of the instrumented implant design, experimental hardware (e.g., type of video motion system, force plates, EMG system, and dynamometer), surface maker placement, and EMG electrode placement can be found in sections 2 and 3 of the workshop presentation.

Experimental data being released for the competition are described in section III of this document. Some data mentioned in the workshop presentation are not being released (e.g., some of the gait trials). These data may be released after the competition depending on available funding and progress made by the research team in publishing the data. Models related to the competition (e.g., OpenSim knee model, implant geometric models, and implant contact models) will be released in the near future once they have been created by the research team. We are currently preparing a manuscript on the competition and associated data and models for submission to the *Journal of Orthopaedic Research*. Once that manuscript is accepted for publication, researchers who use posted data or models in any publications will be requested to reference this article.

As described in the workshop presentation, 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 text files containing their estimated tibial contact forces for the specified gait trials.
- We evaluate all tibial contact force predictions quantitatively using the *in vivo* measurements.
- Best predictions are presented in a special session at the conference.
- Actual tibial contact forces are released after abstracts are submitted.
- Winner is selected based on a modified ASME Summer Bioengineering Conference abstract scoring system.

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 errors between predicted and measured medial and lateral contact forces for two specific gait trials – jw_tsgait_10 and jw_tsgait_11**. Gait trials labeled "tsgait" involved a medial-lateral trunk sway gait pattern similar to that reported by Mündermann *et al*. (2008). Trunk sway gait trials were selected for the competition since the research team has not yet published any *in vivo* tibial contact force results from this gait pattern. Each abstract submitted for the competition will need to include two text files (one for each gait trial) containing three columns of data: Percent gait cycle (0 to 100 in increments of 1 percent), estimated medial contact force (in N), and estimated lateral contact force (in N). These two data files 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 is error free. It has been a much larger task than anticipated 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 "Advanced" and then "Public Forums" at the lower left corner 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.

All data for the competition are being released by Dr. Darryl D'Lima of the Shiley Center for Orthopaedic Research & Education at Scripps Clinic in La Jolla, California. Institutional review board approval and subject informed consent were obtained through Scripps Clinic.

II. SUBJECT INFORMATION

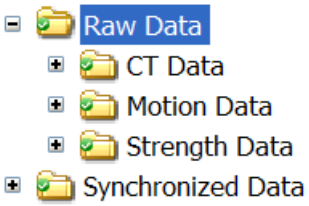
Subject: JW
Height: 166 cm
Weight: 64.6 kg
Instrumented knee side: Right
Shoes: New Balance SL-1 Fit walking shoes

III. AVAILABLE DATA

Below is a brief description of the experimental data available for the competition. Models that may be helpful to some competitors (e.g., contact models of the implant components) are still under development by the research team and will be released in the near future.

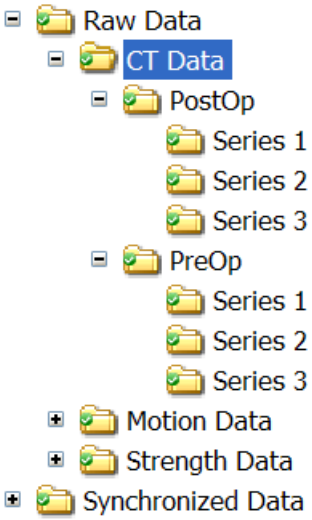
A. Raw Data

The "Raw Data" folder contains original unprocessed experimental data that falls into three categories: 1) CT Data, 2) Motion Data, and 3) 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.



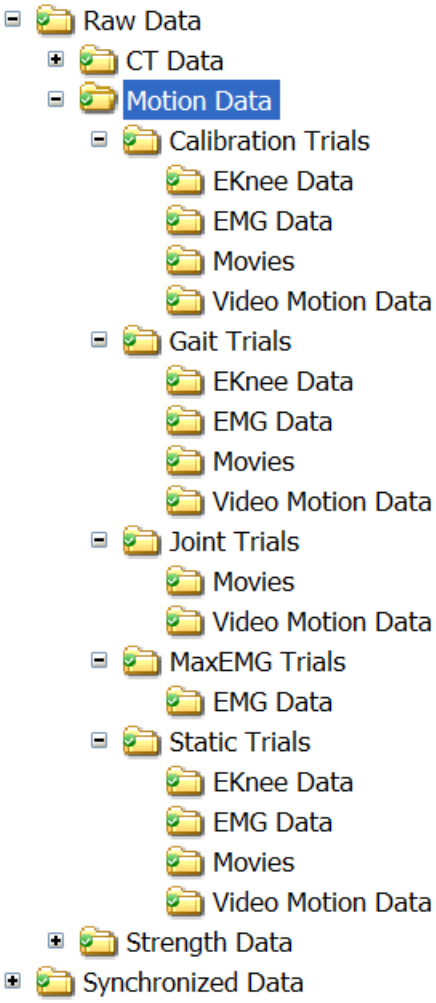
1. CT Data

The "CT Data" folder contains pre-operative and post-operative CT scan data of the knee region stored as separate series. README.txt files in the subfolders provide information on which series are best for segmentation.



2. Motion Data

The “Motion Data” folder contains gait laboratory data for different types of movement trials, including: Musculoskeletal Model Calibration Trials (for testing initial muscle and contact force estimates), Gait Trials (the subject’s normal gait pattern plus a medial-lateral trunk sway gait pattern to alter medial contact force), Isolated Joint Motion Trials (for calibrating lower extremity functional axes), maximum EMG trials (for normalizing muscle EMG signals), and Static Trials (for creating segment coordinate systems).



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

Calibration Trials:

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

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

Gait Trials:

jw_ngait – Five gait trials with clean force plate strikes performed using the subject's normal gait pattern.

Jw_tsgait – Five gait trials with clean force plate strikes performed using a medial-lateral trunk sway gait pattern.

Joint Trials:

jw_ankle_r and jw_ankle_l – Right and left ankle functional axes 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_r and jw_hip_l – Right and left hip joint center calibration trials performed using an unloaded T-shaped flexion-extension followed by abduction-adduction motion.

MaxEMG Trials:

jw_restingEMG – EMG measurements from right leg muscles under resting conditions.

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

Static Trials:

jw_staticfor – Static trials with feet pointed forward. The two trials have different amounts of muscle co-contraction.

jw_staticmaxiso – Static trial with feet pointed forward and subject performing maximum isometric contraction of leg muscles.

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

EKnee Data (.eknee 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):

$$c_1 = 0.9871$$

$$c_2 = 0.9683$$

$$c_3 = 0.0387$$

$$c_4 = 0.0211$$

$$F_{medial} = c_1 F_{AM} + c_2 F_{PM} + c_3 F_{AL} + c_4 F_{PL}$$

$$F_{lateral} = (1 - c_1) F_{AM} + (1 - c_2) F_{PM} + (1 - c_3) F_{AL} + (1 - c_4) F_{PL}$$

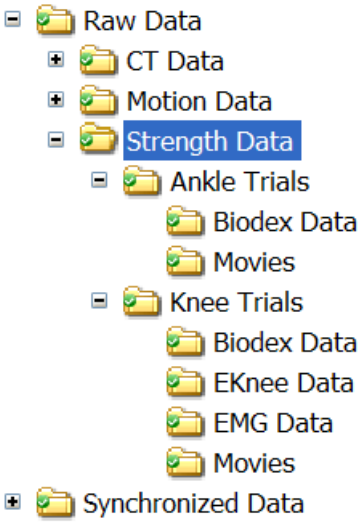
EMG Data (.emg files): Raw EMG measurements from 14 lower extremity muscles on the right (instrumented knee) side.

Movies (.avi files): De-identified movies for some of the trials (movies for additional trials have yet to be de-identified).

Video Motion Data (.trc files for marker data, .anc + forcepla.cal files or .forces files for ground reaction data): Three-dimensional marker position data (.trc files) for 31 markers during dynamic trials and 43 markers during static trials, along with corresponding ground reaction data (.anc + forcepla.cal files or .forces files) from 4 force plates. All file formats follow Motion Analysis Corporation conventions, with .trc files using units of mm and .forces files units of N and Nmm.

3. Strength Data

A Biodex isokinetic dynamometer was used to perform two categories of strength testing trials: ankle trials and knee trials.



Ankle Trials:

jw_isometankle_flex_0, jw_isometankle_flex_30 – Maximum isometric ankle flexion torque at 0 and 30 deg of plantarflexion with 40 deg of knee flexion and 80 deg of hip flexion.

jw_isometankle_ext_0, jw_isometankle_ext_30 – Maximum isometric ankle extension torque at 0 and 30 deg of plantarflexion with 40 deg of knee flexion and 80 deg of hip flexion.

jw_isokinankle_pass – Passive isokinetic ankle flexion-extension torque at 30 deg/s with 40 deg of knee flexion and 80 deg of hip flexion.

jw_isokinankle_maxcon, jw_isokinankle_subcon – Active isokinetic ankle flexion-extension torque under maximum concentric and submaximum concentric conditions at 60 deg/s with 40 deg of knee flexion and 80 deg of hip flexion.

Knee Trials:

jw_isometknee_flex_0, jw_isometknee_flex_30, jw_isometknee_flex_60 – Maximum isometric knee flexion torque at 0, 30, and 60 deg of flexion with 0 deg of ankle flexion and 80 deg of hip flexion.

jw_isometknee_ext_0, jw_isometknee_ext_30, jw_isometknee_ext_60 – Maximum isometric knee extension torque at 0, 30, and 60 deg of flexion with 0 deg of ankle flexion and 80 deg of hip flexion.

jw_isokinknee_pass – Passive isokinetic knee flexion-extension torque at 60 deg/s with 0 deg of ankle flexion and 80 deg of hip flexion.

jw_isokinknee_maxcon, jw_isokinknee_subcon – Active isokinetic knee flexion-extension torque under maximum concentric and submaximum concentric conditions at 60 deg/s with 0 deg of ankle flexion and 80 deg of hip flexion.

Within both groups of strength trials, one or more of the following types of data are available:

Biodex Data (.bdx files): Net muscle isometric and isokinetic strength data. Columns are time (msec), torque (ft-lbs), angle (deg), anatomical angle (deg), and angular speed (deg/sec).

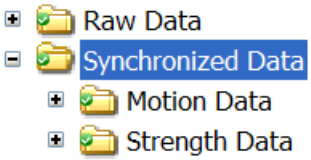
EKnee Data (.eknee files): Same as for Motion Data. Note that EKnee data are available only for the Knee Trials.

EMG Data (.emg files): Same as for Motion Data. Note that EMG data are available only for the Knee Trials.

Movies (.avi files): Same as for Motion Data.

B. Synchronized Data

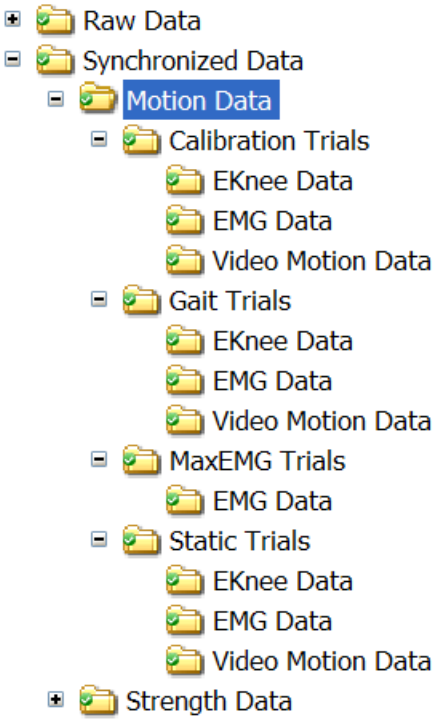
The “Synchronized Data” folder contains the same types of data as the “Raw Data” folder except that the data have been synchronized, resampled, and filtered. Resampling and filtering were performed as described in section 3 of the workshop presentation, while synchronization was performed using a common vertical ground reaction force, muscle EMG, or knee angle signal. Only the Motion Data and Strength Data subfolders are present within the Synchronized Data folder.



1. Motion Data

For Motion Data, synchronization was performed between the video motion/ground reaction, EMG, and EKnee data using common vertical ground reaction force and EMG signals. For the calibration and static trials, the subject was positioned on the wrong force plate, so no vertical ground reaction force signal was available to synchronize the EKnee and EMG data with the

video motion data. Consequently, for these trials, synchronization was performed manually based on corresponding changes in the EKnee and vertical ground reaction force curves.



Categories of trials are the same as for the Raw Data folder except that the Joint Trials folder is omitted, since only video motion and ground reaction data were collected for these trials.

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

EKnee Data: jw_<trial>_knee_forces.csv

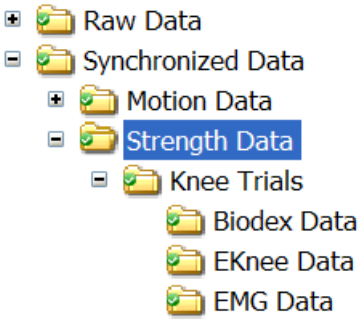
EMG Data: jw_<trial>_emg.csv

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

All movie files are saved within the Raw Data folder.

2. Strength Data

For Strength Data, synchronization was performed between the Biodex, EMG, and EKnee data using a knee flexion angle signal from the Biodex dynamometer and a separate goniometer.



Categories of trials are the same as for the Raw Data folder except that the Ankle Trials folder is omitted, since lack of EKnee and goniometer data for these trials did not permit synchronization of the data.

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

Biodex Data: jw_<trial>_biodex.csv

EKnee Data: jw_<trial>_knee_forces.csv

EMG Data: jw_<trial>_emg.csv

All movie files are saved within the Raw Data folder.

IV. 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.

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.