BME331: Physiological Control Systems

Lab 3

Introduction

The purpose of this lab is to model the control strategies that the neuromuscular system uses to regulate standing balance. Experimental data in the form of electromyography (EMG) and force plate measurements will be collected, and used to explore how modeling can help us to better understand the system.

The lab consists of two parts, which can be completed in any order. You will have two lab sessions to complete the lab:

Part 1: Data collection and analysis

Part 2: Simulink modeling and analysis.

Pre-lab tasks [10 marks]

You will be expected to have read through the entire lab document beforehand, so that you know what needs to be done and can manage your time accordingly.

In addition, prepare yourself as follows:

_Read the "Background" section of the BioRadio "Electromyography I Laboratory" (posted on Quercus), in order to familiarize yourself with the basics of EMG.

_Understand and implement all of the Matlab functions and commands that you will need in this lab. You will not have time to write and debug code during the lab. The segments of the lab for which you need to write Matlab code have been indicated by a  symbol in the margin.

After reading through the lab document, provide brief (1-2 sentences) answers to the following questions. Your answers must be submitted by the beginning of your first lab session.

1. If neural impulses could be converted to muscle contractions and produce joint torques instantaneously, sketch what the cross-correlation plot would look like between the EMG and force plate data.

2. Is an EMG signal produced by the action potentials in the muscle, or in the nerves controlling the muscle?

3. Why is it important that the EMG and force plates be synchronized in this particular experiment?

4. In your Simulink model, do you think that the body parameters (height and weight) that you enter may affect the choice of gains? Why or why not?

5. Very briefly explain how the visual, proprioceptive and vestibular pathways all contribute to maintaining balance.

Background: Relationship between muscle commands and body sway

In this analysis, the human body will be conceptualized as an inverted pendulum. In this simplified model, we are only interested in the ankle joint and we assume that the knees and hips are in fixed, straight positions. The angle of rotation at the ankle must be controlled to keep the body at the desired inclination. We are interested in the following variables. First, the commands to the muscles controlling the ankle joint (i.e., the control signal), and second, the angle of body sway (i.e., the system output). In your modeling you can analyze these quantities directly. In your experiments, the commands to the muscles will be measured using electromyography (EMG) data, and the body sway will be measured using force plate data.

In order to study the relationship between the muscle commands and the body sway, we will use the concept of cross-correlation. The cross-correlation describes to what extent two signals are varying in a similar way. Here, we are interested in describing how variations the muscle commands "match up" with the variations observed in the body sway. The cross-correlation is usually computed as a function of lag. That is, how does the cross-correlation change if the two signals are time-shifted with respect to each other? Informally, if the signals are varying together simultaneously, the cross-correlation will be highest for a lag of 0. If the variations in one signal precede similar variations in the other signal by a time shift τ, then the cross-correlation will be highest at lag τ (whether τ is positive or negative depends on which signal precedes which). Here, we would expect that variations in the muscle commands will precede the corresponding changes in the body sway, as a result of the time it takes for neural impulses to be converted into muscle contractions and for those contractions to generate torque. Examining the cross-correlation function and determining the lab at which it is maximized will allow us to estimate this delay.

Mathematically, the cross-correlation is defined as:

$$\hat{R}_{xy}(m) = \begin{cases} \sum_{n=0}^{N-m-1} x_{n+m} y_n^*, & m \geq 0, \\ \hat{R}_{yx}^*(-m), & m < 0. \end{cases}$$

where x and y are the two signals of length N and m is the lag. The resulting function is then normalized to lie between -1 and 1.

The resulting function may look something like this:

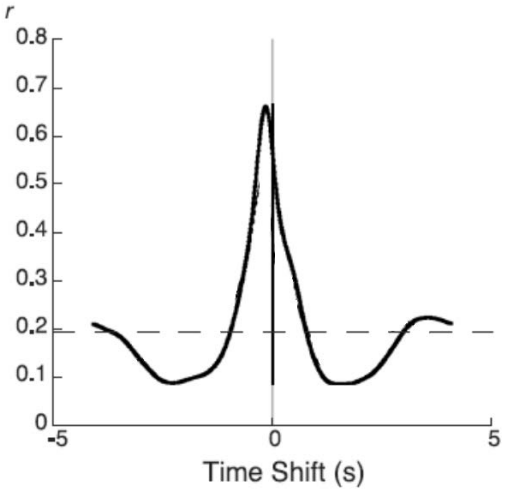

Figure 1: Example cross-correlation function (from [1])

From this figure we can draw conclusions about the amount of similarity between the muscle commands and body sway (by examining the amplitude of the biggest peak), and the delay between them (by examining the time shift at which the peak occurs).

Part 1 – Data Collection and Analysis

Experimental Procedures:

Because there are only 2 force plates available, you will take turns conducting your data collection. Your TA will have assigned you to a specific 30 minute time slot during which you will have access to the force plate. It is your responsibility to set up and test the EMG recording methodology thoroughly before your turn with the force plates starts, and to work efficiently to collect the required data in your 30 minutes. In fairness to other groups, you will have to stop after 30 minutes whether or not you are done. Part 1 and Part 2 of this lab will be performed independently (i.e., it makes no difference what force plate time slot you are assigned to), and the results will be combined during the post-lab analysis.

The data collection from this lab will consist of simultaneously recording two types of data: EMG data from the BioRadio and center-of-pressure data from the force plates. Before you begin your experiments, you will need to have accomplished the following:

1. Understand how to record the EMG data. This should be done and tested before you begin your turn with the force plates.
2. Understand how to record data from the force plates.
3. Understand how to synchronize the two streams of data.

You will not have more than ~10 minutes to work on steps 2 and 3 with the force plates before you need to begin your experiments, so make sure that you have thoroughly read and understood the instructions below beforehand. The following sections provide details on each of the steps.

EMG Data collection procedures (Note: you can work on setting up the EMG even before you have access to the force plates):

One member of the group will be the experimental subject. The other two group members will be responsible for completing the data collection. Place surface electromyography (EMG) electrodes on the subject's tibialis anterior (TA) and soleus (SOL) muscles of the right leg (in total 2 pairs of EMG electrodes per subject). The placement of the electrodes is illustrated in Fig. 2 (refer to pages 14-16 in http://www.thoughttechnology.com/pdf/manuals/MAR908-03 SEMG applied to physical rehabilitation and biomechanics.pdf for additional illustrations if needed). You can find the exact location by feeling for the muscle contraction with your fingers (the TA will be activated when you flex your ankle so that your foot points upwards; the SOL will be activated when you flex your ankle so that your foot points downwards). Placement of the electrodes should be done by first carefully cleaning the skin with alcohol, then placing the electrodes longitudinally over the muscle with an inter-electrode distance of 20 mm. The ground electrode should be placed on the bony part of your ankle.

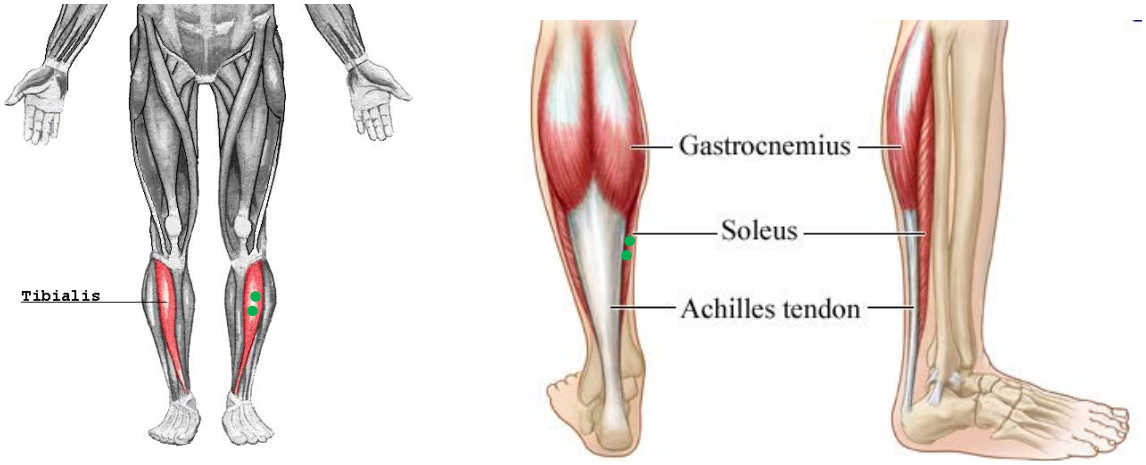

Figure 2: Locations of the tibialis anterior and soleus muscles

Next, you will practice moving your ankle and verify that you are getting clear and repeatable signals from both muscles. To record and visualize your EMG signals, follow these steps:

- Open the CleveLabs software
- Login with your first name
- Select 'Electromyography I'
- 'Begin lab'
- After your system is ready (electrodes connected, etc.), turn on the wireless unit.
- Click on 'Start'
- Wait until you see the EMGs changing with time
- Once you checked that your EMG recordings are good, click 'Save Data'
- Enter a name for the data in the popup
- Evoke EMG activity in soleus and tibialis anterior:
    1. Stand and press down your 'EMG foot' onto the force plate/floor (SOL activation)
    2. Stand and lift up your 'EMG foot' while having your heel in contact with the force plate/floor (TA activation)
- To stop the recordings, click on 'Saving' and then on 'Stop'
- Find your data in: "My Documents\CleveLabs Data\'name you logged in with'\EMGI" and look at it in Excel (plotting).
- Make sure that your data make sense and is clearly picking up muscle activation.

Notes:

- Always turn the wireless unit off in between trials – it needs a lot of battery power, and you don't want to run out of it.
- When you open your data, you will see three columns – the first two columns are the ones you are interested in (1: first display, first muscle; 2: second display, second muscle).

<u>NOTE:</u> Before starting the force plate data collection, disconnect the electrode wires from your BioRadio (keeping the electrodes attached to your leg). You will plug them into the BioRadio at the force plate station instead.

<u>Force plate data collection procedures:</u>

- Open the AMTI-NetForce software
- Startup -> Hardware Zero (Note: the subject should NOT be standing on the forceplate during this step)
- Select "Select Data Folder" from the "DataFolder" menu to your desired location
- Select "Acquisition Settings" from the "Settings" menu, and set "Duration" to 120s and "datasets/second" to 200.

The data collection procedure for each of the experiments described below is as follow:

- Startup -> Hardware Zero
- Have the subject stand on the platform and prepare for the task in a given experiment, as described in the next two sections below.
- Press the Start button to start the real time data acquisition process.
- Perform the required tasks (quiet or perturbed standing, as described below).
- Press the Stop button.
- **Press the Save button. The file is saved as trial0000X.bsf.**
- **<u>Go to File -> Export Data File in order to export the data to a .txt file for analysis in Excel. If you do not perform this step you will not be able to read your data.</u>**

These text files are delimited with commas and can be imported into Excel. They contain 6 columns of information (Fx, Fy, Fz, Mx, My, Mz). You will be able to compute COP X and Y position after your data collection is complete using the following equations (dz = plate thickness = 41.3 mm):

$$x = -(M_y + F_x * d_z) / F_z \qquad y = (M_x - F_y * d_z) / F_z$$

For each of your experiments, save the resulting AP time series in a .txt file which you will be able to import into Matlab for use with the example code in the Analysis section.

Before performing the experiments below, have the subject sway in different directions, examine how the COP varies on-screen, and record a few seconds of data as per the instructions above. Make sure that your data is being saved correctly and that you can load it in Excel. If you do not follow the steps above exactly, your data will not be recorded and you will not be able to complete the lab. Remember that you only have 30 minutes with the force plate.

Synchronization of the EMG and force plate data:

Due to the fact that the measurements are taken at different sampling frequencies, the force plate data (sampled at 200 Hz) have to be interpolated to a sampling frequency of 960 Hz to match the EMG sampling rate. The Matlab function interp1 can be used for this, as follows (assuming a recording 120 seconds long):

```
forceplate_upsampled = interp1(0:1/200:120, forceplate_original, 0:1/960:120);
```

You will also need to make sure that the data of EMG and force plate are synchronized, i.e., that they have a common zero-point in time. You will be provided with a trigger device for this purpose (Fig. 3). Pressing the button on the trigger will cause a detectable pulse in the EMG recording. Do this once or twice before you begin your data collection, and make sure that you are familiar with the changes produced by the trigger in the EMG. At the beginning of **each of the experiments below**, follow these steps:

- In the BioRadio software, click "Start" then "Save Data"
- Click on the force plate software window such that it is the currently selected window (Fig. 4)
- After 5 seconds: SIMULTANEOUSLY click "Start" on the force plate interface and press the button on the sync trigger
- The force plate data can then be used as is. The Bioradio data before the sync pulse must be deleted. The pulse should be around the 5 second mark.

Once you are comfortable with the data collection, you can perform the two experiments described below: Quiet Standing, and Perturbed Standing.

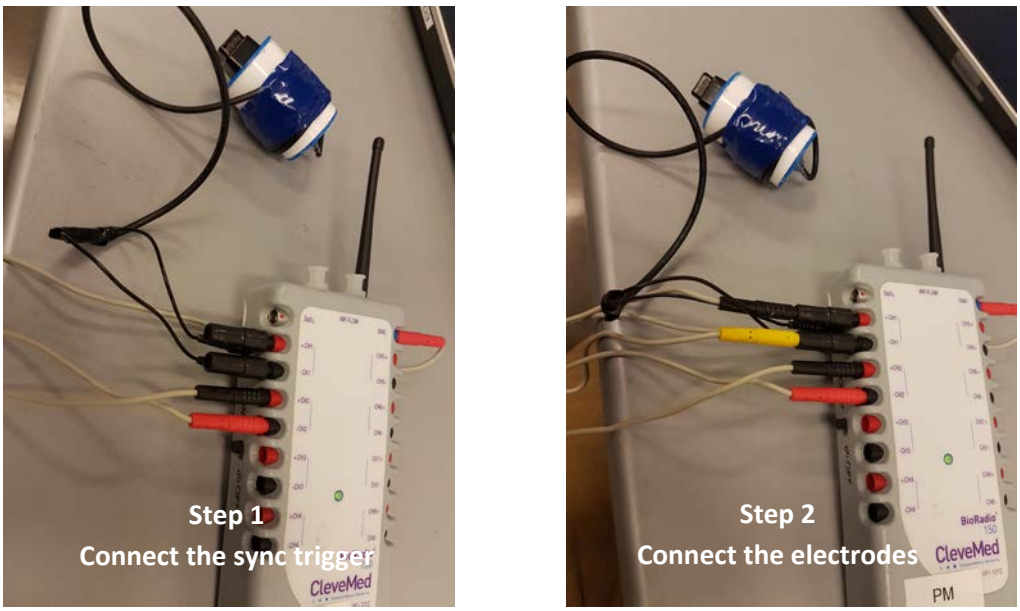

Figure 3: Sync trigger connection

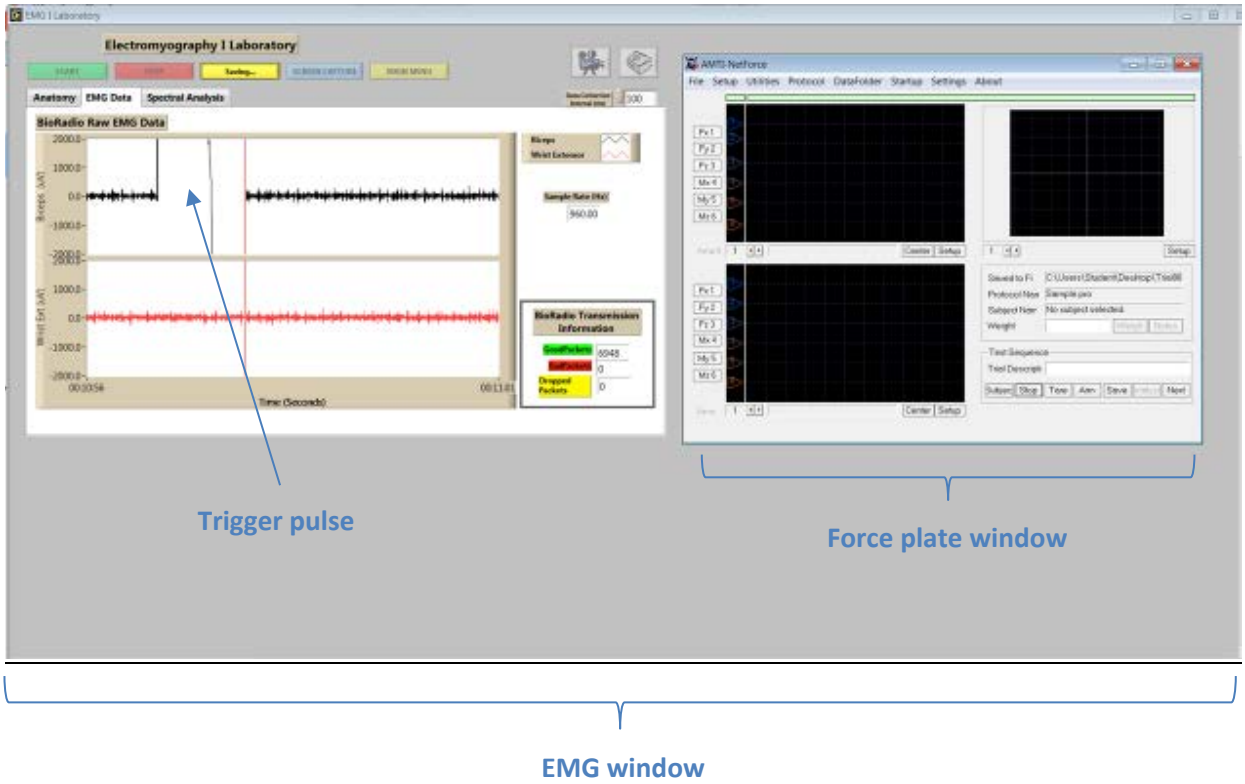

Figure 4: Data collection screenshot

Quiet Standing Experiment

The subject will be asked to stand on the center of the force platform with bare feet (see Fig. 5). Heel to heel distance between the feet should be 17 cm. During the experiment, center of pressure (COP) and EMG measurements will be taken at a sampling frequency of 200 Hz and 960 Hz, respectively. The subject will be asked to stand quietly for 120 seconds with eyes open (EO).

⇨ Save your EMG and COP recordings with appropriate filenames.

Subsequently, the subject will be given 1 minute of time to rest and another quiet standing experiment will be conducted, this time with eyes closed (EC). The duration of the second experiment will be 120 seconds as well.

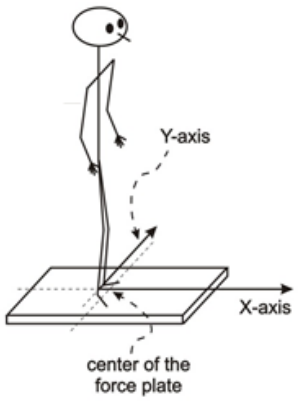

Figure 5: Schematic of quiet standing experiments.

- ⇨ Save your EMG and COP recordings with appropriate filenames.

During the experiments, SOL should be dynamically, but continuously active, whereas TA should only be intermittently active, if at all.

Perturbed Standing Experiment

The subject will be asked to take a 1 minute break after the quiet standing experiments are completed. Then, a rope will be tied around the subject's chest, just below the pectoral muscles. The rope should extent 1 m from the subject's anterior part of the chest to the experimenter (see Fig. 6). The experimenter

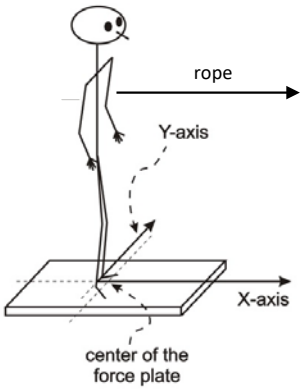

Figure 6: Schematic of perturbed standing experiments.

should hold the rope in the hand and suddenly pull the subject providing an impulse-like perturbation to the subject (**eyes closed!**). Apply 3 such perturbations at random times over the course of the 120 second recording. Record the approximate time when the perturbations occurred, you will need it at the analysis stage. When pulling the subject, the force should be sufficiently strong to cause a COP displacement, but should not cause the subject to make a step forward due to the perturbation.

WARNING: DO NOT PULL THE SUBJECT TOO STRONGLY. WHEN PULLING THE SUBJECT, PULL HIM/HER JUST ENOUGH TO CAUSE A MODERATE MOVEMENT OF THE BODY IN THE ANTERIOR (FORWARD) DIRECTION, BUT NOT SO MUCH TO CAUSE THE SUBJECT TO LOOSE BALANCE.

Analysis methods

The location of the center of pressure (COP) provides a useful measure of how much the body is swaying, and therefore allows us to assess standing balance. The COP displacement is used as the approximated center of mass (COM) of the body. This can be done since 1) the low frequency component of COP (below 1Hz) accords with that of COM, and 2) the low frequency component is the dominant power component in the COP time series. The body's COP is defined by two variables, the anterior-posterior (AP) and medial-lateral (ML) coordinates. The AP and ML time series (AP[n] and ML[n], n=1, …, N) define the COP path relative to the origin of the force platform coordinate system.

To acquire AP[n] and ML[n], the recorded time series (AP_{raw}[n] and ML_{raw}[n]) will be passed through a fourth-order zero phase Butterworth low-pass digital filter with a 5 Hz cut-off frequency [5]. Then, the average values (AP_{filt}_DC and ML_{filt}_DC) will be subtracted from the time series (**resulting time series are AP[n] and ML[n]**). The filter can be implemented with the following commands:

[b a] = butter(4, 5/480, 'low'); *%the first parameter is the filter order, and the second parameter is the cutoff frequency divided by half the sampling frequency.*
y = filtfilt(b, a, x); *%x and y are your original and filtered signals, respectively, to be renamed as appropriate*
y = y – mean(y); *%make the signal have zero-mean*

- **COP-Based Measures:**

The following quantities [3] can be calculated to describe the behaviour of each COP coordinate (the equations are only shown here for the AP coordinate):

1) Mean Distance (MDIST)
   $MDIST_{AP} = 1/N \sum|AP[n]|$.

2) Root Mean Square (RMS) Distance (RDIST)
   $RDIST_{AP} = (1/N \sum AP[n]^2)^{1/2}$.

3) Range (RANGE)

$RANGE_{AP}$ = max(AP[n]) – min(AP[n]),

where max(.) indicates the maximum value of the corresponding time series, and min(.) indicates the minimum value.

4) Mean Velocity (MVELO)
$MVELO_{AP} = (\sum|AP[n+1]-AP[n]|)/T$,

where the integration is from n=1 to n=N-1, and T is the total time of the time series (i.e., 120 s).

- **<u>Cross-Correlation Analysis between COP and EMG:</u>**

You will now carry out the cross-correlation analysis described in the Background section. In this analysis, as above, the COP displacement is used as the approximated COM of the body, because the cross-correlation function (CCF) between COP and EMG is almost equivalent to the one between COM and EMG, though the physiological meaning is different. Before computing the CCF function, the EMG data must be processed appropriately, as described next.

EMG Processing: The recorded EMG (SOL_{raw}[n] and TA_{raw}[n], see "Experimental Procedures" above) will be rectified and then passed through a fourth-order zero phase Butterworth low-pass digital filter with a 5 Hz cut-off frequency [5] (use the same filter provided above). **The resulting time series are SOL[n] and TA[n]** (different to the COP procedure, the DC components will NOT be removed).

Cross-correlation function (CCF) Calculation: Cross-correlation will be calculated for the time series between the anterior-posterior COP displacement and each EMG, i.e., between AP[n] and SOL[n], and between AP[n] and TA[n]. In order to get a high-quality estimate of the CCF, the signal will be divided into several segments. The CCF will be computed for each segment, and the results averaged. The next paragraph describes this process in more detail.

First, discard the initial 4800 data points of the time series (5 seconds) and divide the remaining 115 s long data sets into 13 segments that are 2^{13} points, i.e., 8.53 s long (discard the last 3904 data points). Then, the CCF of each segment will be calculated (Use Matlab function of "xcorr" as described below). Next, an ensemble-averaged CCF of the 'segment CCFs' will be calculated as a CCF for each trial. As the final output parameters, the CCF value ('CVAL') and time shift ('TS') of the highest peak(s) of the ensemble-averaged CCF will be calculated.

Note: 1) The CCF time series (segment and ensemble) always lie between -1 and 1 (and, therefore, also CVAL). In the Matlab code, this is ensured by the *xcorr* appendix 'coeff'.

2) Make sure that you specify the sign of TS. Convention: negative TS means that EMG precedes COP, positive TS means that COP precedes EMG. Hence, ensure that the number tells you what the graph shows you.

*Example Matlab Code to calculate 'segment CCFs' and ensemble-averaged CCFs (shown for **<u>one</u>** CCF, e.g., EO: CCF between AP[n] and SOL[n]):*

Note: this code does not take care of the force plate interpolation, the time synchronization, or the filtering of the force plate or EMG data (see above); all of those steps need to have been completed before you apply this analysis.

```
load AP_EO.txt;  %adapt these load commands to the file names that you use during your data collection
load SOL_EO.txt;
freq = 960;
seg_length = 8192;
for k = 1:13
   a = (k-1)*(seg_length)+ 4801;
   b = (seg_length+4800) + (k-1)*(seg_length);
   ccf = xcorr(SOL_EO(a:b) - mean(SOL_EO(a:b)), AP_EO(a:b) - mean(AP_EO(a:b)),'coeff');
   ccf_seg(k,:) = ccf;
end
avg_ccf = mean(ccf_seg);
time = (-(seg_length-1):1:(seg_length-1))/freq;
plot(time,avg_ccf);

%AP_EO: AP data for eyes open
%SOL_EO: Soleus EMG data for eyes open
%freq: sampling frequency
%seg_length: length of one segment
%k: number of segments
%a,b: boundaries for the segments
%ccf: ccf for one specific segment
%ccf_seg: ccf for all segments
%avg_ccf: ensemble-averaged ccf
%time: time scale for avg_ccf
```

Quiet standing experiment

Perform a cross-correlation analysis of the recorded COP and EMG data, as described above. Make sure beforehand that your data files have been converted and formatted appropriately into .txt files that you can easily load into Matlab. Make sure that you are always extracting the right data from files that include multiple variables.

- ⇨ Compute the quantities MDIST, RDIST, RANGE, and MVELO from the COP data for the AP and ML directions, in the eyes open and eyes closed conditions.
- ⇨ Plot the average CCF between AP and SOL and between AP and TA, in eyes open and eyes closed conditions (4 plots).
- ⇨ Record the values CVAL and TS for each of those 4 comparisons.

Perturbed standing experiment:

In order to investigate the effect of the perturbation as well as the behaviour of the balance control system, we study signal characteristics such as 1) the amplitude of the COP displacement and 2) the delay between the EMG onset and COP displacement. After processing, interpolation and synchronization of the COP and EMG data, perform the following steps for each of the three perturbation trials. First, by visual inspection, detect the onsets of SOL and TA that are due to the perturbation. Second, determine the time and value of the maximum COP displacement (APmax) for each trial (mathematically). Finally, average the following three values across the three trials: 1) the time differential between SOL onset and APmax, 2) the time differential between TA onset and APmax, and 3) the value of APmax. Output: 3 average values. About the time differentials: A negative differential implies that SOL (or TA) precedes APmax, whereas a positive differential implies that APmax precedes SOL (or TA).

Part 2 – Simulink Modeling and Analysis

Introduction

In this part you will use Simulink to model the control system responsible for standing balance. Although the simulations are simplified signals compared to the physiological data that you are collecting, modeling allows us to explore the influence of the different parameters in greater detail.

Modeling Procedures:

Effects of proportional and derivative gains

Consider the Simulink model shown in Figure 8. It includes the following components:

- The model of the human body (plant), approximated by an inverted pendulum (ankle rotation only), as illustrated in Figure 7.
- A noise input that represents small internal/external perturbations during quiet standing.
- A feedback time delay (τ_F) between the body angle θ and the PD controller.
- The PD controller with gains **Kp** and **Kd.** Kp represents the gain for the body angle (proportional), whereas Kd represents the gain for the derivative of the body angle (derivative).
- A motor command time delay (τ_M) between the controller output and the motor command **Mc**.
- An electromechanical time delay (τ_E) between the motor command **Mc** and the ankle torque **Tc**.
- Reference signal of 0 rad (note that, in reality, the body angle is not zero as humans lean slightly forward during quiet standing).
- A conversion from the body angle (rad) to **COM** fluctuation.

We will use this model to investigate the effects on balance of changing the proportional and derivative gains of the PD controller.

Implement this model in Simulink, using the following parameters [4,5]:

- Sampling frequency: 960 Hz. Set the model configuration to use fixed-step solver (ode5).
- The duration of the simulation should be 120s (if your Scope blocks are not showing the entire simulation, you may have to uncheck "Limit data points to last:" in the History tab of the Scope block parameters).
- Noise input: Uniform random number (max = 4, min = -4, sample time = 0.1 s). Note: the sample time has to be matched with the overall sampling frequency using the Simulink "Rate Transition" block.
- Noise filter: 1st order system with gain of 2 and cutoff frequency of 5 Hz.

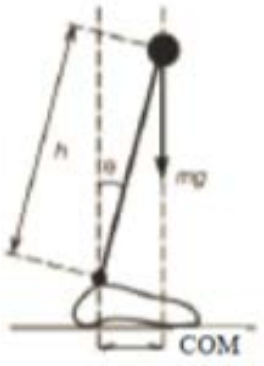

Figure 7: Inverted pendulum model

- Body mass m (without feet): [Mass of the subject] * 0.971 kg.
- COM height h: [Height of the subject in meters] * 0.547 m.
- Body inertia I: [Height of the subject]^2 * [Mass of the subject] * 0.319 kg m^2.
- Gravity: 9.81 m/s^2
- Tau_m: 0.05 s.
- Tau_f: 0.04 s.
- Tau_e: 0.01 s.
- Set the output format of the workspace output blocks to “Array” rather than “Timeseries”

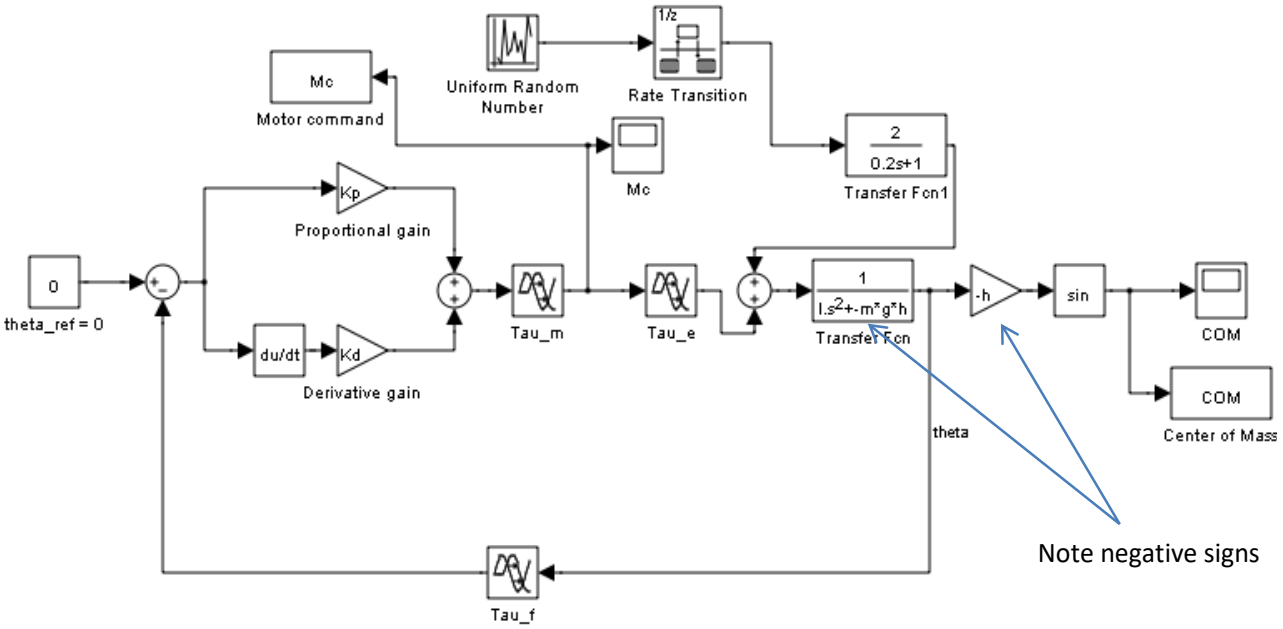

Figure 8: A closed-loop control scheme of quiet stance, where θ is the sway angle, g is the acceleration of gravity, Tc is the total torque about the ankle, and h is the distance of the COM to the ankle [4].

Run the simulations for the following PD gains (120 seconds each) and record the fluctuation of +COM and Mc:

1) Kp = 950 Nm/rad, Kd = 100 Nms/rad
2) Kp = 150 Nm/rad, Kd = 150 Nms/rad
3) Kp = 750 Nm/rad, Kd = 350 Nms/rad
4) Kp = 1000 Nm/rad, Kd = 1500 Nms/rad

⇨ In order to investigate, which PD controller (i.e., which gains) can mimic the physiological control system, CCF analysis will be performed for the abovementioned gains, using the same methods described for the physiological data in Part 1 (filtering of time series not necessary for this simulated data). Using the CCF program and procedure described in Part 1 of this lab,

calculate the CCF value ('CVAL') and time shift ('TS') of the highest peak(s) of the ensemble-averaged CCF. In this case, the AP displacement information is provided by the "COM" output of your model, and the EMG is replaced by the "Mc" output of your model. You will have to modify the first two lines of the example Matlab code accordingly. Later you will compare these results to your experimental data.

Note: Depending on the mass and height of the subject, some of the gain combinations above may in some cases cause numerical instabilities in Simulink, such that the simulation will not complete and give an error. If this happens to you for one of the gain combinations but not the others, you may need to slightly adjust the gains (modifications in the range of 10-50 Nms/rad will typicall suffice). If you do this, please make a note of it in your lab report. Also, it is important to consult with your TA to ensure that this is indeed the source of the error message that you are receiving, and not an incorrect implementation of the model.

Contributions of different feedback pathways

Three different pathways can convey information about the body angle: the visual, proprioceptive, and vestibular systems. The central nervous system may assign different weights to these three feedback pathways.

- ⇨ Expand your Simulink model to explicitly represent each of the feedback pathways. Each pathway should be compared to its own reference level, then assigned its own individual weight. You may assume that they share a single common time delay. You may additionally assume that each of these pathways is conveying the same signal (θ). Set the weights initially to the following values: w_visual = 0.4, w_proprioceptive = 0.5, and w_vestibular = 0.1. Set all three reference signals initially to 0. Use the values of Kd and Kp that gave you the best results based on your work in the previous section.
- ⇨ Record a screenshot of your model.

In the experiments for this lab, collect data will be collected in the case where the standing balance is unperturbed, and in the case where a physical perturbation is applied to the body. In this section, you will you the Simulink model to investigate the effects of additional scenarios, as follows:

a. In some individuals, the vestibular system may be impaired, for example as the result of a viral infection or as a side-effect of certain types of antibiotics.
    - ⇨ Modify the weights in your sensory feedback Simulink model to simulate this situation, and record your modifications.
    - ⇨ Run the simulation for 120 seconds and record the fluctuation of +COM and Mc. Perform the CCF analysis and calculate CVAL and TS.
b. In order to investigate the control mechanisms regulating standing balance, it can be useful to perform experiment in which we apply *sensory* perturbations. Vibration applied to the Achilles

tendons bilaterally will perturb proprioceptive input and cause freely standing subjects to lean backwards. This experiment is performed with eyes closed.

- ⇨ Modify your sensory feedback Simulink model to simulate this experiment. You can assume that the proprioceptive perturbation causes the CNS to perceive a leaning of 10°. Record your modifications to the model.
- ⇨ Run the simulation for 120 seconds and record the fluctuation of +COM and Mc. Perform the CCF analysis and calculate CVAL and TS.

Report

Your report should include the following components:

- What aspects of the experimental protocol seemed the most likely to introduce errors in the results? To what extent to you think that these issues affected the results that you are reporting, and how could the protocol be improved to address these points?
- For the quiet standing experiments:
    - Plots showing representative portions of your COP and EMG data for both eyes open and eyes closed conditions. Plot the COP data as y vs x, rather than plotting the coordinates vs time.
    - The results of the analysis described in the Data Analysis section in Part 1.
- For the perturbed standing experiments:
    - A plot showing the perturbation effect on a) AP, b) SOL, and c) TA, shown for one trial and on a common time axis. (*pick a good trial and an appropriate data length to show all the features due to the perturbation, including sufficient 'quiet' time before and after! The synchronized signals have to be used, of course*).
    - The results of the analysis described in the Analysis section in Part 1 (Mean $\pm$ SD of APmax, Δt between SOL onset and APmax, and Δt between TA onset and APmax).
- For the modeling portion – PD controllers:
    - Plots of COM and Mc for each of the four controllers investigated.
    - Plots showing the average CCF between COM and Mc for each of the four controllers investigated.
    - Average CVAL and TS values from the CCF analysis between COM and Mc for each of the four controllers.
- For the modeling portion – Feedback pathways:
    - Each of your model modifications.
    - Plots showing the fluctuations in COM and Mc for each feedback modification.
    - Plots showing the average CCF between COM and Mc for each feedback modification.
    - Average CVAL and TS values from the CCF analysis between COM and MC for each feedback modification.
- Briefly describe your simulation results for each of the four PD controllers investigated. What is notable about each result? Why did it occur? Is the simulation in each case reflective of what would occur in reality?
- How do the results of the quiet standing experiments compare to what was predicted by the simulations (for the case of stable gains and no feedback modifications)? What factors may have contributed to any differences observed?

Marking scheme

Pre-lab quiz: 5% (individual mark – pass/fail; all questions must be answered)
Modeling – PD controllers: 15%
Modeling – Feedback pathways: 15%

Quiet standing experiments: 20%
Perturbed standing experiments: 15%
Discussion: 20%
Clarity, organization, and language: 10%

Your lab report is due on the dates indicated in the course syllabus. Submit the report via Quercus no later than 5pm on the due date.

References

[1] K. Masani, M. R. Popovic, K. Nakazawa, M. Kouzaki, and D. Nozaki, "Importance of body sway velocity in controlling ankle extensor activities during quiet stance," *Journal of Neurophysiology*, vol. 90, pp. 3774-3782, 2003.

[2] S. D. Perry, W. E. McIlroy, and B. E. Maki, "The role of plantar cutaneous mechanoreceptors in the control of compensatory stepping reactions evoked by unpredictable, multi-directional perturbation," *Brain Research*, vol. 877, pp. 401-406, 2000.

[3] T. E. Prieto, J. B. Myklebust, R. G. Hoffmann, E. G. Lovett, and B. M. Myklebust, "Measures of postural steadiness: Differences between healthy young and elderly adults," *IEEE Transactions on Biomedical Engineering*, vol. 43, pp. 956-966, 1996.

[4] K. Masani, A. H. Vette, and M. R. Popovic, "Controlling balance during quiet standing: Proportional and derivative controller generates preceding motor command to body sway position observed in experiments," *Gait and Posture*, vol. 23, no. 2, pp. 164-172, 2006.

[5] D. A. Winter, *Biomechanics and motor control of human movement.* Toronto, ON: John Wiley & Sons Inc., 1990.

This lab is adapted from a lab developed by Drs. Kei Masani, Milos R. Popovic, and Albert H. Vette.