CHAPTER III

STANDING BALANCE EXPERIMENT WITH LONG DURATION RANDOM SQUARE PERTURBATION

Non-peer Reviewed Publication:

1. Wang, Huawei, van den Bogert, Antonie. (2020). Standing Balance Experiment with Long Duration Random Pulses Perturbation (Version 1.0) [Data set]. Zenodo. http://doi.org/10.5281/zenodo.3631958

ABSTRACT

Standing balance experiment and its measurements are fundamental for identifying postural feedback controllers. As the complex feedback controllers can only be identified from long duration balance data (under random external perturbations), a standing balance experiment was conducted and the long duration motion data was recorded. The recorded data-set consists of the standing balance data of 8 participants. Each participant performed 4 experiment trials, including 2 quiet standing and 2 perturbed standing trials. Each trial lasted 5 minutes long. A total of 80 minutes quiet standing and 80 minutes perturbed standing data are included in the data-set. Recorded data includes three dimensional (3d) motion of 32 markers (27 on participants' trunks and legs and 5 on treadmill frame), six dimensional ground reaction forces (GRF), and nine Electromyography signals (EMGs, of participants' right legs' muscles). In addition, the marker data was post-processed that filled the missing frames. The GRF was compensated to remove the inertia artifacts of the moving treadmill. The joint angles and torques were calculated using a 2d human body model.

3.1 Introduction

Standing balance experiment with external stimuli has become a common way to study the postural feedback control in humans' central nervous system (CNS)[1–5]. External stimuli evoke participants' body sway motion at variety situations, so that generalized motion controllers that cover these situations can be extracted. Two types of stimuli signals were mainly used in previous studies: short duration ramp perturbation[2, 4] and long duration random perturbation [1, 3, 5–8]. Postural feedback controllers and the mathematical models of CNS have been identified from the experimental data with these two types of stimuli. However, these identified controllers are far from engineering applicable (on humanoid robots and P/O devices). The postural controllers identified from ramp perturbations showed that the control gains vary based on the amplitude of ramp perturbations, whereas it is impossible, in practise, to predict perturbation amplitudes before choosing the feedback control gains. This also suggested that the postural control in human standing balance is nonlinear in overall. Mathematical models of CNS identified from the experimental data with random perturbations have an assumption that the human standing balance system is linear. To make this assumption valid, the power spectrum of random perturbation was usually small. In this dissertation work, we proposed that a new controller identification method (trajectory optimization with direct collocation) can identify nonlinear controllers from long duration experimental data. As a result, human standing balance data with perturbation that is long duration and large amplitude is required. Whereas, no suitable data sets were shared by previous studies. Therefore, the human standing balance experiment was conducted to provide motion data for the postural controller identification in chapter IV and V. We also shared this data set on Zenodo for public usage `https://doi.org/10.5281/zenodo.3631958`.

3.2 Methods

In this section, the experiment design, participants, and the experiment setup are described first. Then, the design of mechanical perturbation is described.

3.2.1 Participants

Eight able bodied participates, including one female and seven males, with an average age of 27 ± 5.3 years, an average height of 1.71 ± 0.08 m, an average mass of 65.3 ± 9.2 kg joined in this study. This study was approved by the Institutional Review Board of Cleveland State University(# IRB-FY2018-40). Also, written informed consent was obtained from each participant. Participation exclusion criteria is showing below. All five conditions need to be satisfied.

- No any past extremity injuries on legs or feet and still affect movement and balance functions now.
- Not diagnosed with any neuron-muscle disease.
- Body Mass Index (BMI: body wight/body height) below 30 lbs/ft^2.
- No neurological or other impairments that affects movements and balance.
- No pain or discomfort that could affect your movements.

Recorded data were anonymized with respect to the participants' identities. A unique identification number was assigned to each subject. A selection of the meta data collected for each participant is shown in Table V. Participants were divided into those that were used for the protocol pilot trials, i.e., the first two (grey background), and those used for the final protocol (last six). The final four columns provide the trial numbers associated with each experiment trials, Q means the quiet standing trial; P means the perturbed trial. The mass information was computed from the mean of vertical ground reaction forces at quiet standing trials, if possible. Additional trial in the data set with the trial number 0 is the unloaded trial that was used for the inertial artifact compensation.

Table I: Information of the eight participants in the order of collection date.

Id	Gender	Age (yr)	Height (m)	Mass (kg)	Q1	P1	P2	Q2
1	male	22	1.60	74.29 ± 0.26	1	2	3	4
2	female	–	–	48.37 ± 0.21	5	6	7	8
3	male	18	1.80	79.12 ± 0.20	9	10	11	12
4	male	27	1.78	63.10 ± 0.16	13	14	15	16
5	male	32	1.79	70.56 ± 0.19	17	18	19	20
6	male	35	1.65	58.24 ± 0.27	21	22	23	24
7	male	28	1.75	68.75 ± 0.17	25	26	27	28
8	male	27	1.63	60.33 ± 0.19	29	30	31	32

3.2.2 Equipment

Experiments were conducted in the Human Motion and Control lab at the Cleveland State University. In the experiment, ten Osprey motion capture cameras (Motion Analysis) were used to track participants' motions during experiment. A computer software *Cortex* (version 5.0.1.1497) was used to control the recording process of these cameras. Motion data was recorded at a frame rate of 100 Hz. A four degree of freedom (DOF) V-Gait (Motek Medical) treadmill was used as standing platform to execute perturbation. Force sensors in the V-Gait were used to detect the six DOF ground reaction forces and moments under both feet. Nine EMG sensors (Delsys Inc.) were used to record participants' muscle activation. EMG data was recorded at 1000Hz rate. The experiment setting is shown in Figure 4. In the experiment, *D-Flow* (version 3.26.0) software was used as an integral control tool that controlled all equipment as well as saved the measured data. The *D-Flow* application designed for the standing balance experiment is shown in Figure 5. The MoCap module controlled the motion capture system and recorded the EMG, ground reaction forces, and 32 markers' data. The V-Gait module controlled the motion of V-Gait treadmill with a perturbation signal written in a text file. The XSens module connected with two accelerometers on the V-Gait. The record data module recorded the V-Gait motion and XSens accelerometers' data.

In the experiment, 27 markers were used to track the participants' movement (trunk and legs). Five extra markers were placed on the standing platform to record its movement during the experiment. Table II describes the landmarks of these 32 markers. Nine Electromyography (EMG) sensors were used in the experiment to record nine muscle activations in the right leg. The EMG sensors were placed according to ABC of EMG (SENIAM) [9]. The EMG sensor number, corresponding analog channel number, and the measuring muscles are shown in Table III.

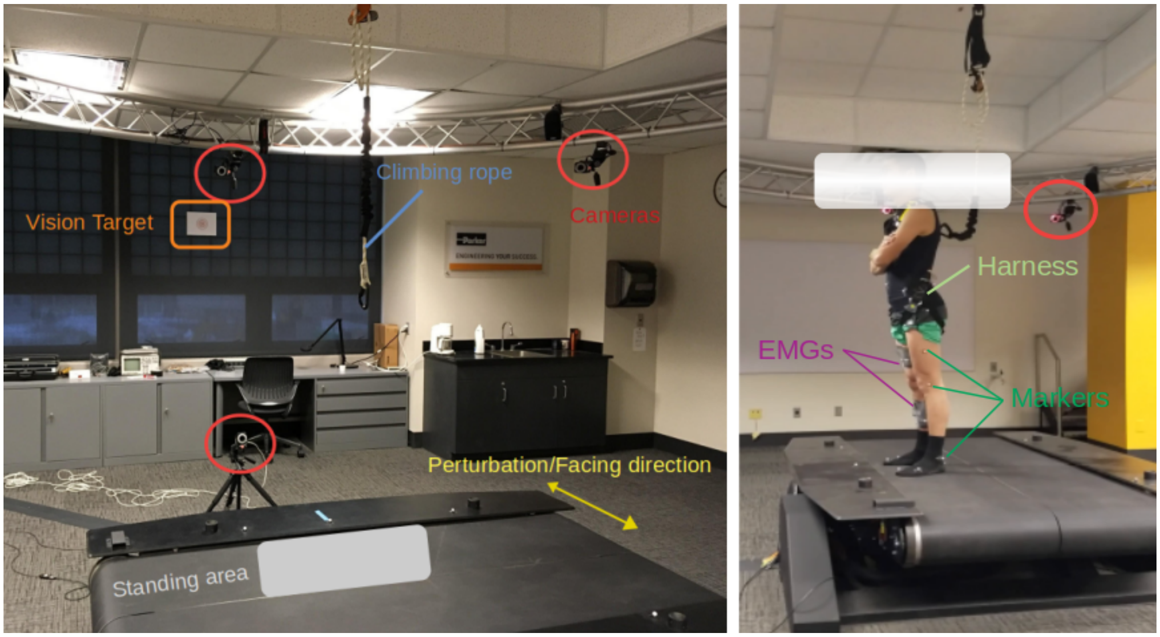

Figure 4: Standing balance experiment setting. Perturbation was applied in anterior and posterior direction using the sway motion of V-Gait. EMG sensors were placed on the right leg. Twenty-seven markers were put on participant's body to tracking motion.

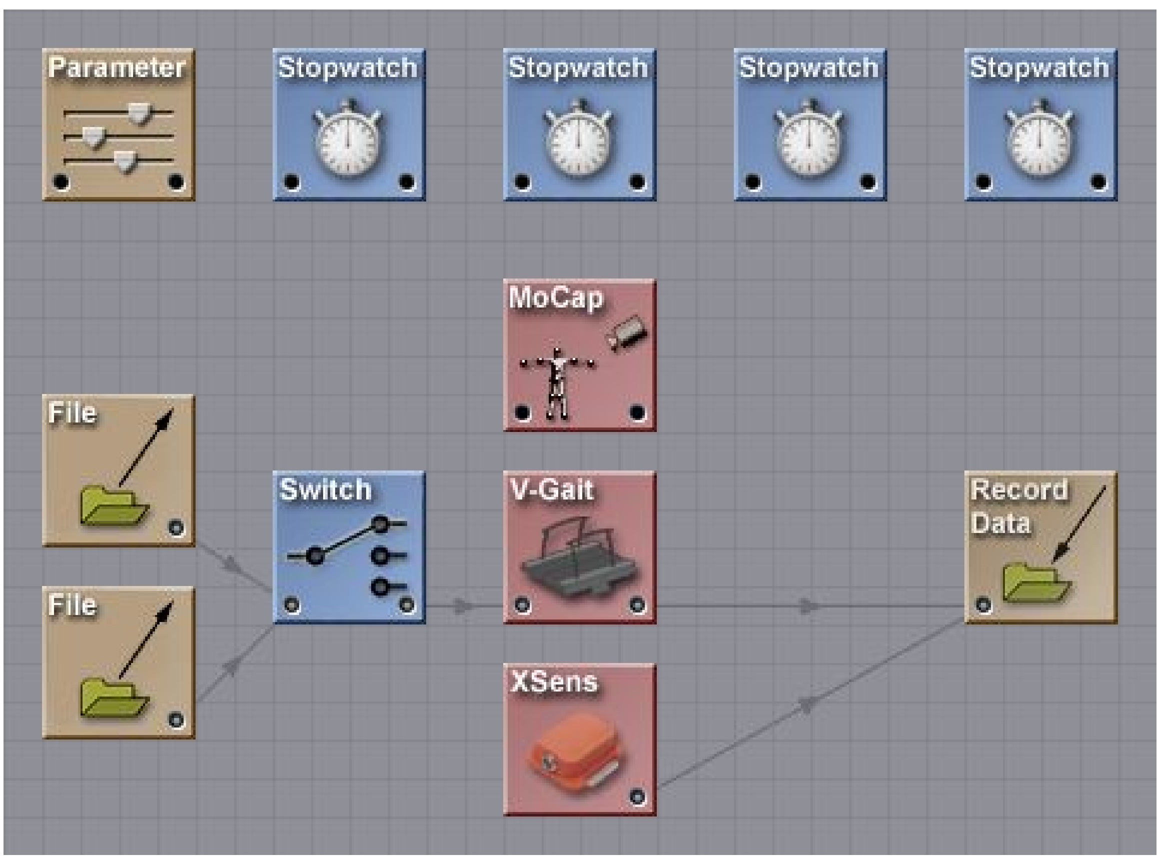

Figure 5: D-Flow application in standing balance experiment.

Table II: Reflex markers used in the experiment, including 27 subject markers and 5 treadmill markers. The label column matches the column headers in the mocap-xxx.txt files. Location of these markers on human body are in the last column.

Label	Name	Description
T10	T10	On the 10th thoracic vertebrae
SACR	Sacurm bone	On the sacral bone
NAVE	Navel	On the navel
XYPH	Xiphoid process	Xiphoid process of the sternum
STRN	Sternum	On the jugular notch of the sternum
LASIS	Pelvis bone left front	Left anterior superior iliac spine
RASIS	Pelvic bone right front	Right anterior superior iliac spine
LPSIS	Pelvic bone left back	Left posterior superior iliac spine
RPSIS	Pelvic bone right back	Right posterior superior iliac spine
LGTRO	Left greater trochanter of the femur	On the center of the left greater trochanter
FLTHI	Left thigh	At 1/3 of the line between the LGTRO and LLEK
LLEK	Left lateral epicondyle of the knee	On the lateral side of the joint axis
LATI	Left anterior of the tibia	On 2/3 on the line between the LLEK and LLM
LLM	Left lateral malleoulus of the ankle	The center of the heel at the same height as the toe
LHEE	Left heel	Center of the heel at the same height as the toe
LTOE	Left toe	Tip of the big toe
LMT5	Left 5th metatarsal	Caput of the 5th metatarsal bone, on joint line midfoot/toes
RGTRO	Right greater trochanter of the femur	On the center of the right greater trochanter
FRTHI	Right thigh	At 1/3 of the line between the RGTRO and RLEK
RLEK	Right lateral epicondyle of the knee	On the lateral side of the joint axis
RATI	Right anterior of the tibia	At 2/3 of the line between the RLEK and RLM
RLM	Right lateral malleoulus of the ankle	The center of the heel at the same height as the toe
RHEE	Right heel	Center of the heel at the same height as the toe
RTOE	Right toe	Tip of the big toe
RMT5	Right 5th metatarsal	Caput of the 5th metatarsal bone, on joint line midfoot/toes
RACR	Right shoulder	Right acromion
LACR	Left shoulder	Left acromion
T1	Treadmill marker 1	On the left rear corner of the treadmill
T2	Treadmill marker 2	At 1/2 of the line between T1 and T2
T3	Treadmill marker 3	On the left front corner of the treadmill
T4	Treadmill marker 4	On the right front corner of the treadmill
T5	Treadmill mraker 5	On the right rear corner of the treadmill

Table III: Nine EMG sensors used in this study. # means the EMG numbers in Delsys system. EMG 6 was not used due to a wireless connection issue. Analog channel column listed the corresponding analog column number in the recorded analog files.

#	Analog Channel	Muscle Names	Muscle Locations
EMG 1	17	Tibialis anterior	In the upper two-thirds of the lateral (outside) surface of the tibia
EMG 2	21	Soleus	In the back part of the lower leg (the calf)
EMG 3	25	Medial gastrocnemius	On the medial back portion of the lower leg
EMG 4	29	Lateral gastrocnemius	On the lateral back portion of the lower leg
EMG 5	37	Vastus medialis	In the anterior and medial compartment of thigh
EMG 7	41	Vastus lateralis	In the anterior and lateral compartment of thigh
EMG 8	45	Rectus femoris	Situated in the middle of the front of the thigh
EMG 9	49	Biceps femoris	Begins in the thigh area and extends to the head of the fibula near the knee
EMG 10	53	Gluteus maximus	Located in the buttocks

3.2.3 Perturbation Signal

In the standing balance experiment, perturbation was designed as random square signals, instead of the Gaussian random signals used in previous studies [1, 3, 5]. The main reason is to avoid damaging the V-Gait treadmill. The total mass of the V-Gait is a about 800 lbs. In the experiment, the whole V-Gait will move laterally according to the perturbation signal (Figure 4). Large impact forces can be generated on the treadmill motors due to the frequent direction changes in the Gaussian random perturbation.

Parameters that determined the random square signal are the stage amplitude and the stage duration. The principle of designing the signal is to let participants feel a large perturbation but no so large that they respond by taking a step. After several tests, a suitable perturbation signal was designed using square pulses with five amplitudes [-5, -2.5, 0, 2.5, 5] cm, and six stage duration [0.25, 0.5, 0.75, 1.0, 1.25, 1.5] seconds. Amplitudes and duration series were randomly generated to obtain a 300 second perturbation signal. All

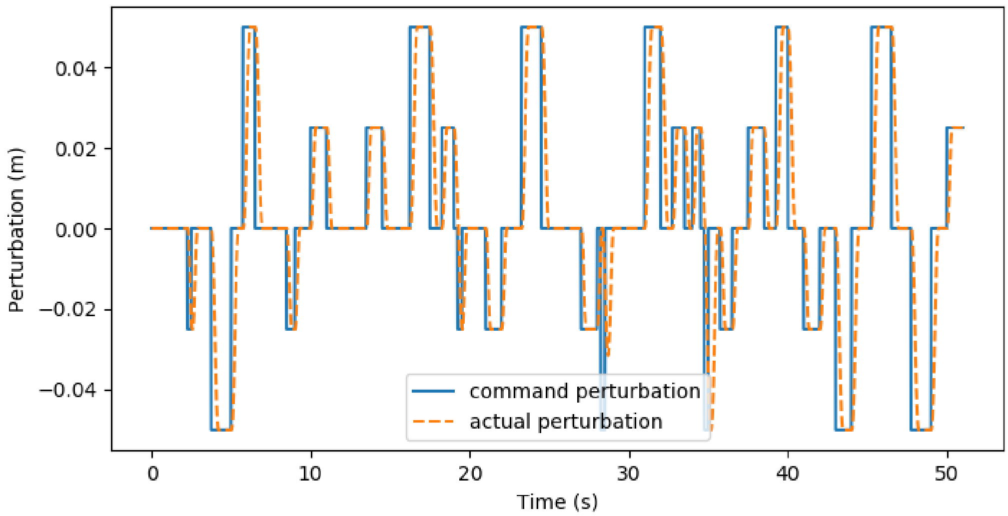

Figure 6: Comparison between the designed and actual standing balance perturbation. Designed perturbation has no dynamics and actual perturbation has a slow transient because of dynamics. Only the first 50 seconds is shown here.

participants experienced the same random square perturbations to check whether they have similar responses.

The actual sway motion of the V-Gait was calculated by averaging the motion of five reflect markers that were placed on the treadmill frame. The comparison between designed perturbation command and recorded V-Gait movement is shown in Figure 6. The difference between them was mainly caused by the dynamics of the V-Gait treadmill. In general, the actual perturbation closely tracked the designed signal.

3.2.4 Protocol

The experimental protocol consisted of both static measurements and experimental recordings. Experimental recordings include standing on the treadmill for five minutes with and without perturbation. On the day of experiment, the motion capture system was calibrated first using the manufacturer's recommended procedure. Prior testing, participants were asked to change into barefoot, shorts, and tight t-shirts (sports bra for female). All twenty-seven markers were applied directly to the skin except for the heel, toe, and hip markers, which were placed on the respective article of clothing. Then age, gender, height, and mass were documented. Their knee and ankle widths were measured by the experimentalist. After obtaining the informed consent and a briefing by the experimentalist on the trial protocol, the experimental protocol for a participant was as follows:

1. The participant stepped onto the treadmill and markers were identified with Cortex.

2. A safety rope was attached loosely to the rock climbing harness such that no forces were acting on the subject during experiment. But the harness would prevent a full fall.

3. The participant started by stepping on sides of treadmill so that feet did not touch the force plates and the force plate signals were zeroed. Then participants were asked to step back to the treadmill.

4. A verbal countdown to the first quiet standing trial (Trial 1) was given by the experimentalist. Participants were asked to look at a target at roughly same height as their eyes. The quiet standing trial was five minutes long.

5. After the quiet standing trial, participant was asked to continue the first perturbation trial (Trial 2), in which 5 minutes anterior and posterior perturbation was applied on the treadmill . In the perturbation trial, participants were asked to keep balance without taking a step. However, he/she is free to adjust his/her pose by actively control his/her joints.

6. The participant was instructed to step off the force plate after the second trial to have a rest for five minutes.

7. The participant was asked to repeat the perturbation trial after rest (Trial 3).

8. The participant was asked to have another five minutes quiet standing trial (Trial 4) after the repeated perturbation trial.

Participants 3-8 were instructed to keep their vision on the horizontal target, having the feet width similar to the width of shoulder, and feel free to bend their trunk to keep balance. The first two participants were in the process of testing experiment protocol. The first participant had a wider stance, and the second participant used a strange (freezing) strategy to keep balance, instead of the normal strategy. The identification work in chapter IV and V used the last six participants' data.

3.3 Raw Experimental Data and Post Processing

3.3.1 Raw Data

Each participant performed four trials. Each trial produced three raw data files.

1. Mocapxxxx.txt: contains motion capture marker data, ground reaction force, and 76 analog channels. Data was recorded at 100 Hz sampling rate.

2. Mocapxxxx_Motion Analysis_analog.txt: contains 76 high sampling rate (1000Hz) analog channels' data (Figure III)

3. Recordxxxx.txt: contains the sway motion data of treadmill and the three-axis acceleration data of two Xsens MTi-10 series sensors. Data was recorded at roughly 300 Hz.

The mocap data (marker motion) might missed some frames when markers were obscured or not recognized by the Cortex software. The quality of the marker data of all eight participants was assessed by determining the percentage of data missing and the maximum missing gaps. Most of the 32 markers had very small missing percentages, which were less than 0.5%, except the marker of NAVE, XYPH, STRN, LASIS. The data quality of these four markers over all participants and experiment trials is shown in Table IV. These markers had relatively bad quality in the experiment trials of participant 2. In other participants' data, their missing percentages were either lower than 1% or the maximum gaps of them were less than 200 frames (2 seconds).

Table IV: Maximum numbers of continual missing frames and overall percentage of missing frames of all participants.

Marker names		NAVE	XYPH	STRN	LASIS
Participant No.	Trial	Maximum gap (frames) {Missing data (%)}			
Participant 1	1	0 {0.0}	144 {2.4}	0 {0.0}	0 {0.0}
	2	6 {0.03}	9 {0.32}	5 {0.07}	0 {0.0}
	3	0 {0.0}	8 {0.5}	6 {0.14}	0 {0.0}
	4	4 {0.2}	20 {0.46}	0 {0.0}	0 {0.0}
Participant 2	1	0 {0.0}	28 {0.46}	0 {0.0}	0 {0.0}
	2	0 {0.0}	49 {20.36}	1581 {5.12}	256 {37.06}
	3	76 {2.22}	45 {7.44}	1434 {7.55}	2021 {90.93}
	4	0 {0.0}	0 {0.0}	0 {0.0}	402 {4.34}
Participant 3	1	0 {0.0}	0 {0.0}	0 {0.0}	0 {0.0}
	2	6 {0.08}	15 {2.84}	1 {0.0}	0 {0.0}
	3	2 {0.11}	22 {1.03}	10 {0.55}	0 {0.0}
	4	99 {17.29}	0 {0.0}	16 {0.24}	0 {0.0}
Participant 4	1	0 {0.0}	0 {0.0}	0 {0.0}	0 {0.0}
	2	0 {0.0}	5 {0.15}	3 {0.03}	0 {0.0}
	3	0 {0.0}	1 {0.0}	0 {0.0}	0 {0.0}
	4	0 {0.0}	0 {0.0}	0 {0.0}	0 {0.0}
Participant 5	1	0 {0.0}	0 {0.0}	0 {0.0}	0 {0.0}
	2	65 {1.29}	6 {0.13}	0 {0.0}	0 {0.0}
	3	0 {0.0}	0 {0.0}	0 {0.0}	0 {0.0}
	4	0 {0.0}	0 {0.0}	0 {0.0}	0 {0.0}
Participant 6	1	0 {0.0}	159 {32.72}	0 {0.0}	0 {0.0}
	2	14 {0.08}	95 {4.33}	4 {0.11}	2 {0.01}
	3	15 {0.17}	82 {3.8}	1 {0.0}	0 {0.0}
	4	0 {0.0}	0 {0.0}	0 {0.0}	0 {0.0}
Participant 7	1	0 {0.0}	0 {0.0}	0 {0.0}	0 {0.0}
	2	8 {0.14}	2 {0.02}	13 {0.59}	3 {0.02}
	3	0 {0.0}	0 {0.0}	64 {1.75}	0 {0.0}
	4	0 {0.0}	0 {0.0}	0 {0.0}	0 {0.0}
Participant 8	1	0 {0.0}	0 {0.0}	0 {0.0}	0 {0.0}
	2	0 {0.0}	2 {9.68}	3 {9.68}	0 {0.0}
	3	0 {0.0}	0 {0.0}	1 {3.23}	0 {0.0}
	4	0 {0.0}	0 {0.0}	0 {0.0}	0 {0.0}

3.3.2 Missing Data Filling

Gaps (missing) of the marker data were filled using the interpolation function in *MATLAB*. The filling process contained the following three steps:

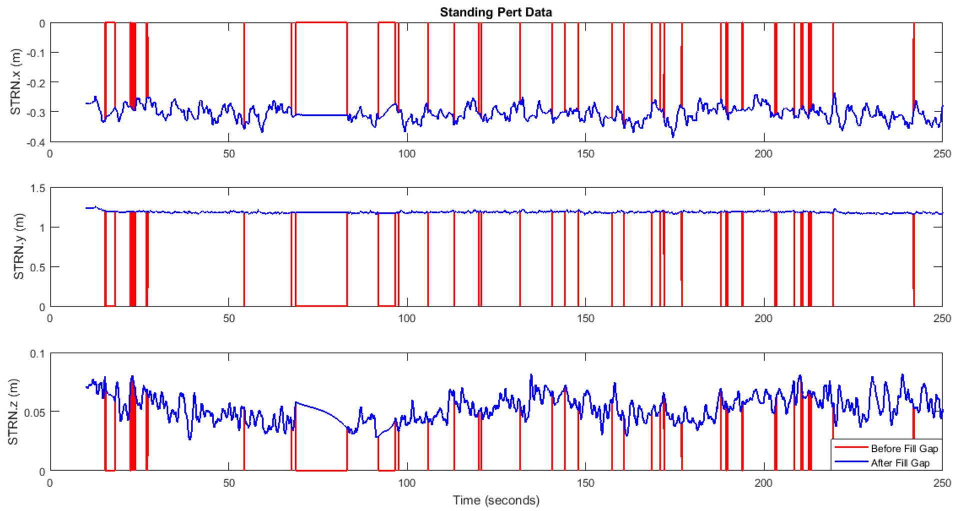

Figure 7: Gap filling result in experiment trial three of participant two. Red lines are original recorded data, which several frames' data were zero due to marker missing. Blue lines are filled marker data, which all the gaps were filled with reasonable data.

1. Find out the index of marker data with value zero. (D-Flow writes zero value in the file when a marker is not recognized. We assume that the position of marker will never be exactly zero if the marker was not missing.)

2. Generate recorded marker data and corresponding time vector after removing the missing marker data and corresponding time stamps.

3. Generate the estimated value of missing marker data using interp1 function in *MATLAB* with generated marker data in the above step.

Piece-wise Cubic Hermite Interpolating Polynomial (PCHIP) option was used in the 'interp1' function in *MATLAB*. Good filling results were achieved even with large data gap period. One example of the gap filling is shown in Figure 7.

3.3.3 Calculation of Joint Angles and Torques

Joint angles and torques were calculated using a 2d gait model (`https://github.com/csu-hmc/GaitAnalysisToolKit`). In the calculation, joint angles were averaged between the left and right legs based on the assumption that participants' movement were symmetric. Sign definition of the ankle, knee, and hip joints are shown in Figure 8. Ground reaction forces(GRF) in the perturbed trials were compensated [10] to remove the inertia artifact of the moving treadmill. A comparison of raw GRF and the compensated GRF is shown in Figure 9. Compensated GRF has much lower amplitude than the raw GRF, showing that the measured GRF was largely affected by the inertia of the heavy treadmill. Since almost all reactions to perturbation were in the sagittal plane, a two dimensional seven-link human body model was used [11] to calculate joint torques through inverse dynamics. Joint torques were also averaged between left and right legs. The sign convention for joint torques are the same as joint angles. An example (participant 7 trial 3) of the calculated joint angles and torques is shown in Figure 10. Both joint angles and torques were zeroed by subtracting the mean value of the quiet standing period (first 10 second) in each trial. The assumption here is that human trends to save energy in quiet standing, so that the joint angles should be close to zero which requires the minimum joint torques. In addition, because the postural feedback controllers that will be identified from the motion data is for controlling the humanoid robots or P/O devices, it is better to have zero joint angles at quiet standing, so that less joint torques will be required.

3.3.4 Repository of Processed Data

Processed data in each experiment trial were saved into four files:

1. Mocapxxxx.txt: contains the gap filled motion capture data and the inertia compensated ground reaction force data.

2. Motionxxxx.txt: contains the calculated trajectories of three joints' (hip, knee, and ankle) angles, angular velocities, moments, and joint contact forces.

3. Data_infoxxxx.txt: contains the quality of recorded raw marker data (percentage and biggest duration of missing marker data), and the percentage of removed the inertia artifacts in ground reaction forces.

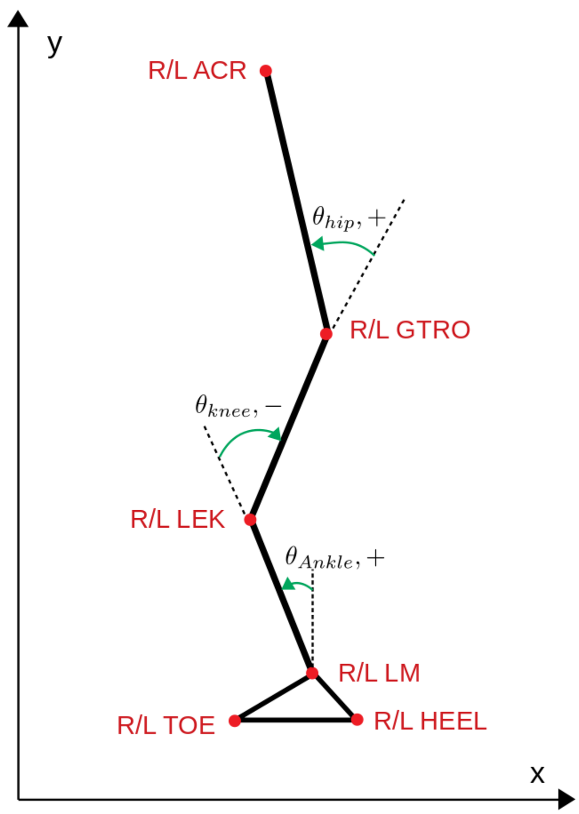

Figure 8: Human body diagram in standing balance task. The markers used for joint angles calculation is named in red color. The definition of joint angles is shown in the plot. Positive joint angles are defined with counterclockwise rotation. Joint torques have the same sign as joint angles.

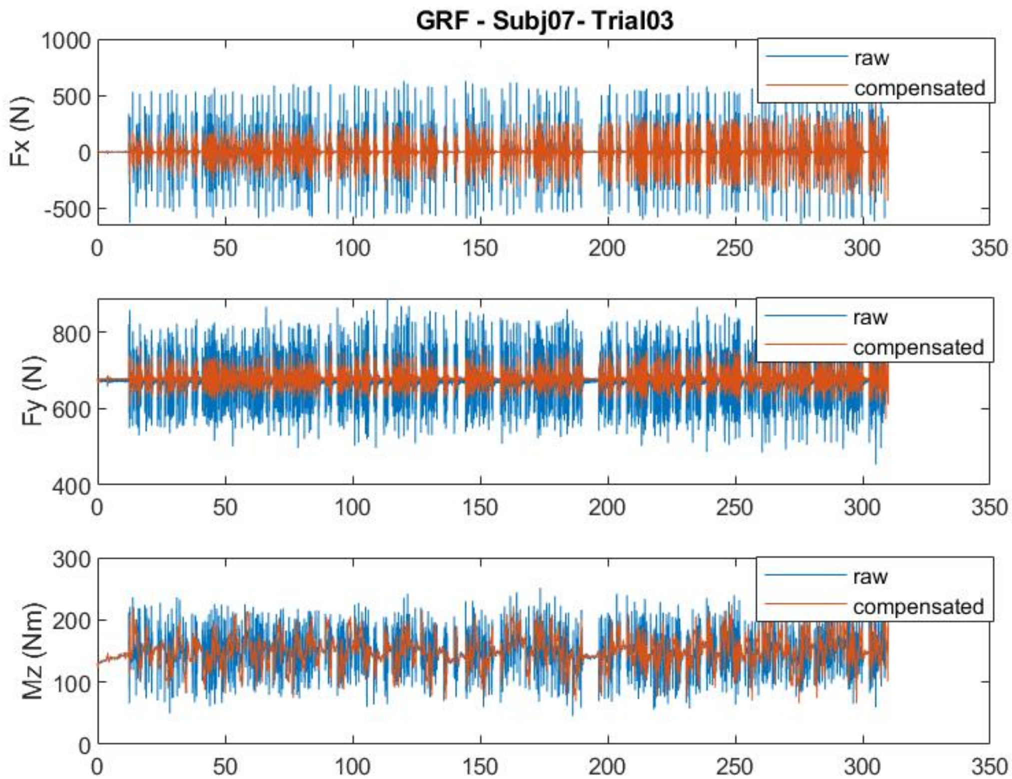

Figure 9: A comparison of raw ground reaction force and compensated ground reaction force.

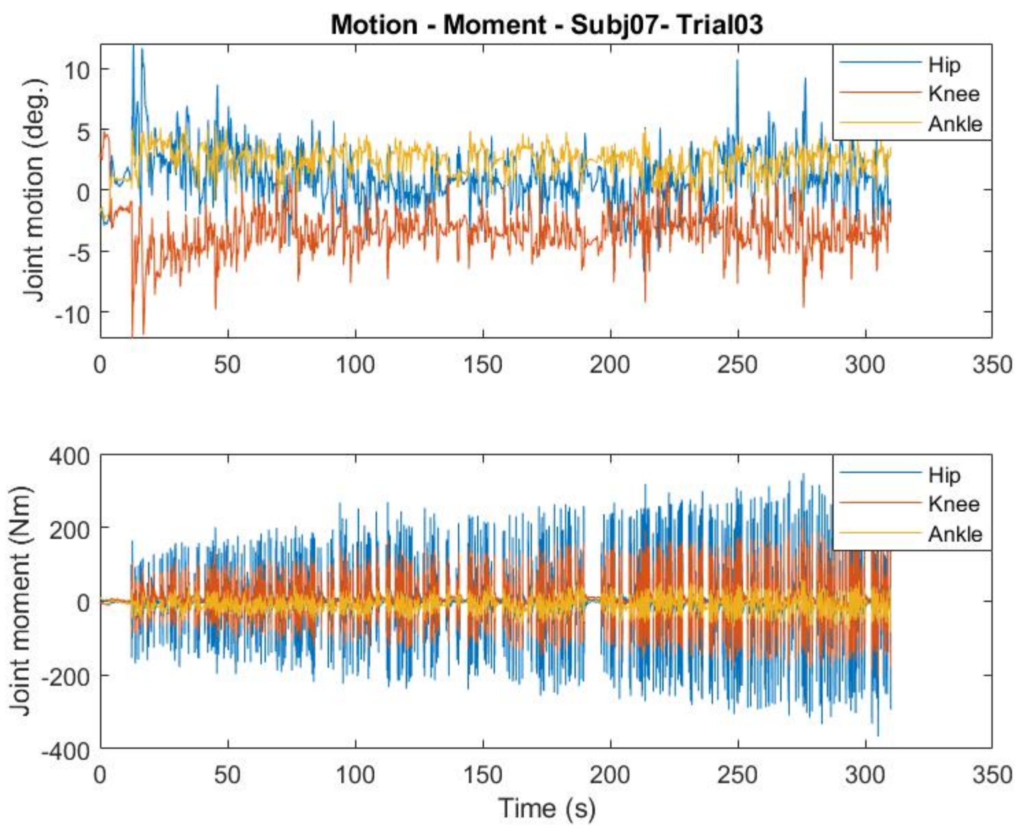

Figure 10: Joint angles and torques of participant 7 and experiment trial 3.

4. MotionAnalysis.fig: shows the mean and standard deviation of three joints' trajectories in four experimental trials.

3.3.5 Analysis of Joint Motions

Here we calculated the means and standard deviations of the joint angles for the last six participants. These statistical information are shown in Figure 11 - 16. The first and fourth experimental trials were quiet standing trials. The second and third trials were perturbed trials. Motion variations in perturbed trials were much larger than quiet standing trials, showing that perturbation had evoked the human standing system in a larger variety situations. The two quiet standing trials had similar variation of joint motion. However, there was a difference in the variation of joint motion between two perturbed trials. The second perturbation trials (repeated perturbation trial) had a relative smaller variation than the first perturbation trial for almost all participants.

3.4 Discussion

Based on our analysis, the measured data from the standing balance experiment has good quality for postural controller identification. Most marker data had less than 1% missing data or less than 20 frames (0.2 second) of the maximum missing gap, except for the third trial of the second participant. With 0.2 second data missing period, interpolation can help fill them up very well. Considering the first two participants were pilot studies (their data were not used in the identification study), the quality of the standing experiment data is good.

As expected, the perturbation trials had larger motions than the quiet standing trials. This means that perturbation did cause participants to control their body motions while maintaining standing balance. The averaged knee angles are positive and averaged hip angles are negative for most participants. This means that they bent their knee and leaned their trunk forward in the standing balance experiment. This is typical reaction for most

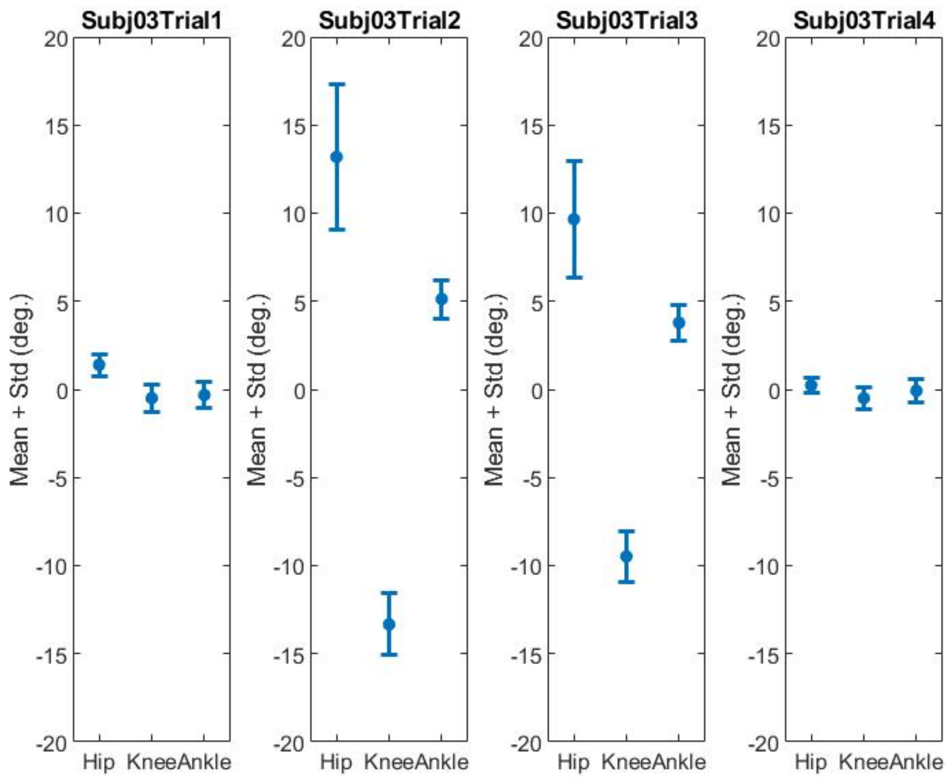

Figure 11: Joint angle analysis of subject 3. Analysis includes the mean and standard deviation of the ankle, knee, and hip joint motions.

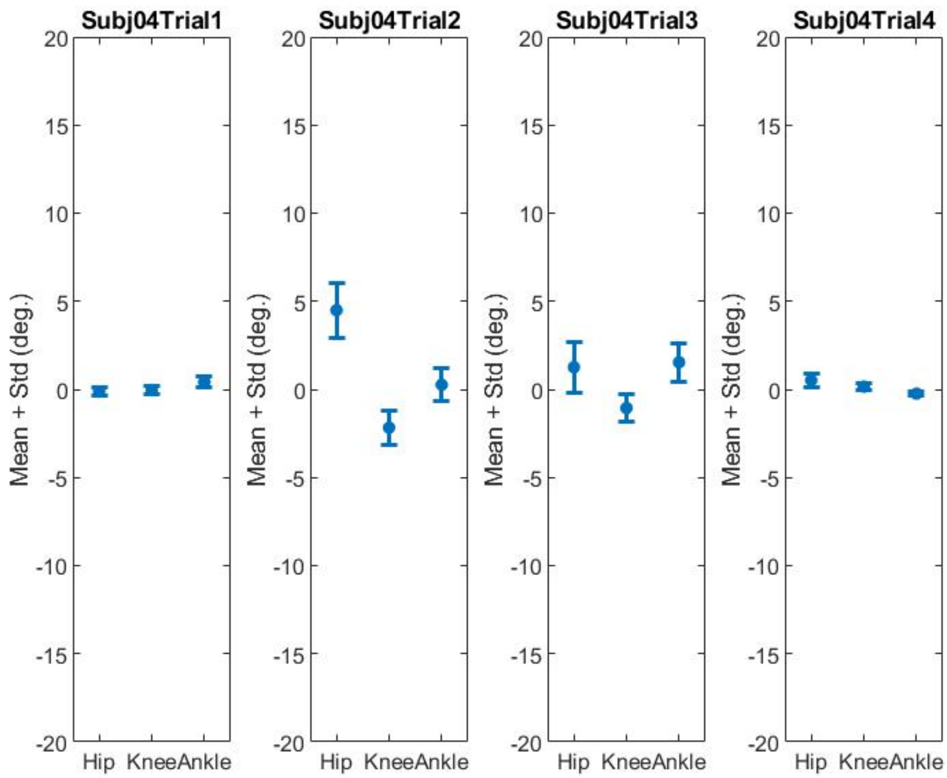

Figure 12: Joint angle analysis of subject 4. Analysis includes the mean and standard deviation of the ankle, knee, and hip joint motions.

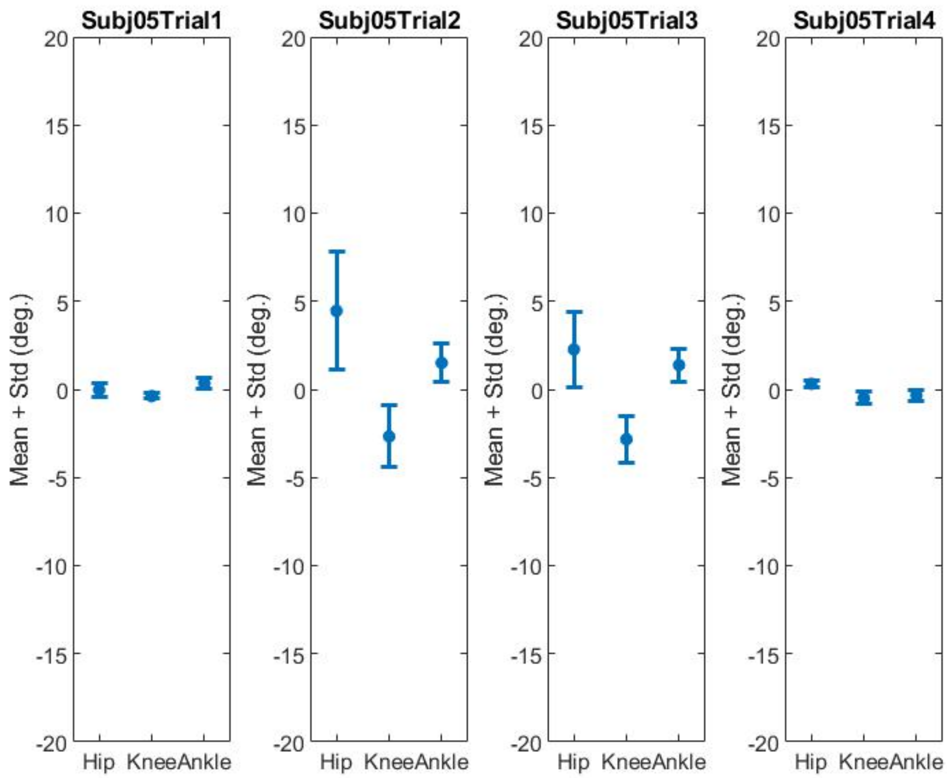

Figure 13: Joint angle analysis of subject 5. Analysis includes the mean and standard deviation of the ankle, knee, and hip joint motions.

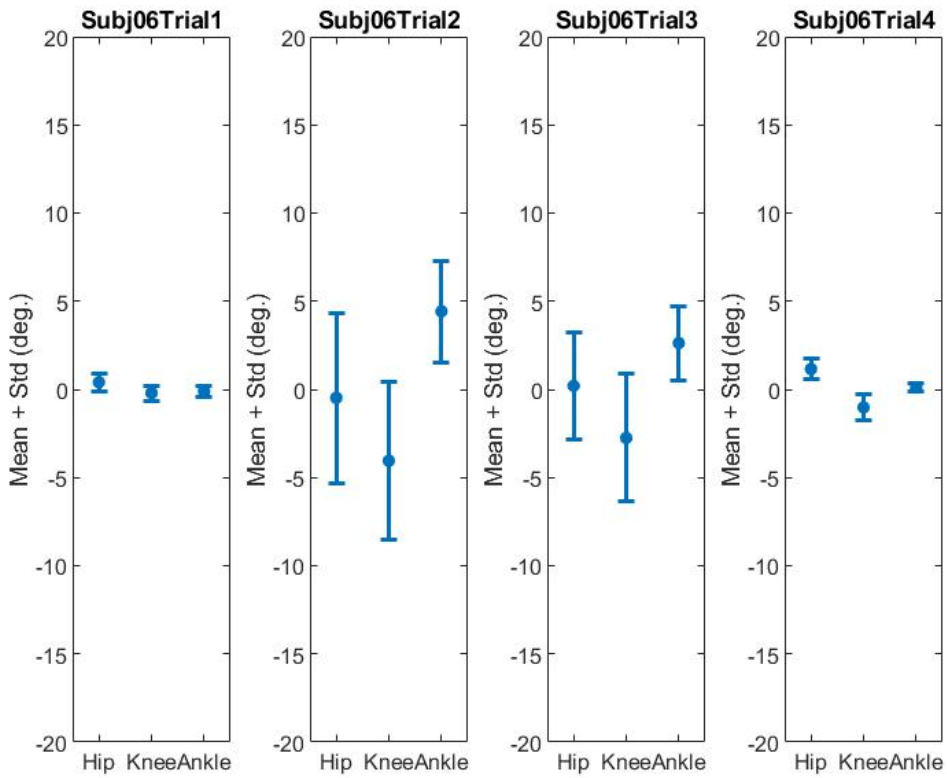

Figure 14: Joint angle analysis of subject 6. Analysis includes the mean and standard deviation of the ankle, knee, and hip joint motions.

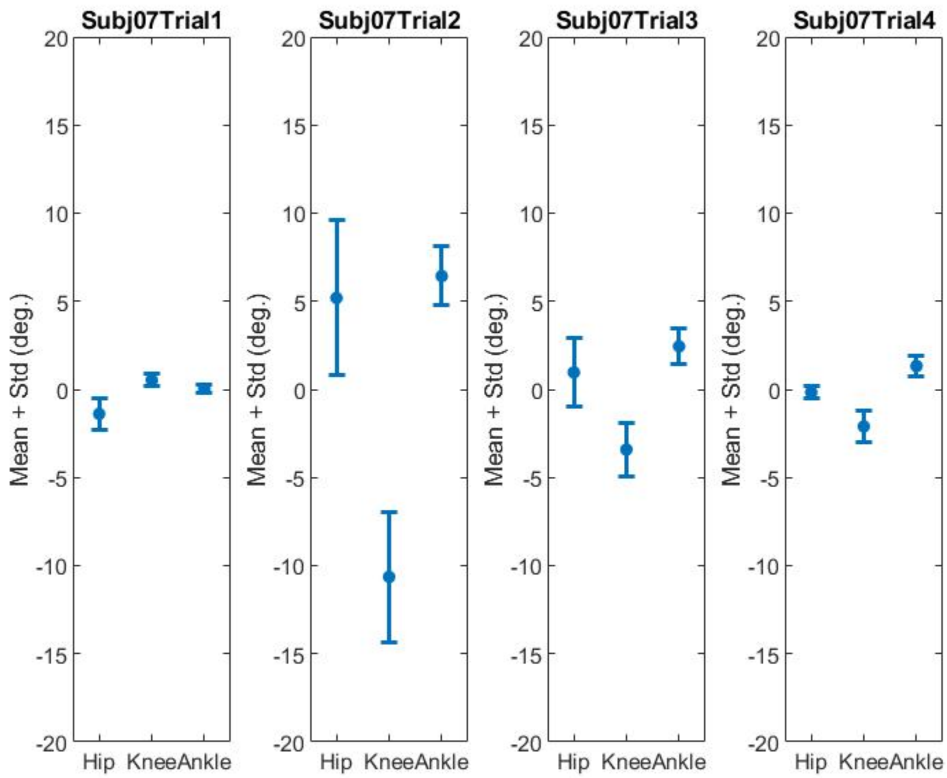

Figure 15: Joint angle analysis of subject 7. Analysis includes the mean and standard deviation of the ankle, knee, and hip joint motions.

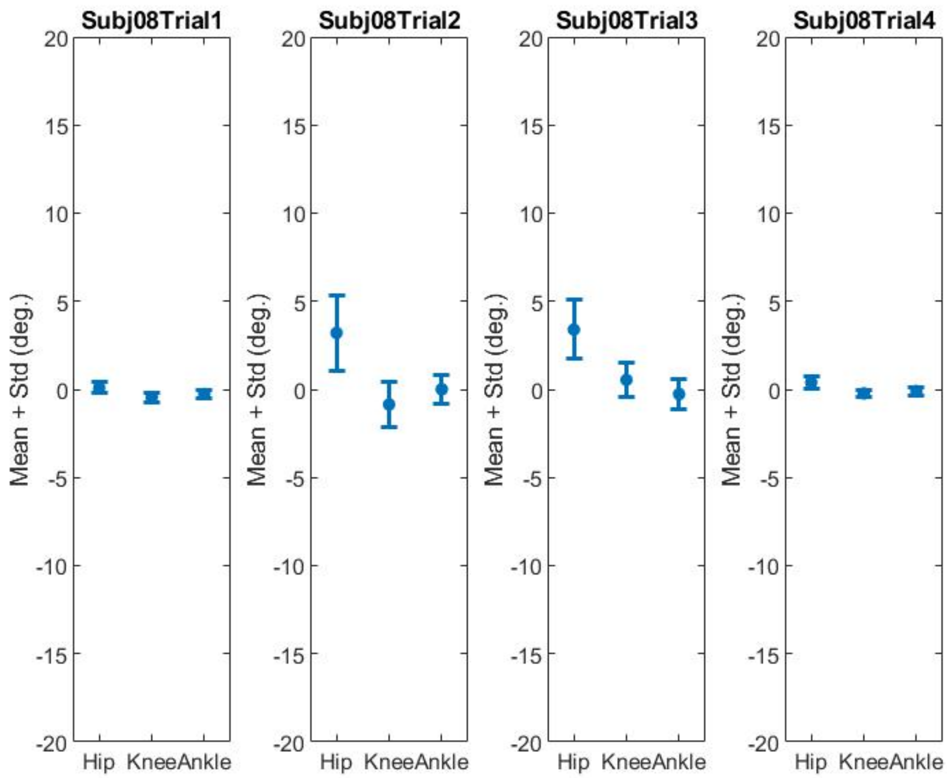

Figure 16: Joint angle analysis of subject 8. Analysis includes the mean and standard deviation of the ankle, knee, and hip joint motions.

people in daily experience during standing balance.

Perturbation trials did not have a significant effect on the quiet standing balance. The first and fourth trials of each participant are two quiet standing trials which were before and after perturbation trials. The range of joint motion in these two trials does not have a significant difference. This suggests that perturbation experience does not affect quiet standing balance. However, this have not been confirmed by qualitative study. We encourage some qualitative studies be done with the experiment data in future.

Participants had smaller joint motion range after the first perturbation experience. The repeated perturbation trial always has smaller motion range than the first perturbation trial when comparing the motion range for each participant. Since the same perturbation signal was used in both trials, this means participants adapted to the perturbation and could keep balance using smaller body swing motions. The first perturbation trial was more appropriate for extracting postural balance information in daily activity situation, since participants haven't got used to the perturbation yet.

3.5 Conclusion

In the standing balance experiment, over 160 minutes standing balance data of 8 participants were recorded. From the analysis, the collected standing balance data are in good quality. Joint motions are reasonable and confirm with our daily standing balance experience. The collected experiment data is suitable for identifying generalized postural feedback controllers in the standing balance task.

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