Validation of Reboot Motion Single Camera Motion Capture

Last Updated: Dec 2, 2022

Summary

The purpose of this study was to assess the accuracy and repeatability of Reboot Motion's single camera motion capture methodology by comparing its output to a KinaTrax lab motion capture setup. KinaTrax was chosen as a basis for comparison because it is a broadly implemented, multi-camera, markerless motion capture solution used by many MLB and upper-level baseball programs. A recent study validated KinaTrax for use in academic gait research.

For this study, a right-handed, MLB-caliber pitcher threw 18 pitches in a practice session, while 240 fps videos were collected using an iPhone 12 simultaneously with the KinaTrax data.

Comparing to KinaTrax joint angles as the ground truth, and using the Coefficient of Determination (R-squared) and Root Mean Squared Error (RMSE) as measurements of accuracy, Reboot Motion's single camera motion capture methodology had a median R-squared of 0.92 and a median RMSE of 10.4 deg across joint angles of interest. The averages were 0.86 and 10.3, respectively. The average R-squared was pulled downward due to a low R-squared in the pitcher's non-dominant shoulder rotation angle, which is the shoulder hidden from the view of the camera.

Within the realm of single camera motion capture, Reboot Motion's methodology outperformed the previous state of the art at many joints, including all the joints of the throwing arm, often with more repeatable standard deviations.

Overall joint angle repeatability, assessed as the standard deviations at several key time points in the pitching delivery (Max Knee Height, Max External Shoulder Rotation, and Ball Release), was under 4 degrees for almost every joint at every time point.

Additionally, when assessed via the Mean Per Joint Position Error After Rigid Alignment (MPJPE-RA), which is a typical assessment of existing single camera motion capture methods, our methodology outperforms previous single camera methods by 0.7 cm, at 2.4 cm of error compared to 3.1 cm for capturing activities of daily living. Note that no available research exists giving MPJPE-RA for pitching motions.

Accuracy and Repeatability Summary

Body Part	R-squared	RMSE (deg)	StD at Ball Release with Single Camera (deg)	StD at Ball Release with KinaTrax (deg)
Throwing Arm	0.923 +/- 0.03	10.53 +/- 1.55	2.454	2.225
Glove Arm	0.79 +/- 0.062	11.08 +/- 2.16	2.932	2.41
Knees	0.841 +/- 0.063	9.101 +/- 1.721	3.219	3.13
Pelvis and Trunk	0.883 +/- 0.04	9.864 +/- 0.873	3.265	2.558

Body Part	StD at Max Knee Height with Single Camera (deg)	StD at Max Knee Height with KinaTrax (deg)	StD at Max Ext Rot with Single Camera (deg)	StD at Max Ext Rot with KinaTrax (deg)
Throwing Arm	2.671	3.324	2.538	3.317
Glove Arm	1.829	3.312	3.282	2.294
Knees	1.63	3.224	3.223	3.578
Pelvis and Trunk	1.993	3.842	3.35	2.493

Methods

Data collection was carried out on one subject, who was a male right-handed pitcher with MLB experience. He was throwing approximately 90 miles per hour (mph) throughout the collection. Collection involved simultaneous capture of a practice session on an indoor mound using both a KinaTrax lab setup and slow motion 240 fps iPhone 12 video captured in landscape mode from the pitcher's open side.

The pitcher's arm slot was "three-quarters" - i.e. about midway between side-arm and overhead. This is notable because previous studies have only analyzed pitchers with overhead arm slots. Overhead arm slots can be easier to capture with a single camera from the open side because the arm and other body parts rotate in a more vertical plane that is parallel to the camera lens. Lower arm slots have more motion that goes towards and away from the lens, which is harder to capture for a single camera motion capture system.

In total, 18 pitches were successfully captured and compared. The KinaTrax data sets were processed to get joint centers using their proprietary methods. The 240 fps iPhone videos were processed using Reboot Motion's two stage approach. In the first stage, 2D joint centers were identified in each video frame. In the second stage, the 2D joint centers were elevated into 3D space using Reboot Motion's proprietary 2D to 3D model, which was adapted from several open source models.

During model training, model performance was assessed via the Mean Per Joint Position Error After Rigid Alignment (MPJPE-RA). This was calculated by first aligning the joint center predictions in space using the Procrustes method, and then calculating the average position error between the predicted joint centers and the ground truth joint centers.

For each pitch, the paired KinaTrax and Reboot Motion joint centers were cropped and synchronized in time from just before max knee height to just after ball release. Each set of joint centers was processed into joint angles using the same proprietary inverse kinematics algorithm, with joint coordinate definitions commonly used for baseball pitching motions.

The methodology for assessing the accuracy and repeatability was adapted from the methods used for the previous state of the art to allow comparison. For each pitch, the Coefficient of Determination (R-squared) and Root Mean Squared Error (RMSE) were calculated for the set of paired joint angle time series measurements, then an average and standard deviation of each statistic was calculated across all pitches.

To assess overall repeatability, three key time points in the pitching delivery were selected at which to calculate joint angle measurement standard deviations: *max knee height* during the leg lift, *max external shoulder rotation,* and *ball release*. At each of these key time points, for each joint angle of interest, the standard deviation of that joint angle was calculated for both the KinaTrax data set and the Reboot Motion data set across all pitches.

It is important to note that the calculation of repeatability here includes variability due to the pitcher's underlying ability to repeat his delivery, as well as the repeatability of the motion capture methodology, so the measurements should be interpreted in this context.

Results

During model training, an MPJPE-RA of 2.4 cm was achieved, which outperforms the state of the art in existing single camera motion capture research literature by 0.7 cm. The state of the art there is 3.1 cm for capturing activities of daily living (no available research exists giving MPJPE-RA results for pitching motions).

When assessing the correlation between Reboot Motion's single camera methodology and the KinaTrax output across joint angles, the median R-squared was 0.92 and the median RMSE was 10.4 degrees. The means were 0.86 and 10.3 deg, respectively. The mean R-squared was pulled lower by an outlier low value for the *left, non-dominant, shoulder rotation*, on the opposite side of the pitcher from the camera.

Reboot Motion's highest performing joint angle was *right shoulder rotation* with an R-squared of 0.98. Other high performing joint angles with R-squared values over 0.9 include: *right elbow flexion, right shoulder abduction, left elbow flexion, left shoulder abduction, left knee flexion, pelvis rotation, torso extension, and torso side bend.*

All joint angle correlations were over 0.8 with the exception of *left shoulder rotation* and *torso rotation*. The poor correlation in the left shoulder rotation angle was likely due to this joint being on the opposite side of the pitcher, away from the view of the camera. The poor correlation in torso rotation was primarily due to a drop in the correlation towards the end of the trials, near ball release, when the pitcher's shoulders were fully turned towards home plate. Improving this joint angle will be a focus as the single camera model is continuously trained and improved.

Looking at the RMSE, the highest performing joint angle was *torso side bend* with an average joint angle error of 3.5 deg. The lowest performing joint angle was *left shoulder rotation* with an error of 20 degrees. This was somewhat expected at the left shoulder joint, because for this pitcher, it was the shoulder joint on the opposite side of the body from the camera. Notably, the standard deviations of the RMSE values were generally 3 degrees and below, indicating strong repeatability in the joint angle measurements, despite the differences relative to the KinaTrax ground truth data..

Overall joint angle repeatability measurements, assessed as the standard deviations at the aforementioned key time points in the pitching delivery, were under 4 degrees for almost every joint at every time point. In fact, most were within 3 degrees or less. The least repeatable joint angle measurement was the *right elbow* at max knee height, at a little over 6 degrees, but all other joint angles at all other time points were repeatable within 5 degrees or less.

See the Appendix for figures comparing all joint angles.

Accuracy and Repeatability

Accuracy

joint_angle	R-squared	R-squared StD	RMSE (deg)	RMSE StD (deg)
right_elbow	0.93	0.027	9.878	1.325
right_shoulder_flex	0.843	0.048	11.603	0.951
right_shoulder_abd	0.939	0.019	9.484	0.777
right_shoulder_rot	0.98	0.013	11.144	2.517
left_elbow	0.956	0.019	11.571	1.796
left_shoulder_flex	0.881	0.039	7.499	1.103
left_shoulder_abd	0.977	0.014	4.969	1.21
left_shoulder_rot	0.344	0.116	20.285	3.559
left_knee	0.96	0.022	11.579	2.28
right_knee	0.722	0.087	6.623	0.854
pelvis_rot	0.968	0.011	15.209	1.139
torso_ext	0.911	0.024	10.205	0.681
torso_side	0.913	0.049	3.456	0.687
torso_rot	0.739	0.056	10.585	0.901

Repeatability

joint_angle	StD at Ball Release with Single Camera (deg)	StD at Ball Release with KinaTrax (deg)
right_elbow	3.290	3.036
right_shoulder_flex	1.940	1.540
right_shoulder_abd	1.523	1.537
right_shoulder_rot	3.179	2.418
left_elbow	4.104	1.815
left_shoulder_flex	3.635	1.908
left_shoulder_abd	2.039	3.483
left_shoulder_rot	3.339	2.042
left_knee	2.911	3.474
right_knee	1.825	2.744
pelvis_rot	4.615	3.235

torso_ext	2.963	1.598
torso_side	1.559	2.167
torso_rot	3.150	2.910

joint_angle	StD at Max Knee Height with Single Camera (deg)	StD at Max Knee Height with KinaTrax (deg)	StD at Max Ext Rot with Single Camera (deg)	StD at Max Ext Rot with KinaTrax (deg)
right_elbow	6.497	3.988	3.524	6.060
right_shoulder_flex	4.827	3.158	2.398	1.499
right_shoulder_abd	1.937	2.028	1.946	1.459
right_shoulder_rot	2.822	3.768	1.856	1.704
left_elbow	1.689	3.016	5.054	1.918
left_shoulder_flex	2.395	3.131	2.790	1.544
left_shoulder_abd	1.369	3.578	2.528	3.157
left_shoulder_rot	1.775	3.491	3.679	2.240
left_knee	2.893	2.660	3.007	4.004
right_knee	1.324	3.703	2.174	3.094
pelvis_rot	2.474	5.660	4.586	3.201
torso_ext	1.227	1.487	2.548	1.416
torso_side	2.046	2.812	1.433	2.063
torso_rot	1.735	4.111	3.554	2.891

Conclusions

Reboot Motion's single camera motion capture methodology outperforms the previous single camera state of the art at many joints. Furthermore, its joint angle measurements are typically repeatable within several degrees.

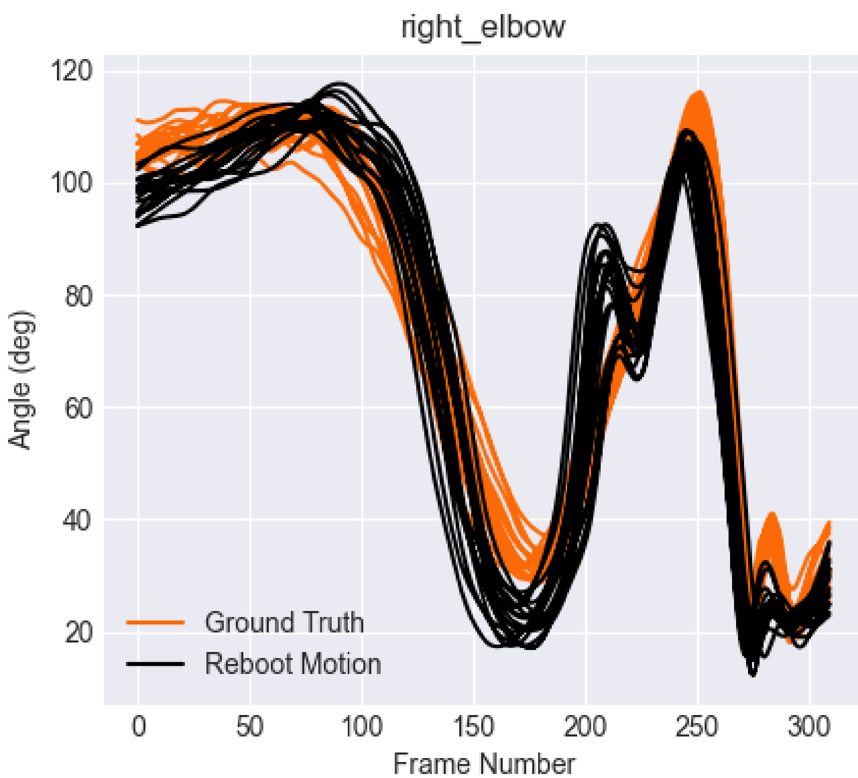
Though we would always recommend collecting with a multi-camera motion capture system when possible, we believe Reboot Motion's single camera methodology is a viable and effective alternative when collecting with a multi-camera system is not possible.

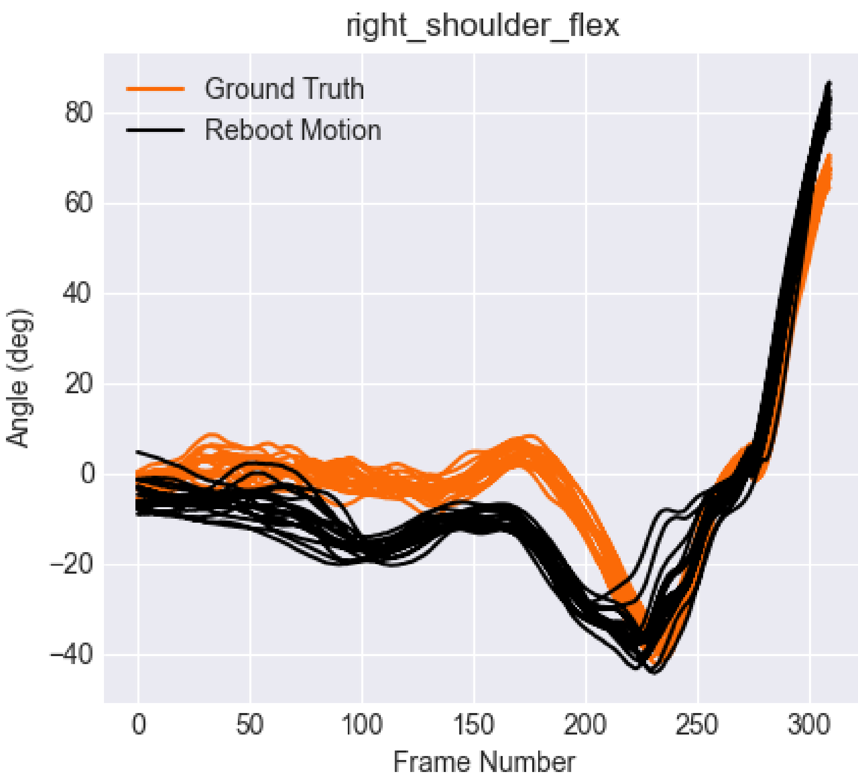
Future work will include validating on more subjects in more environments, but we believe this study suggests Reboot Motion's single camera methodology is on its way to becoming the state of the art in the single camera motion capture space.

Future work will also include continually training and updating the model, as better methods and more data become available.

Appendix

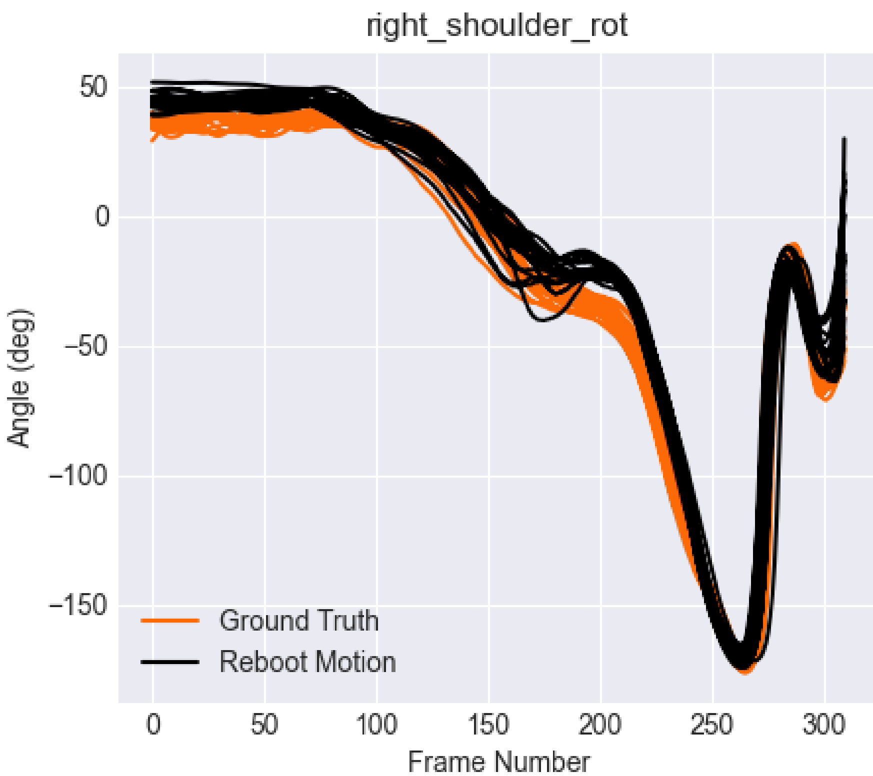
Ground Truth: KinaTrax
Reboot Motion: Single Camera

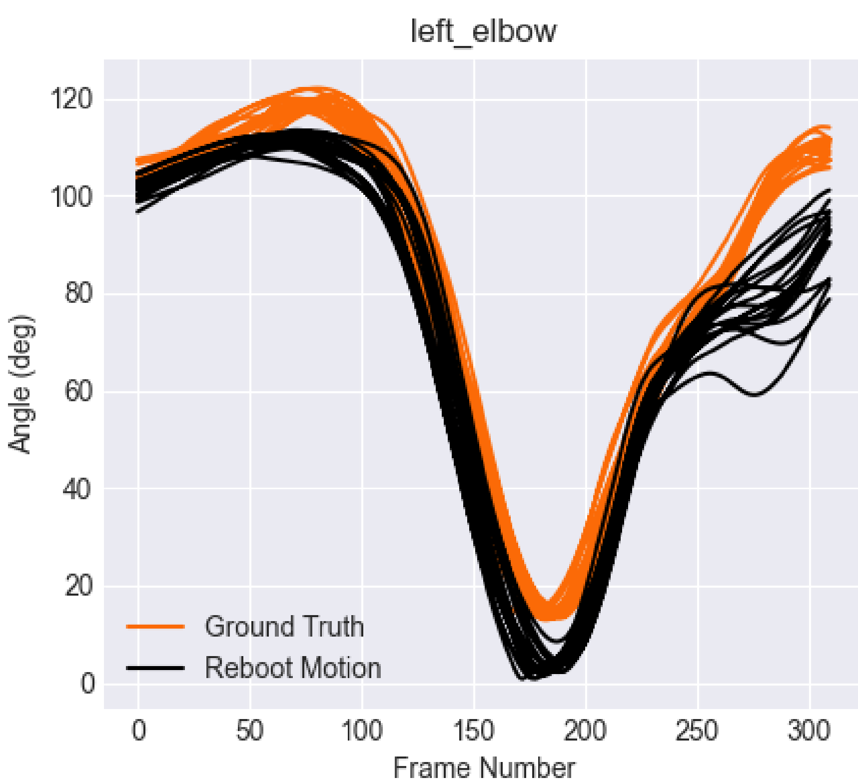




right_shoulder_flex
Ground Truth
Reboot Motion
Angle (deg)
Frame Number
80
60
40
20
0
−20
−40
0
50
100
150
200
250
300

right_shoulder_abd
Ground Truth
Reboot Motion
Angle (deg)
Frame Number
140
120
100
80
60
40
20
0
50
100
150
200
250
300


right_shoulder_rot
50
0
−50
−100
−150
Angle (deg)
Ground Truth
Reboot Motion
0
50
100
150
200
250
300
Frame Number

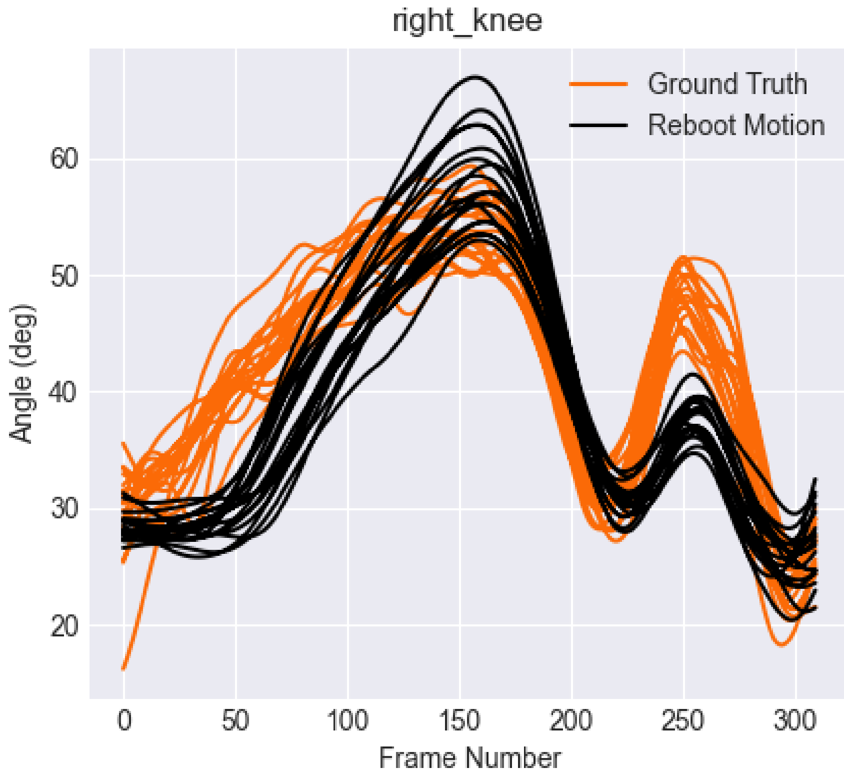

left_elbow
120
100
80
60
40
20
0
Angle (deg)
Ground Truth
Reboot Motion
0
50
100
150
200
250
300
Frame Number

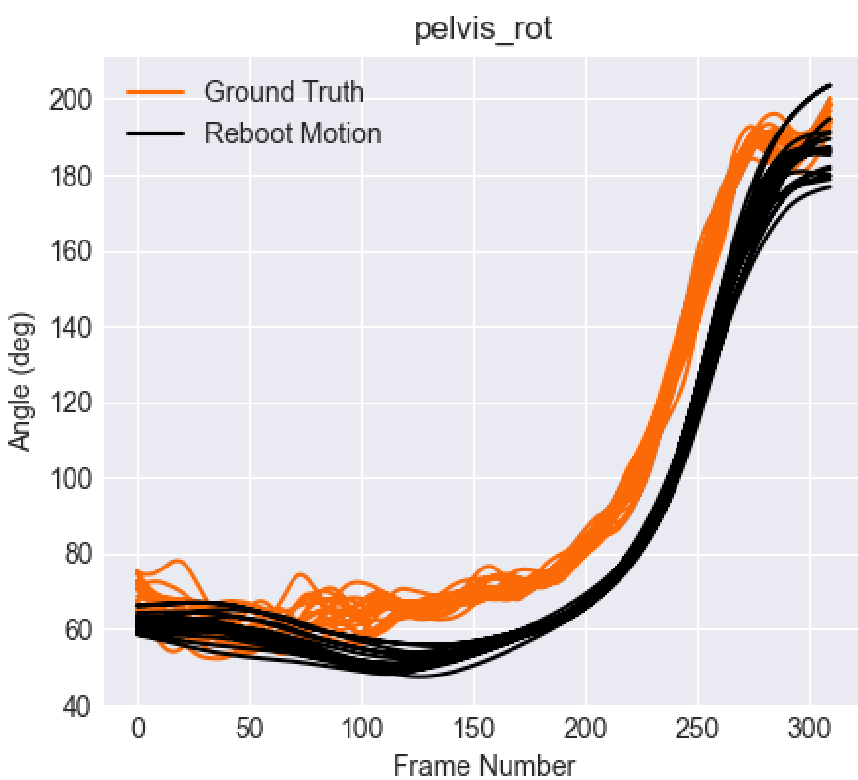

left_shoulder_flex
Ground Truth
Reboot Motion
Angle (deg)
Frame Number
20
10
0
−10
−20
−30
−40
−50
0
50
100
150
200
250
300

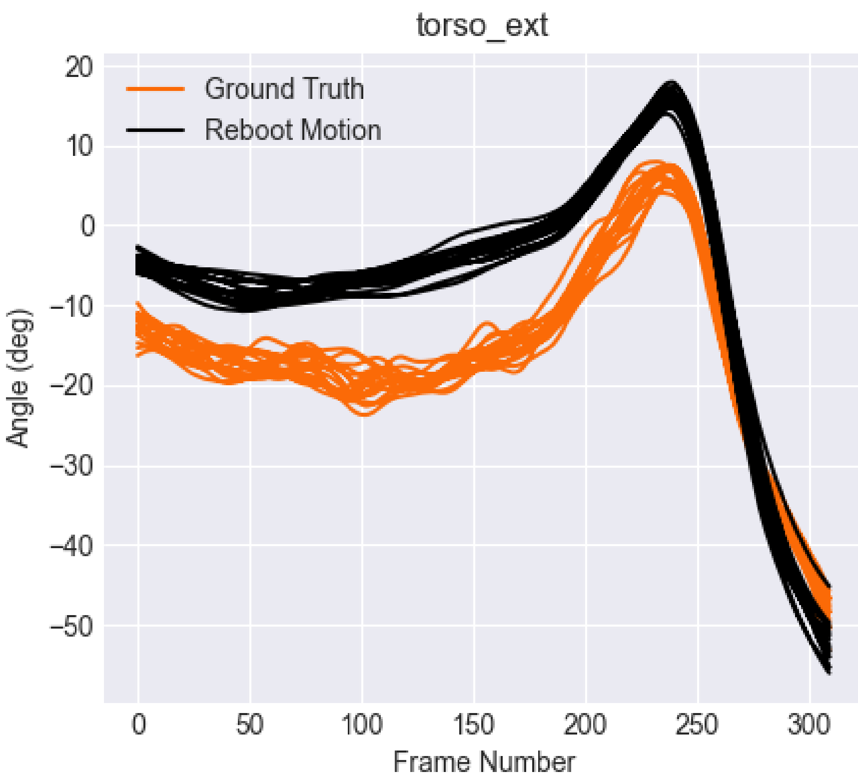

left_shoulder_abd
Ground Truth
Reboot Motion
Angle (deg)
Frame Number
100
80
60
40
20
0
50
100
150
200
250
300

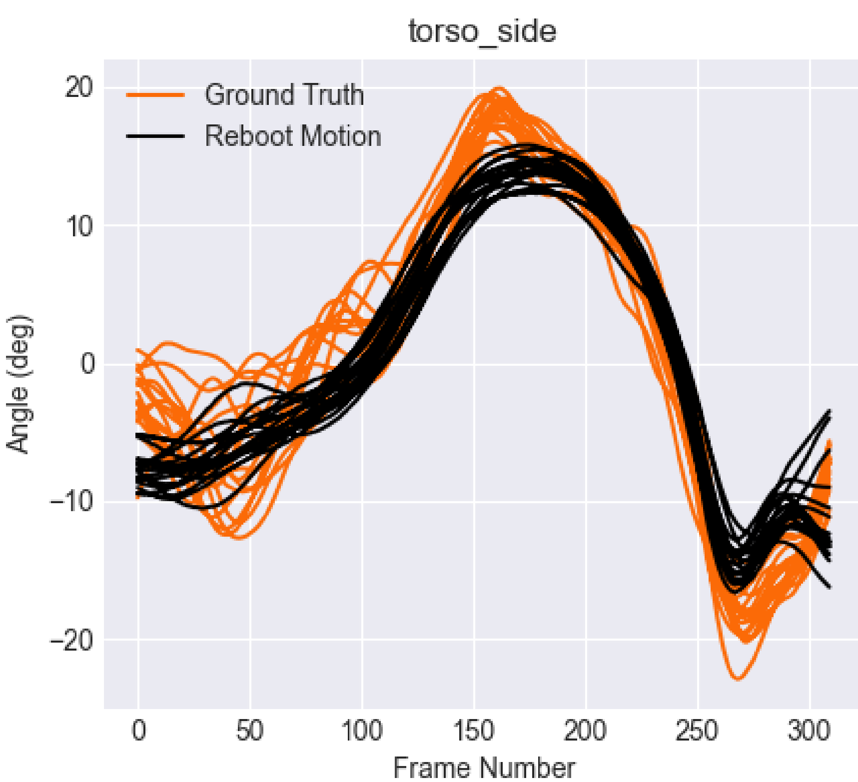

left_shoulder_rot
Ground Truth
Reboot Motion
Angle (deg)
Frame Number
0
20
40
60
80
100
0
50
100
150
200
250
300


left_knee
Ground Truth
Reboot Motion
Angle (deg)
Frame Number
0
20
40
60
80
100
0
50
100
150
200
250
300


right_knee
Ground Truth
Reboot Motion
Angle (deg)
20
30
40
50
60
0
50
100
150
200
250
300
Frame Number


pelvis_rot
Ground Truth
Reboot Motion
Angle (deg)
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
Frame Number


torso_ext
Ground Truth
Reboot Motion
Angle (deg)
Frame Number
20
10
0
−10
−20
−30
−40
−50
0
50
100
150
200
250
300


torso_side
Ground Truth
Reboot Motion
Angle (deg)
Frame Number
20
10
0
−10
−20
0
50
100
150
200
250
300


torso_rot
Ground Truth
Reboot Motion
40
20
0
−20
−40
Angle (deg)
0
50
100
150
200
250
300
Frame Number