Validation of Reboot Motion Single Camera Motion Capture v2.0

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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 an overall R-squared of 0.93 and an overall RMSE of 10.6 deg across all joint angles of interest.

Within the realm of single camera motion capture, Reboot Motion's methodology outperformed its previous version (v1.0) at many joints. It also 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), averaged 5 degrees across joints and key time points.

Compared to v1.0 of Reboot Motion's Single Camera Motion Capture, v2.0 has improved correlations for many body segments:

- Throwing Arm = 2% improvement
- Knees = 5% improvement
- Pelvis and Trunk = 4% improvement

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	0.94 +/- 0.025	11.7 +/- 2.2	6.135	7.316
Glove Arm	0.77 +/- 0.099	12.3 +/- 2.6	6.74	2.035
Knees	0.89 +/- 0.051	8.6 +/- 1.6	3.817	3.847
Pelvis and Trunk	0.92 +/- 0.037	8.2 +/- 1.4	3.5	1.95

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	4.823	2.28	8.561	3.172
Glove Arm	4.798	2.753	7.051	2.075
Knees	4.324	2.298	6.11	3.472
Pelvis and Trunk	3.218	3.416	5.783	2.136

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 2D to 3D model, which was adapted from 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

When assessing the correlation between Reboot Motion's single camera methodology and the KinaTrax output across joint angles, the overall R-squared was 0.93 and the overall RMSE was 10.6 degrees.

Reboot Motion's highest performing joint angle was *pelvis 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 flexion, right shoulder abduction, right shoulder rotation, left knee flexion, and torso extension.*

All joint angle correlations were over 0.8 with the exception of the joint angles of the left (non-dominant) shoulder. The lower correlations for the left shoulder were likely due to this joint being on the opposite side of the pitcher, away from the view of the camera.

Looking at the RMSE, the highest performing joint angle was *torso extension* with an average joint angle error of 4.0 deg. The lowest performing joint angle was *right shoulder rotation* with an error of 16 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 2 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 4 degrees and below for many joints and time points.

Compared to v1.0, Motion Capture v2.0 represents the following improvements in correlations:

- + 10% right shoulder flexion
- + 2% right shoulder abduction
- + 13% right knee flexion
- + 11% torso rotation

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	0.932	0.03	9.43	1.471
right_shoulder_flex	0.945	0.028	9.384	1.968
right_shoulder_abd	0.954	0.019	11.857	1.339
right_shoulder_rot	0.942	0.024	16.322	3.367
left_elbow	0.891	0.036	15.122	1.227
left_shoulder_flex	0.779	0.074	9.3	1.686
left_shoulder_abd	0.66	0.079	14.156	2.224
left_shoulder_rot	0.757	0.161	10.777	4.196
left_knee	0.916	0.042	11.746	1.609
right_knee	0.854	0.058	5.504	1.613
pelvis_rot	0.978	0.007	13.946	1.942
torso_ext	0.955	0.02	3.966	0.995
torso_side	0.879	0.034	4.4	0.718
torso_rot	0.851	0.063	10.572	1.543

Repeatability

joint_angle	StD at Ball Release with Single Camera (deg)	StD at Ball Release with KinaTrax (deg)
right_elbow	5.49	2.045
right_shoulder_flex	3.325	1.092
right_shoulder_abd	3.964	0.685
right_shoulder_rot	9.676	14.431
left_elbow	5.095	1.954
left_shoulder_flex	2.949	1.07
left_shoulder_abd	7.126	2.341
left_shoulder_rot	9.812	2.473
left_knee	4.805	4.013
right_knee	2.46	3.674
pelvis_rot	4.4	2.394

torso_ext	2.311	1.322
torso_side	1.751	1.638
torso_rot	4.608	2.247

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	4.871	2.285	15.666	5.876
right_shoulder_flex	4.825	3.076	3.576	1.497
right_shoulder_abd	3.953	1.441	3.355	0.677
right_shoulder_rot	5.516	2.011	4.869	1.739
left_elbow	3.259	1.919	5.224	1.865
left_shoulder_flex	6.244	2.507	5.279	1.62
left_shoulder_abd	3.197	3.507	6.994	2.397
left_shoulder_rot	5.678	2.838	9.734	2.316
left_knee	2.295	2.071	8.262	3.959
right_knee	5.668	2.503	2.529	2.905
pelvis_rot	2.801	4.208	8.706	2.774
torso_ext	3.814	1.674	6.053	1.523
torso_side	2.286	4.557	1.75	1.697
torso_rot	3.715	2.322	4.277	2.315

Conclusions

Reboot Motion's single camera motion capture methodology outperforms its previous version (v1.0) by several percentage points at many joints. It also outperforms the previous single camera state of the art at many joints. Furthermore, its joint angle measurements are typically repeatable within several degrees.

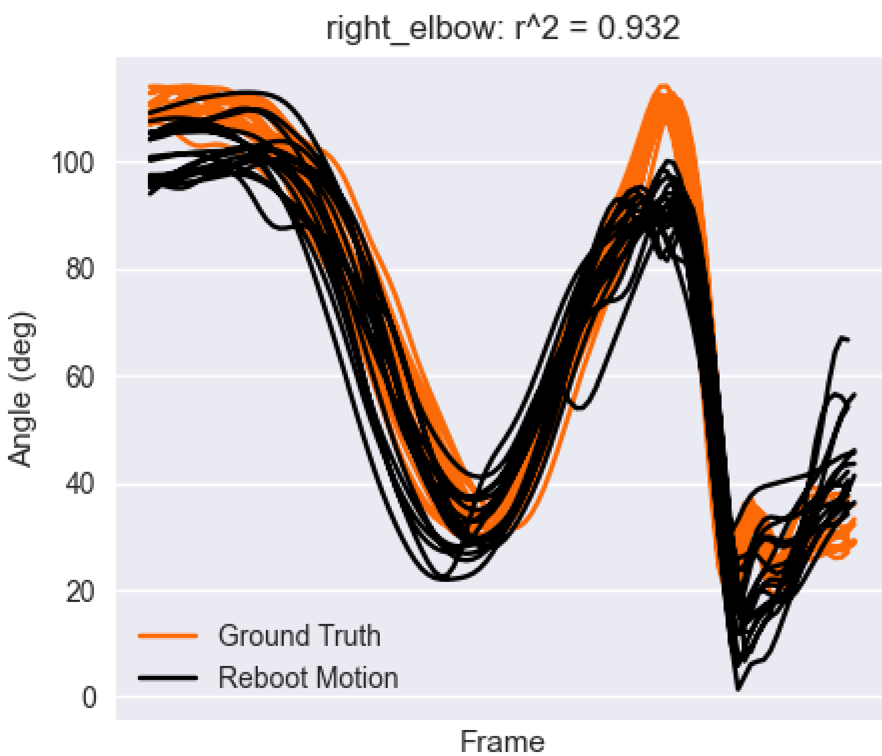
Though we would always recommend collecting with a multi-camera motion capture system when possible, we believe Reboot Motion's single camera methodology is a viable and effective alternative when collecting with a multi-camera system is not possible.

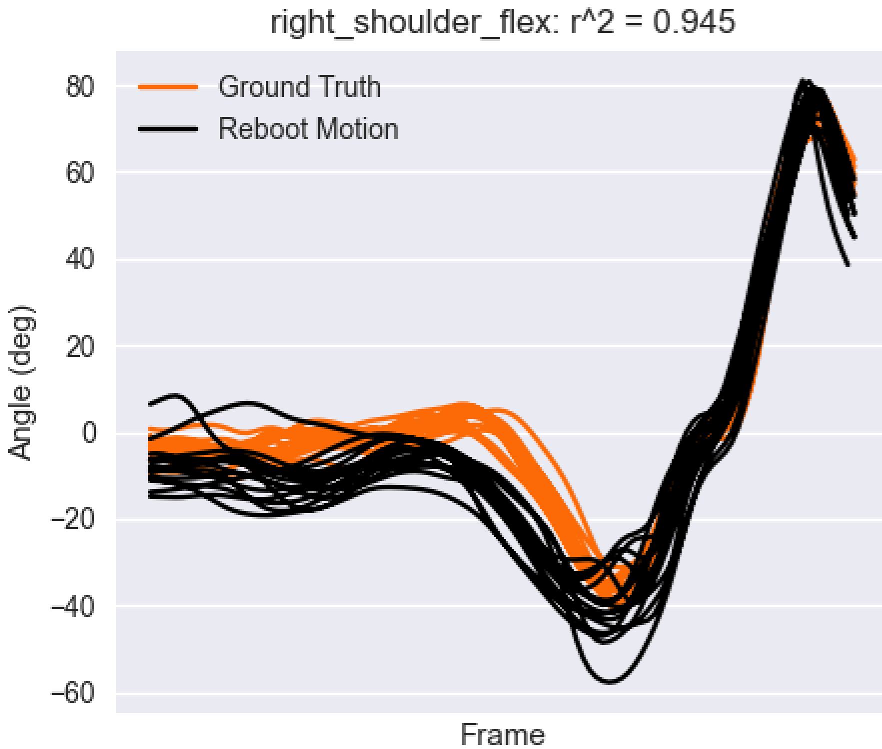
W**e believe this study suggests Reboot Motion's single camera methodology is becoming the state of the art in the single camera motion capture space.**

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

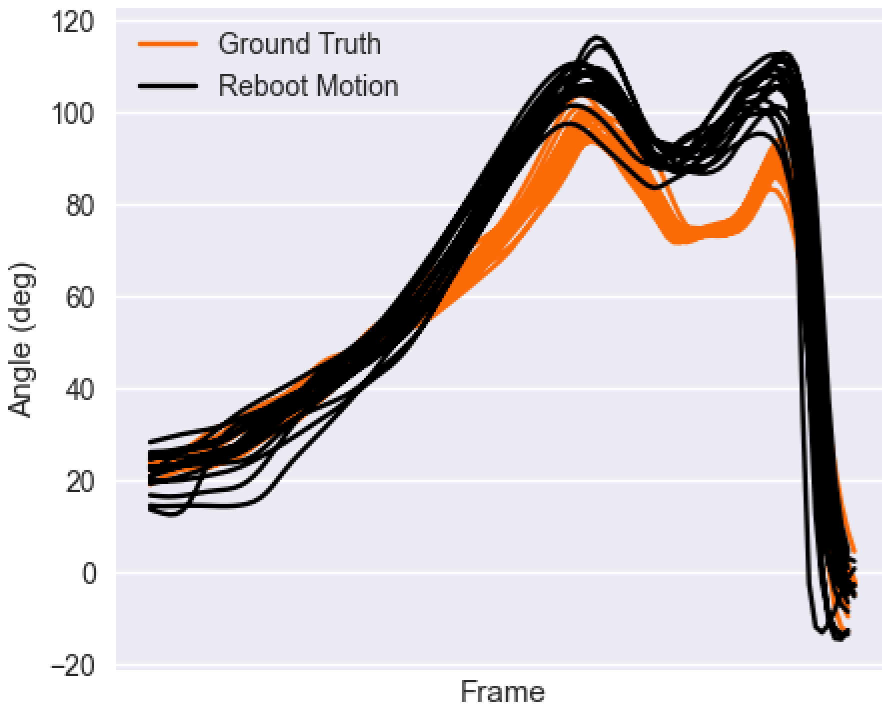
Appendix

Ground Truth: KinaTrax
Reboot Motion: Single Camera

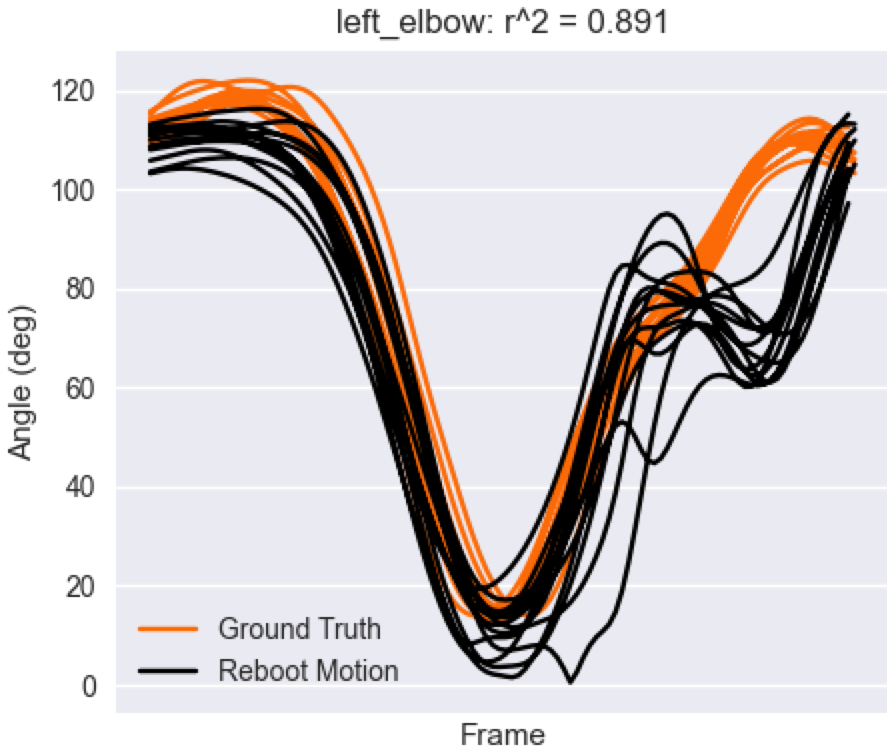


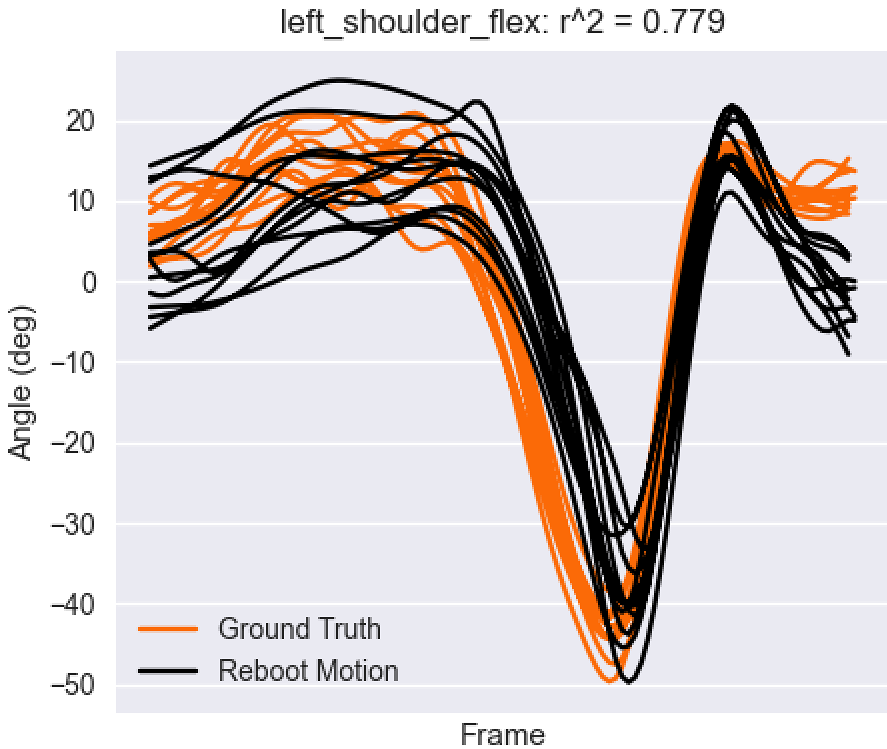

right_shoulder_flex: r^2 = 0.945
Ground Truth
Reboot Motion
80
60
40
20
0
−20
−40
−60
Angle (deg)
Frame

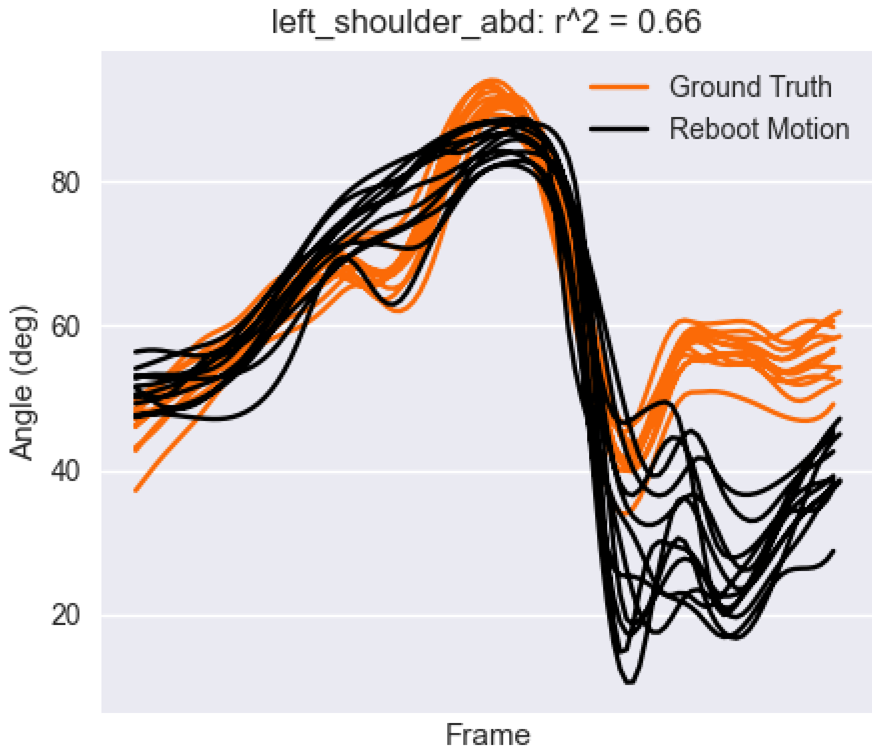
right_shoulder_abd: r^2 = 0.954




right_shoulder_rot: r^2 = 0.942
100
50
0
−50
−100
−150
Angle (deg)
Ground Truth
Reboot Motion
Frame

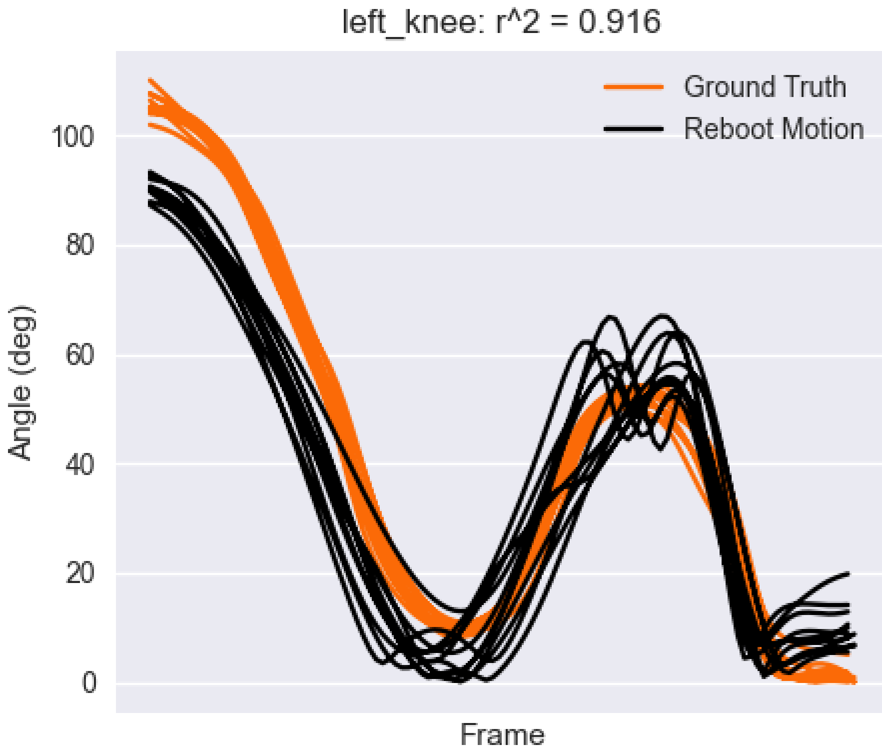

left_elbow: r^2 = 0.891
120
100
80
60
40
20
0
Angle (deg)
Frame
Ground Truth
Reboot Motion

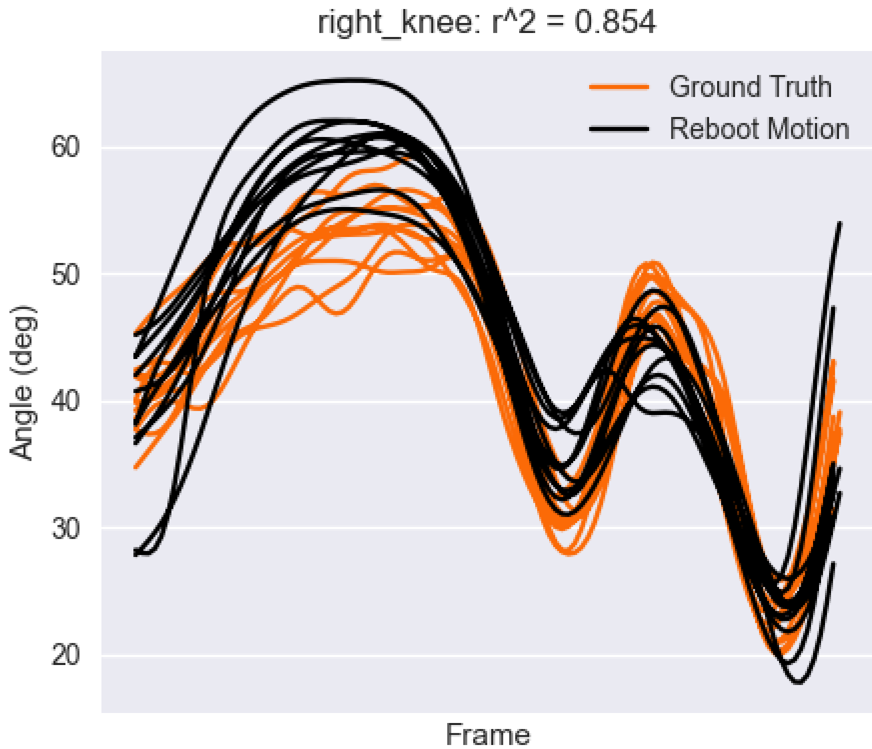

left_shoulder_flex: r^2 = 0.779
20
10
0
−10
−20
−30
−40
−50
Angle (deg)
Frame
Ground Truth
Reboot Motion

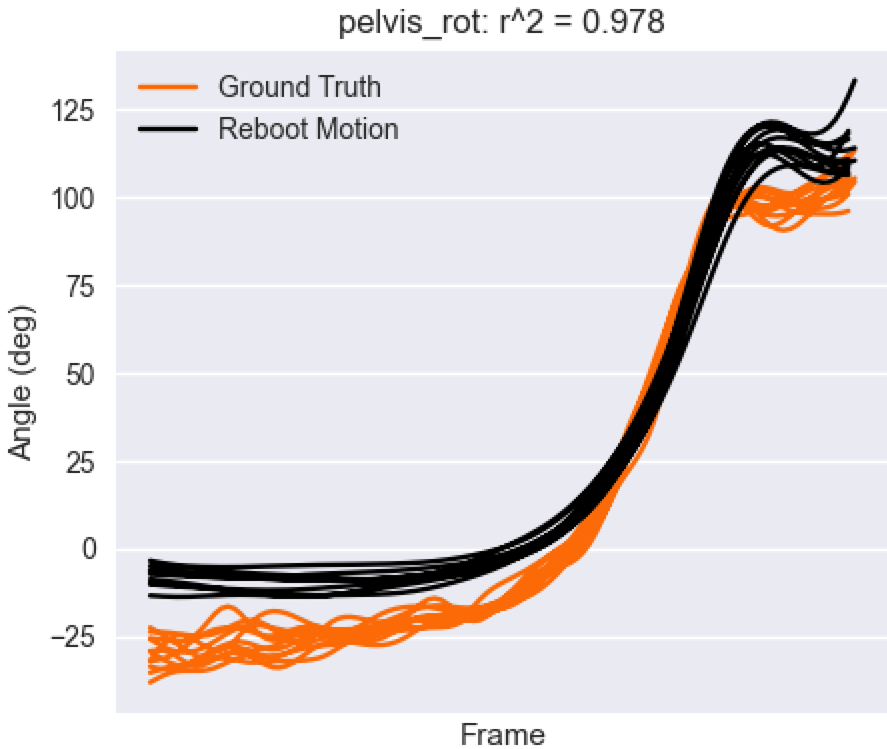


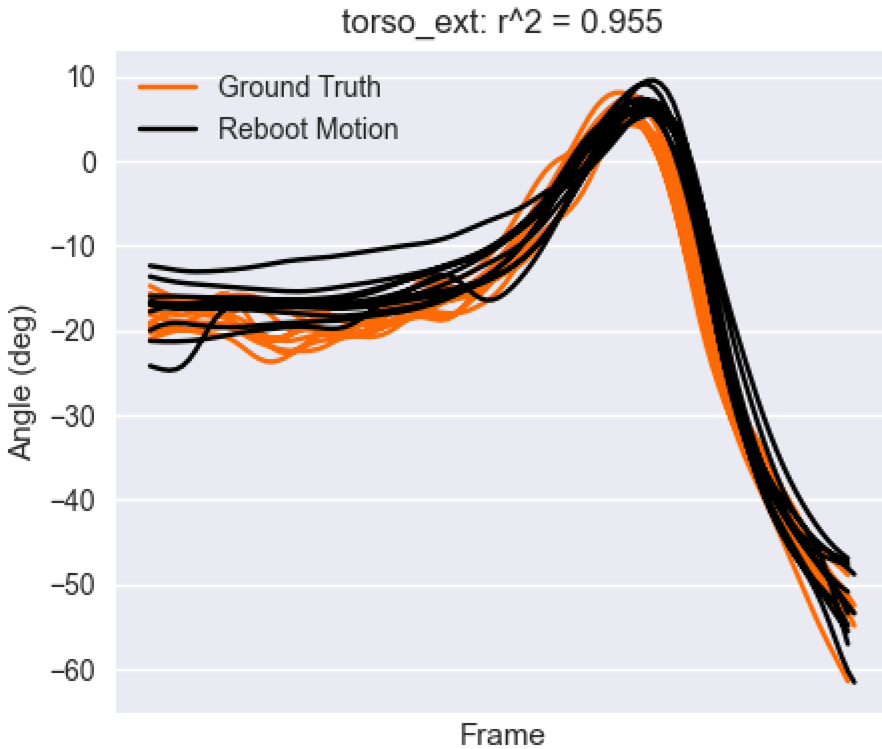
left_shoulder_abd: r^2 = 0.66
Ground Truth
Reboot Motion
80
60
40
20
Angle (deg)
Frame

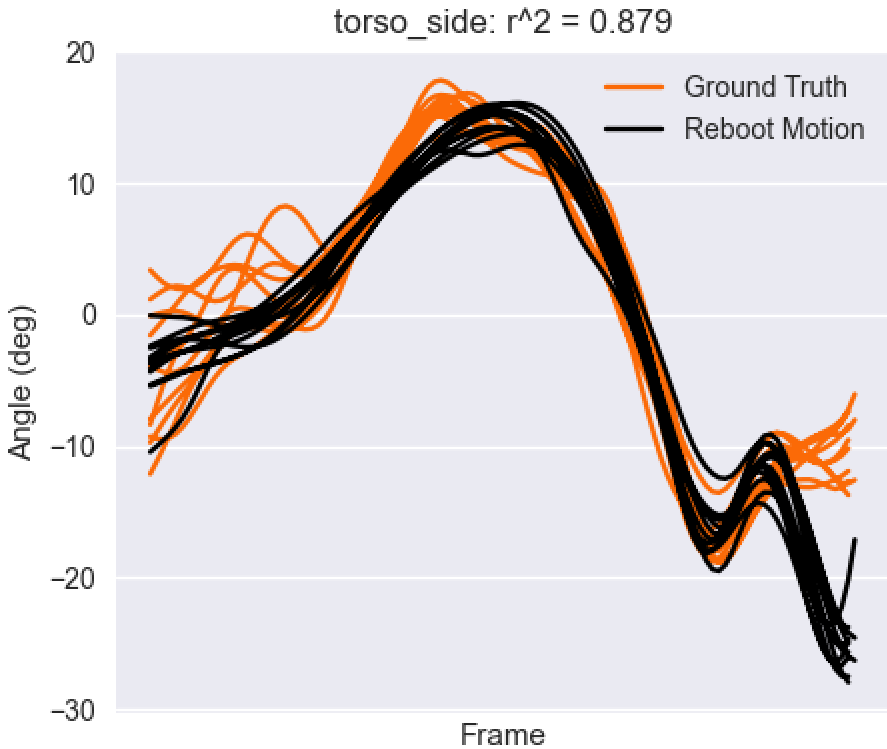

left_shoulder_rot: r^2 = 0.757
Ground Truth
Reboot Motion
40
20
0
−20
−40
−60
Angle (deg)
Frame

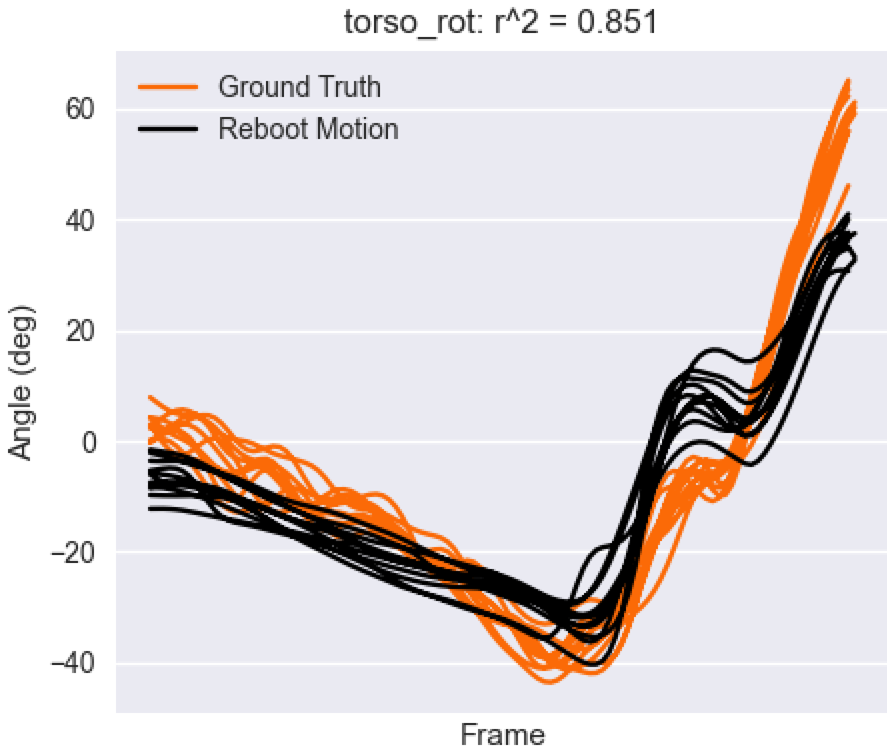

left_knee: r^2 = 0.916
Ground Truth
Reboot Motion
100
80
60
40
20
0
Angle (deg)
Frame


right_knee: r^2 = 0.854
Ground Truth
Reboot Motion
60
50
40
30
20
Angle (deg)
Frame


pelvis_rot: r^2 = 0.978
Ground Truth
Reboot Motion
Angle (deg)
Frame
125
100
75
50
25
0
−25


torso_ext: r^2 = 0.955
Ground Truth
Reboot Motion
10
0
−10
−20
−30
−40
−50
−60
Angle (deg)
Frame


torso_side: r^2 = 0.879
Ground Truth
Reboot Motion
20
10
0
−10
−20
−30
Angle (deg)
Frame


torso_rot: r^2 = 0.851
Ground Truth
Reboot Motion
60
40
20
0
−20
−40
Angle (deg)
Frame