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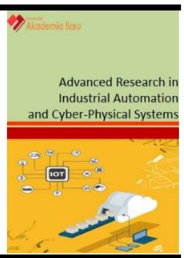

Test-Retest Reliability of Kinect's Torso Joint Prediction for Compensatory Assessment After Stroke

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ABSTRACT

Stroke patients typically incorporate compensatory strategies to complement the minimal use of distal segment of the upper limb to perform daily activities. The ability to monitor compensatory strategies in terms of abnormal torso and shoulder movements through Kinect is attractive due to its portability and cost. However, Kinect's joint proposals can be undermined with the occluded pose typical of stroke patients. This study investigated these discrepancies through test-retest procedures of static pose typical to stroke patients. It was found that at the distance of approximately 2.5 meters, all the joint proposals were reliable for normal pose. However, only joints attributed to the torso were reliable when stroke pose is prevalent. Therefore, joints attributed to torso can be readily measured from the intrinsic biomechanical model but model fidelity of distal segments must be improved for useful assessment.

1. Introduction

Compensatory strategies were prevalent in reaching to complement the minimal use of distal segment to complete function [9]. In clinically accepted photogrammetric method, the extent of torso movement when compensatory strategies are prevalent is defined by three independent torso angles namely forward bending, axial rotation and lateral flexion. Previous research on Kinect's torso joint predictions was promising, in which lateral flexion angle was reported to have excellent agreement with marker-based motion capture system [3]. However, the intrinsic model was also reported to have false axial rotation [16] which inspired the development of Torso-Principal-Component-Analysis (TPCA) model [11] to represent the dynamics of torso in space.

Kinect is an RGBD camera which provides color images and depth data. Kinect's intrinsic biomechanical model provides real-time position and orientation of various human joints [13] as depicted in Figure 1 (a)). Joint proposals named waist, spine, chest, collar, shoulder, elbow and hand

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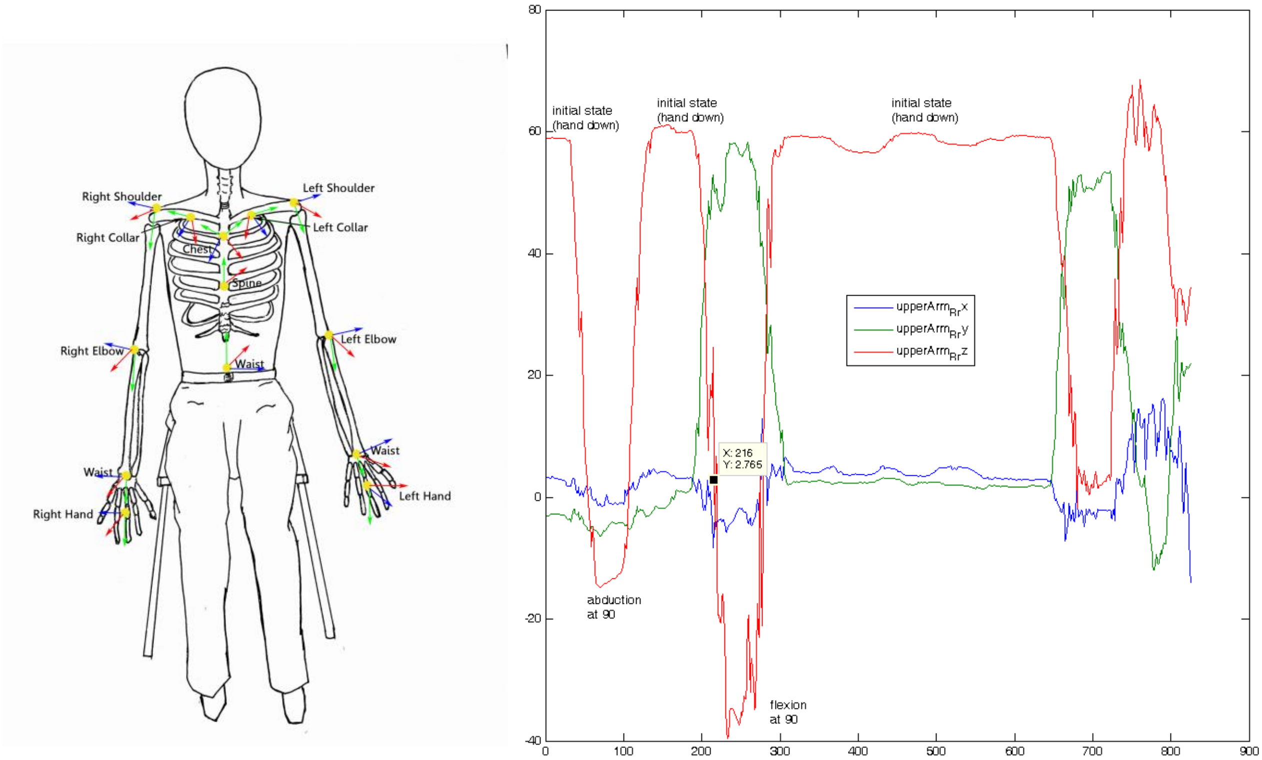
were valuable for assessment of the upper limb movement quality after stroke since the ability to monitor these joints would provide holistic overview of the improvement [12].

Compensatory movement typically performed by stroke patients in daily activities also include the shoulder hike [7] whenever the arm transport becomes difficult due to paresis of the affected arm. Monitoring such movement using Kinect is possible by observing the orientation of the shoulder joint. The trajectory of shoulder joint orientation, depicted as decomposed orientation quaternion to Z-X-Y Euler angles are depicted in Figure 1 (b)). It can be seen that abduction to 90° was recorded as the angular position's change from approximately 60° to -15, 75° in total. As angular position attributed to Z-axis were perpendicular to the arm length in space, flexion to 90° was also recorded with apparent change. Based on these observations, shoulder joint orientation estimates were able to determine the gross movements to some extent which may be influenced by the accuracy of joint proposals at the time of prediction [5].



(a) (b)

Fig. 1. (a) Location and orientation of Kinect's joint proposals on the upper body based on intrinsic biomechanical model; (b) Orientation trajectory of shoulder joints of a person performing abduction to 90˚ followed by flexion to 90˚. The independent axis is the number of recording sample and dependent axis is the angle in degrees.

Existing study however expressed concerns on the effect of distance between camera and the subjects on the joint prediction [4]. That is, the joint predictions can be severely undermined at the distance too close to the camera and near the end of Kinect's field of view (close to 4 meter). Greater outliers are typically observed in a form of spikes in the trajectory trace of the dynamic movements. Furthermore, the subject's physique may also be the influencing factor of inaccurate tracking as upper limbs are prone to be occluded in large person.

For the purpose of upper limb assessment after stroke, the study emphasized only on 11 joint proposals; waist, spine, chest, left and right collar, left and right shoulder, left and right elbow, and left and right hand in order to determine the outcome of stroke task assessment. While the usability and cost of Kinect are attractive, the challenges of obtaining repeatable measurements are tremendous due to probable inclusion when abnormal flexor synergy is apparent after stroke.

In the assessment of upper limb movement quality after stroke, besides the gross body movements in coronal and sagittal plane, the tasks that are performed to assess flexor and extensor synergy for example; require a cross-body movement in which the arm is highly occluded by the torso [6,15]. Similarly, with planar assessment task, the hand movement is restricted to a slightly tilted transverse plane, occluded by the torso and possibly by the table [8]. Hence, with numerous reports addressing concerns on the accuracy of Kinect when fine movement is measured, the data provided by Kinect can be hypothetically unreliable for assessment. A further insight on the repeatability of Kinect in predicting the upper body joints in seated condition is warranted.

2. Methodology

In order to determine the extent of inaccuracies in the assessment of upper limb movements, an analysis on the repeatability of all upper limb joint position for subjects performing repeated seated T-Pose as well as initial pose typical to stroke patients was conducted. Stroke patients with either a flexor synergy or extensor synergy will have difficulty trying to maintain a stretched affected arm. Three additional static pose typical to stroke patients were analyzed, namely Flex-Extend, Flexed and Relaxed pose. T-Pose is a recommended pose to initialize joint position as all the upper limb joints are in direct view of the camera without occlusion [2]. Relaxed pose is the typical seated position with hand on lap. T-Pose and typical stroke poses are depicted in Figure 2.

Physically, bone lengths of a person should remain relatively constant regardless of the distance of the subject from the camera. Therefore, it was selected as the dependent variable in order to assess the constancy of the Kinect's joint prediction. Ten different bones are computed based on the joint positions provided. Lower Spine is computed from the Euclidean length between Spine position and Waist position, Upper Spine (Chest and Spine), Left and Right Collar (Collar and Chest), Left and Right Clavicle (Upper Arm and Collar), Left and Right Arm (Forearm and Upper Arm), and also Left and Right Forearm (Forearm and Hand).

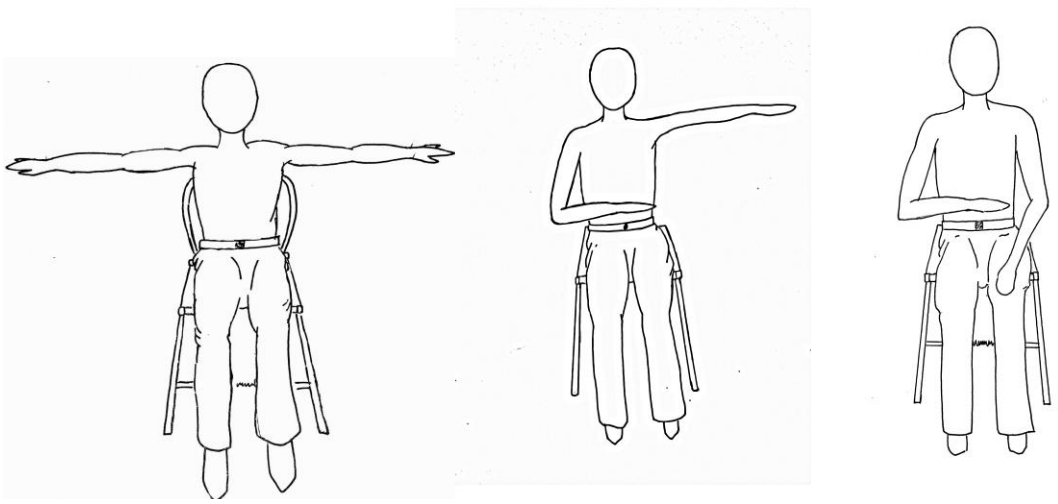


Fig. 2. From left: A seated T-Pose, Flex-Extend, Flexed pose

A Microsoft Kinect Sensor v2 was placed at roughly 4 different position in sequential order; 1.5 meter, 2 meter, 2.5 meter and 3 meter from subjects sitting on a chair without armrest. The data was captured and streamlined using *Brekel Kinect Pro Body v2* [1] for easier database built-up. The sensor was mounted on a tripod and placed on the floor at an approximately -10 degrees angle from the horizontal axis, at the height higher than the head of the subject and looking down, without any particular attempt to secure it from vibrations.

Two healthy subjects without upper limb impairment were recruited, both are of different physique and coded as Medium and Large built subject. The Medium subject is female, 1.62-meter-tall with body mass index (BMI) of 28 kg/m2. The Large subject is male, 1.8-meter-tall with BMI of 33 kg/m^2.

First, they were asked to perform series of a static seated T-Pose. The task consists of performing the pose repeatedly 5 times at each distance. The predicted joint position of waist, spine, chest, collar and shoulder of the person was provided by Kinect V2. The repeatability of the bone lengths was observed and analyzed. Then, a series of static stroke poses was performed repeatedly 5 times at selected distance from the camera based on the repeatability of the bone length initialized using T-Pose.

3. Results

3.1 Reliability of joint predictions initialized by T-Pose

The descriptive statistics of the comparison between all the captures are presented in Table 1. Standard error of the mean for all bone lengths were in the order of millimetre. In this sample, standard deviation of bone lengths for large subject was greater than 0.5cm for left arm at 1.5 meter and 3 meter from the camera, and greater than 0.5 cm for left forearm when recorded at 2 meter from the camera. However, the standard deviation of any bone length for medium subject was less than 0.5 cm for all distance. The sum of standard deviation for all bones was the smallest at 2.5 meter from the camera for both subjects and the largest at 3 meter from the camera.

With these discrepancies, a further analysis is warranted to examine the effects of distance from camera on ten of the predicted upper limb bone lengths inclusive of lower spine, upper spine, left collar, right collar, left clavicle, right clavicle, left arm, right arm, left forearm and right forearm and whether this effect was dependent on the physique of the subject.

In order to choose an appropriate test to examine both effects, Shapiro-Wilk's Test of Normality was performed to analyze the normality of the data. As evident in Table 2, residuals were normally distributed for measurements at 2.5 meter from the camera regardless of the physique. However, it was striking that majority of bone lengths of the large-built subject violated the normality assumption (6 out of 7 occurrences of violation) at $p < .05$. Furthermore, at the distance of 2 meter from the camera, large-built subject has the majority of violations as left collar, left clavicle and right forearm violated the assumption of normality. This results intrinsically support the large standard deviation observed earlier.

Due to the violations of normality, a non-parametric alternative to one-way repeated measures ANOVA (Friedman Test) [10] was run to determine if there were differences on the bone lengths at 4 different recording distances from the camera. Pairwise comparisons were performed [14] with a Bonferroni correction for multiple comparisons.

Separate tests were run for both subjects and the results were presented in Table 3. All bone lengths of medium built subject showed very small variation between the tested recording distances, and were not statistically significant as evident in Table 3 under column 'Sig' in which all the asymptotic significance were higher than 0.05. For example, the right forearm length for medium built subject performing a static T-Pose shows a very small variation in median values at each distance and the differences were not statistically significant, $\chi2(3) = 0.989$, $p = .804$. This results proved that for medium subject, the measurements are stable and reliable for static pose.

Table 1
Descriptive statistics of Kinect Measurements of Bone Length at Different Distance

Bone		Lower Spine				Upper Spine				Left Collar			
Built	Distance from camera	at 1.5m	at 2m	at 2.5m	at 3m	at 1.5m	at 2m	at 2.5m	at 3m	at 1.5m	at 2m	at 2.5m	at 3m
Large	Mean	27.61	26.34	25.99	26.12	20.24	19.17	19.02	19.12	2.12	2.22	2.19	2.16
	Std. Deviation	0.14	0.06	0.08	0.16	0.10	0.05	0.06	0.12	0.05	0.03	0.02	0.01
	Std. Error of Mean	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Median	27.64	26.33	25.97	26.18	20.26	19.17	19.00	19.16	2.13	2.23	2.20	2.16
	Minimum	27.22	26.20	25.86	25.57	19.97	19.02	18.95	18.70	2.06	2.13	2.14	2.13
	Maximum	27.79	26.54	26.23	26.28	20.38	19.29	19.16	19.24	2.23	2.27	2.24	2.18
	Range	0.57	0.34	0.37	0.71	0.41	0.27	0.22	0.54	0.17	0.13	0.11	0.05
Medium	Mean	24.90	25.26	24.41	24.06	18.20	18.60	17.95	17.75	1.73	1.84	1.79	1.69
	Std. Deviation	0.12	0.13	0.05	0.13	0.08	0.09	0.04	0.10	0.00	0.02	0.01	0.02
	Std. Error of Mean	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Median	24.84	25.25	24.43	24.06	18.16	18.59	17.96	17.75	1.73	1.85	1.79	1.68
	Minimum	24.72	24.93	24.15	23.46	18.09	18.37	17.73	17.34	1.73	1.81	1.77	1.65
	Maximum	25.14	25.47	24.49	24.27	18.35	18.73	18.02	17.95	1.74	1.86	1.81	1.73
	Range	0.41	0.54	0.34	0.81	0.27	0.35	0.29	0.62	0.02	0.05	0.04	0.09

Bone		Right Collar				Left Clavicle				Right Clavicle			
Built	Distance from camera	at 1.5m	at 2m	at 2.5m	at 3m	at 1.5m	at 2m	at 2.5m	at 3m	at 1.5m	at 2m	at 2.5m	at 3m
Large	Mean	2.23	2.15	2.18	2.08	19.10	19.99	19.76	19.41	20.08	19.32	19.66	18.74
	Std. Deviation	0.05	0.03	0.02	0.03	0.46	0.28	0.18	0.14	0.45	0.32	0.18	0.25
	Std. Error of Mean	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.01	0.00	0.01
	Median	2.25	2.15	2.19	2.08	19.15	20.05	19.79	19.41	20.21	19.37	19.71	18.69
	Minimum	2.13	2.05	2.12	2.04	18.54	19.14	19.22	19.07	19.09	18.36	19.10	18.36
	Maximum	2.30	2.20	2.21	2.16	20.08	20.39	20.20	19.65	20.71	19.85	19.94	19.45
	Range	0.17	0.16	0.09	0.11	1.54	1.25	0.98	0.58	1.61	1.49	0.84	1.09
Medium	Mean	1.70	1.75	1.83	1.74	15.59	16.52	16.07	15.24	15.27	15.77	16.47	15.66
	Std. Deviation	0.01	0.02	0.01	0.04	0.06	0.16	0.13	0.24	0.09	0.13	0.11	0.36
	Std. Error of Mean	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01
	Median	1.70	1.75	1.83	1.75	15.59	16.55	16.08	15.16	15.26	15.75	16.49	15.77
	Minimum	1.68	1.72	1.81	1.67	15.44	16.17	15.86	14.82	15.07	15.46	16.30	14.91
	Maximum	1.72	1.79	1.85	1.79	15.72	16.80	16.30	15.71	15.48	16.13	16.65	16.15
	Range	0.04	0.07	0.04	0.12	0.29	0.64	0.44	0.89	0.41	0.67	0.35	1.24

Bone		Left Arm				Right Arm			
Built	Distance from camera	at 1.5m	at 2m	at 2.5m	at 3m	at 1.5m	at 2m	at 2.5m	at 3m
Large	Mean	28.29	26.10	27.44	26.60	27.62	27.04	27.17	26.50
	Std. Deviation	0.62	0.34	0.29	0.66	0.40	0.42	0.30	0.37
	Std. Error of Mean	0.02	0.01	0.01	0.02	0.01	0.01	0.01	0.01
	Median	28.51	26.19	27.45	26.47	27.80	27.02	27.17	26.47
	Minimum	25.85	25.02	26.49	25.50	26.79	25.85	26.61	25.68
	Maximum	28.96	27.41	28.37	28.22	28.23	28.13	28.30	27.61
	Range	3.11	2.39	1.89	2.72	1.44	2.28	1.69	1.92
Medium	Mean	22.06	25.46	24.67	26.51	22.00	24.83	24.35	24.21
	Std. Deviation	0.01	0.20	0.28	0.31	0.01	0.17	0.27	0.32
	Std. Error of Mean	0.00	0.01	0.01	0.01	0.00	0.00	0.01	0.01
	Median	22.05	25.45	24.65	26.51	22.00	24.81	24.42	24.33
	Minimum	22.04	25.05	24.14	25.98	21.98	24.50	23.83	23.50
	Maximum	22.07	25.89	25.34	27.54	22.03	25.31	24.75	24.55
	Range	0.04	0.85	1.21	1.56	0.05	0.81	0.92	1.05

Table 2
Results of Shapiro-Wilk's Test of Normality

Distance from camera		Lower Spine			Upper Spine			Left Collar			Right Collar			Left Clavicle		
		Statistic	df	Sig.	Statistic	df	Sig.	Statistic	df	Sig.	Statistic	df	Sig.	Statistic	df	Sig.
1.5 meter	Large	0.895	5	0.384	0.855	5	0.209	0.869	5	0.264	0.865	5	0.247	0.852	5	0.200
	Medium	0.878	5	0.301	0.871	5	0.272	0.979	5	0.927	0.875	5	0.286	0.901	5	0.417
2 meter	Large	0.915	5	0.499	0.974	5	0.898	0.706	5	**0.011**	0.850	5	0.196	0.709	5	**0.012**
	Medium	0.961	5	0.812	0.948	5	0.724	0.914	5	0.494	0.939	5	0.661	0.931	5	0.601
2.5 meter	Large	0.954	5	0.763	0.950	5	0.740	0.968	5	0.864	0.905	5	0.439	0.966	5	0.852
	Medium	0.966	5	0.852	0.992	5	0.985	0.930	5	0.597	0.994	5	0.993	0.957	5	0.787
3 meter	Large	0.745	5	**0.026**	0.760	5	**0.037**	0.897	5	0.395	0.901	5	0.417	0.936	5	0.639
	Medium	0.739	5	**0.023**	0.810	5	0.098	0.920	5	0.528	0.871	5	0.270	0.910	5	0.466

Distance from camera		Right Clavicle			Left Arm			Right Arm			Left Forearm			Right Forearm		
		Statistic	df	Sig.	Statistic	df	Sig.	Statistic	df	Sig.	Statistic	df	Sig.	Statistic	df	Sig.
1.5 meter	Large	0.859	5	0.225	0.773	5	**0.048**	0.877	5	0.297	0.830	5	0.139	0.850	5	0.194
	Medium	0.956	5	0.783	0.990	5	0.981	0.843	5	0.173	0.894	5	0.377	0.979	5	0.931
2 meter	Large	0.833	5	0.146	0.826	5	0.131	0.939	5	0.656	0.835	5	0.151	0.748	5	**0.029**
	Medium	0.888	5	0.347	0.933	5	0.617	0.903	5	0.425	0.970	5	0.873	0.985	5	0.959
2.5 meter	Large	0.956	5	0.778	0.960	5	0.811	0.962	5	0.825	0.970	5	0.874	0.858	5	0.220
	Medium	0.906	5	0.444	0.926	5	0.568	0.919	5	0.527	0.969	5	0.869	0.879	5	0.303
3 meter	Large	0.896	5	0.390	0.977	5	0.916	0.979	5	0.927	0.716	5	**0.014**	0.927	5	0.578
	Medium	0.863	5	0.238	0.954	5	0.764	0.809	5	0.095	0.978	5	0.926	0.908	5	0.456

Table 3
Results of Friedman Test for bone length differences at different recording distance from Kinect

Bone Length	Medium Built						Large Built					
	$\chi^2(3)$	Sig	Median				$\chi^2(3)$	Sig	Median			
			at 1.5m	at 2m	at 2.5m	at 3m			at 1.5m	at 2m	at 2.5m	at 3m
Lower Spine	0.994	0.803	24.071	24.070	24.071	24.070	2.64	0.4500	24.065	24.071	24.070	24.072
Upper Spine	1.103	0.776	17.750	17.747	17.747	17.747	1.869	0.6000	17.746	17.751	17.747	17.750
Left Collar	0.335	0.953	1.683	1.683	1.683	1.683	46.487	0.0005	1.684	1.683	1.683	1.683
Right Collar	0.040	0.998	1.754	1.755	1.755	1.755	47.856	0.0005	1.751	1.755	1.755	1.755
Left Clavicle	0.342	0.952	15.141	15.141	15.141	15.142	42.926	0.0005	15.157	15.141	15.143	15.141
Right Clavicle	0.370	0.946	15.788	15.789	15.789	15.790	44.392	0.0005	15.768	15.790	15.788	15.790
Left Arm	0.281	0.964	26.539	26.538	26.541	26.541	6.803	0.0780	26.512	26.536	26.539	26.543
Right Arm	3.414	0.332	24.285	24.288	24.278	24.289	9.128	0.0280	24.328	24.285	24.288	24.283
Left Forearm	0.045	0.997	21.473	21.474	21.472	21.474	14.191	0.0030	21.459	21.474	21.474	21.475
Right Forearm	0.989	0.804	21.348	21.349	21.348	21.348	41.113	0.0005	21.343	21.349	21.349	21.349

Post-hoc Analysis

Bone Length	1.5m -2m pair		1.5m -2.5m pair		1.5m - 3m pair		2m -2.5m pair		2m-3m pair		2.5-3m pair	
	Stat	Adj Sig.	Stat	Adj Sig.	Stat	Adj Sig.	Stat	Adj Sig.	Stat	Adj Sig.	Stat	Adj Sig.
Left Collar	0.27	0.0005	0.249	0.0005	0.299	0.0005	-0.021	1	0.029	1	0.05	1
Right Collar	0.29	0.0005	-0.254	0.0005	-0.288	0.0005	0.036	1	0.002	1	-0.034	1
Left Clavicle	0.274	0.0005	0.242	0.0005	0.275	0.0005	-0.032	1	0.0005	1	0.033	1
Right Clavicle	-0.28	0.0005	-0.234	0.0005	-0.284	0.0005	0.046	1	-0.004	1	-0.05	1
Right Arm	0.114	0.128	0.113	0.136	0.135	0.039	-0.001	1	0.021	1	0.022	1
Left Forearm	-0.151	0.015	-0.148	0.017	-0.159	0.008	0.003	1	-0.008	1	-0.011	1
Right Forearm	-0.257	0.0005	-0.229	0.0005	-0.281	0.0005	0.028	1	-0.024	1	-0.053	1

However, in large-built subject; left and right collar, left and right clavicle, left and right forearm and left arm lengths were all statistically significantly different at the tested recording distances. Median values for these bone lengths were however quite similar between tested distance. This would suggest that the different between group ranks were significant, and there exist large outliers which would undermine the accuracy of recordings.

Post-hoc analysis revealed that for every bone length of the large built subject, the difference at the tested distance were not statistically significant at the comparison between distance of 2 meter to 2.5 meter, 2 meter to 3 meter and 2.5 meter to 3 meter. This is evident as the Bonferroni adjusted asymptotic significance were at $p > .05$ for all bone lengths measured at these distances.

Thus it can be concluded that for both subjects, the measurements of bone length on the upper limb were not statistically significantly different in a non-occluded pose when measured from 2 meter to 3 meter from Kinect. This is an important conclusion as the joint prediction in the non-occluded dynamic movements may be undermined if the static pose has statistically significant variance at the recording location.

3.2 Reliability of joint predictions initialized by poses typical to stroke patients

While normal person can easily perform a seated T-Pose, stroke patients with either a flexor synergy or extensor synergy will have difficulty trying to maintain a stretched affected arm. Flexed pose was analyzed as it is the typical possible static pose to initialize joint position as affected arm with flexor synergy is naturally flexed after stroke. Relaxed pose was also investigated as patients with extensor synergy has affected arm that is too weak to be raised for a T-Pose initialization. These poses would hypothetically induced problem in joint prediction as they appear occluded in front of the Kinect.

Affected arm with flexor synergy will appear occluded with the patient's torso. On contrary, patients with extensor synergy will have difficulty flexing their arm and remain naturally extended. This affected arm will be occluded when the forearm is rested on the lap. An additional Flex-Extend pose was also investigated to determine whether the visibility of the unaffected arm will affect the prediction of the occluded and affected arm.

With the knowledge that the non-occluded static pose appears repeatable at recording distances of 2 meter onward, similar protocol is conducted to determine the effect of recording distances and the physique of the subject to the repeatability of joint predictions. The same subjects from previous protocol performed Flexed, Flex-Extend and Relaxed pose sequentially at 3 different distance (2 meter, 2.5 meter and 3 meter) with 5 repetitions at each recording distance. Affected arm was assumed as right hand in all the repetitions. All poses were recorded to a similar number of frames for balanced comparison analysis. A total of 2704 samples spanning five repetitions were collected. The differences between bone lengths when performing Flexed and Relaxed pose and bone lengths at seated T-Pose are examined to determine the extent of deviation.

Friedman Test was performed to determine if there were differences on the bone lengths when performing different static pose at the distance of 2 meter, 2.5 meter and 3 meter. As expected, the difference of bone lengths between different poses were all statistically significant as the asymptotic significance were lower than 0.005 for all cases.

Post-hoc analysis revealed that for every bone length of both large and medium built subject, the difference at the tested distance were all statistically significant at the comparison between distance of 2 meter to 2.5 meter, 2 meter to 3 meter and 2.5 meter to 3 meter. This is evident as the Bonferroni adjusted asymptotic significance were at $p < .005$ for all bone lengths measured at these distances. Figure 3 presents the overview of the median difference in bone lengths recorded at different pose.

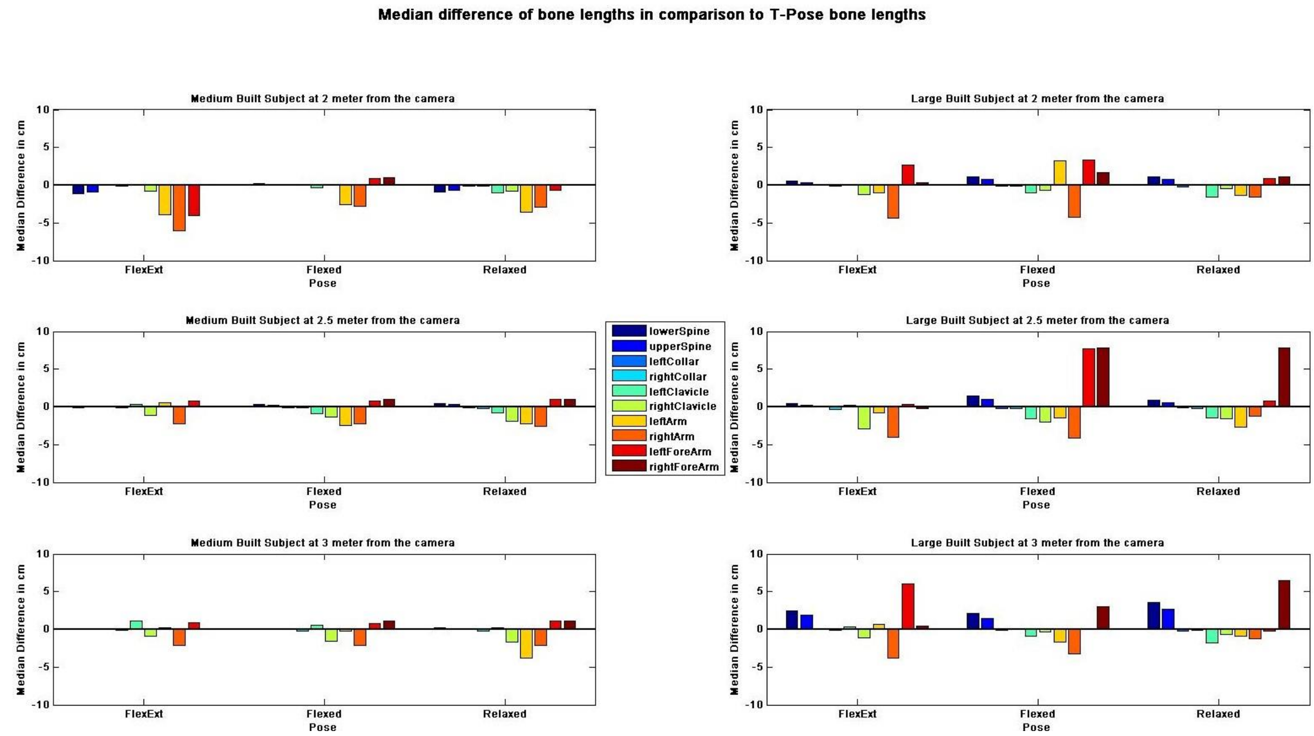


Fig. 3. The overview of discrepancies in upper limb joint position predictions in comparison with bone lengths predicted using T-Pose for medium-built subject (left) and large-built subject (right) at different recording distances

It can be observed that for all examined poses for both subjects, right arm (performed as the affected side by all subjects) appeared shorter than the length of the arm when performing T-Pose. For medium built subject, the affected arm was recorded with similar median difference for all poses at 2.5 meter from the camera. However, right forearm's median difference was at the minimum at this recording distance when performing Flex-Extend pose in comparison to Flexed and Relaxed pose in which both arms were rested on the lap.

4. Conclusions

From these analyses, it can be confirmed that the distance of approximately 2.5 meter from the camera is ideal to minimize the inaccuracies of predicted joints. However, it is also evident that distal joints such as elbow and wrist which directly influenced the length of arm and forearm require refinements to be accepted as accurate measures. On the bright side, joints related to the torso, namely waist, chest, collar, and shoulder are all statistically accurate (with the mean difference of at most ±2 cm when affected arm are flexed or extended). Hence, the existing biomechanical model can be used without further refinement to provide data as foundation to torso assessment model.

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