Performance Analysis of a Generalized Motion Capture System Using Microsoft Kinect 2.0

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Abstract

This work presents a fine-grained analysis of the performance and limitations of the Microsoft Kinect sensor for tracking human movement in the context of biomechanical research and clinical applications. Earlier work in this field has focused on scalar summary measures or ad-hoc metrics with respect to specific movements that do not generalize well across clinical applications. In this work, the performance of the Microsoft Kinect is compared to motion tracking from a concurrently sampled professional grade Qualisys motion capture system. Subjects performed a range of clinically relevant tasks such as Sit-to-Stand and Timed Up-and-Go. Captured data included both three-dimensional joint center displacements and joint angles as recorded from both systems. Kinect performance was measured using cross correlation coefficients (CCR), root mean squared error (RMSE) relative to the Qualisys gold-standard and a new summary metric (SM) that combines both. Our results show that the Kinect-based system provides adequate performance when tracking joint center displacements in time, with overall CCR=0.78, RMSE=3.35cm and SM=1.21. On the contrary, lower accuracy was measured when tracking joint angles, with CCR=0.58, RMSE=24.59 degrees, and SM=3.76. Although performance differences for various movements and motion planes have been found, the results suggest that the Kinect is a viable tool for general biomechanical research, with specific limits on what levels of performance can be expected under various conditions.

1 Background

Capturing three-dimensional movement (or *kinematics*) is a central laboratory technique in the study of human movement. Kinematic studies have played an instrumental role in the study of joint pathology, mild traumatic brain injury, ergonomics, and athletic performance. Despite the importance of this technique, standard data acquisition methods are subject to considerable limitations. Stereophotogrammetry and electromagnetic motion tracking, for instance, require expensive, stationary equipment and time-consuming procedures for system calibration and post-processing of data. In contrast, low-cost depth sensing cameras (also known as time-of-flight or RGB-D cameras) are available off-the-shelf and may represent viable alternatives to more complex and expensive 3D camera setups. These cameras are capable of capturing RGB color images augmented with depth data at each pixel, thus providing 3D images. Such images can be used to track human motion in real-time. Among these cameras, the Microsoft Kinect™ 2.0 provides a low-cost, portable, user-friendly alternative which holds the potential to substantially increase the accessibility of kinematic data. The main advantage of using the Kinect sensor over the commercially available alternatives lies in the proprietary Microsoft algorithm that performs body and joint detection in real-time and that can be exploited using the Microsoft Software Development Kit (SDK) [1] available to .NET developers.

The performance of the Kinect™ 2.0 as a tool to evaluate kinematic variables, as compared to current standard methods, is a subject of great interest. Although several studies have been published in this area, the general trend has been to compare motion capture (MOCAP) systems based on scalar summary measures a selected metric. Examples from previous work include excursion range [2]–[5], mean or peak displacement [4], [6]–[11] or timing of discrete signal events [4], [5], [9], [11]–[15]. While such metrics are commonly studied in biomechanics, they do not adequately quantify the temporal structure of the signals under comparison, and are thus limited in terms of the generalizability of their results. To date, three laboratories have presented a more thorough treatment of Kinect 2.0 time series data in comparison to an existing standard. These studies still present certain limitations which restrict broader generalizability [16]–[19].

The first study [19] was based on a composite signal, namely, total body center of mass, which represents a weighted sum of body segments derived from the Kinect joint center time dynamics. As a weighted sum, this output suppresses the variability inherent to the underlying time series data. Another study [17] reports measures of signal agreement measured as Intraclass Correlation Coefficients (ICC) between Kinect 2.0 sensors and an OptoTrak system (Northern Digital Inc., Waterloo, Canada). This investigation analyzed the consistency between the systems in each dimension for nearly all the joint center data natively exported from the Kinect. While this approach offers an appropriate comparison of the two systems, the results are specific to gait, a primarily sagittal plane movement pattern, and therefore represent a relatively narrow range of the human motion repertoire. Finally, a pair of studies [16], [18], by a third group, quantifies Kinect signal error by its 3D L^2 norm distances from a ground truth signal as given by a 3D professional-grade MOCAP system. While they were able to classify individual data points as outliers vs. inliers based on error magnitude, information regarding the dimension and direction of signal offset is lost when using the 3D distance. As a result, this approach is not suitable for identifying systematic, direction-specific errors such as those noted by other investigators[6]. Additionally, their approach, which collapsed analyses across six tested movements, may obscure any relationships between the Kinect and ground truth signals that are specific to a given experimental condition or movement.

Considering these limitations and the expanded use of Kinect based systems in quantitative kinematic studies, a more thorough evaluation of Kinect 2.0 raw data performance as a MOCAP tool and its validation against a gold-standard 3D system is needed. The overarching goal of this research is the development of a system to collect reliable, valid kinematic data using low-cost sensors. The applications of such a technology are wide-reaching and may involve physical medicine clinics, athletics settings, and home entertainment, as well as other research domains in which kinematic data are not commonly acquired owing to prohibitive costs. The specific aim of this study was to identify limitations (and, ultimately, corrective measures) in Kinect 2.0 performance as an off-the-shelf technology for a flexible and multi-purpose MOCAP system. To that end, we have validated the Kinect against a professional three-dimensional motion capture system with 12 IR-cameras (Qualisys AB, Gothenburg, Sweden) over a range of dynamic movements and clinical tests that can be used as broad indicators of functional movement. In addition to this Kinect-vs-gold standard comparison, we present raw data from a second Kinect 2.0 sensor positioned alongside the first. These data provide an indication of reliability between Kinect 2.0 sensors. We acquired data from four healthy subjects and calculated results for point kinematics and joint angles, the latter of which are derived independently for the Kinect data using both quaternions and trigonometry applied to the joint positions.

2 Body Segment Orientation

The Microsoft Kinect 2.0 senses depth using an infrared camera sensor. A proprietary on-board algorithm locates bodies within the depth image and extracts parameters that describe the positions of up to six bodies in three-space in real time. For each tracked body, Kinect produces two data streams. The first is "joint location", which tracks the three-dimensional coordinates of 25 joints. The Kinect estimates three dimensional coordinates on a frame-by-frame basis using a probabilistic model that compares data from the depth image to a comprehensive database of human poses [20] [21]. These measurements are in meters and are measured relative to an origin that is represented by the sensor camera itself. The second stream is "body segment orientation," in which the orientation and rotation of each segment relative to its parent, (e.g. forearm relative to upper arm) can be represented numerically by a *quaternion*. These real-time data streams are both complicated by the fact that the sampling rate varies between 5 and 30 frames per second according to instantaneous demands on the computer's processor.

A quaternion is a 4-tuple that represents the orientation and rotation of an object in three dimensions relative to some parent coordinate axis. Specifically, quaternion u can be expressed as

$$u = u_0 + u_x i + u_y j + u_z k = M\cos(\alpha) + M\boldsymbol{u}\sin(\alpha) = Me^{\boldsymbol{u}\alpha}$$

If v is some other quaternion, then v can be rotated around unit quaternion u (eg. $M = 1$) by 2α radians using the following transform: $v_{rot} = uvu^*$. Although the Kinect produces a stream of "body segment orientations", these measurements must be numerically manipulated to yield clinically relevant kinematic data.

In some cases, this calculation is straightforward. For example, elbow angle can be calculated by simply calculating the angle between the quaternions of the upper arm and forearm as

$$\theta = \cos^{-1}\left(\frac{\boldsymbol{u}\cdot\boldsymbol{v}}{|\boldsymbol{u}||\boldsymbol{v}|}\right)$$

In other cases, the transformation from quaternion orientations to clinical kinematic data requires projecting body segments into the three cardinal planes (mediolateral, vertical, and anteroposterior).

Kinect quaternion mathematics are complicated by two main factors. The first is that all Kinect quaternions are defined with respect to their "parent segment" quaternion, and the second is that quaternions do not describe anatomically significant angles. Specifically, each Kinect quaternion is defined so that its y-axis points to its "child segment" quaternion, while the z-axis is normal to both the y-axis and the body segment. The x-axis is normal to both the previous axes. Since the root joint is the lower spine, all relative orientations can be re-referenced to this initial orientation by consecutive parent/child multiplication along the quaternion body chain, using Hamilton products, as follows:

$$\begin{aligned}
q3_0 &= q1_0 * q2_0 - q1_z * q2_z - q1_y * q2_y - q1_x * q2_x \\
q3_x &= q1_0 * q2_x + q1_z * q2_y - q1_y * q2_z + q1_x * q2_0 \\
q3_y &= q1_0 * q2_y - q1_z * q2_x + q1_y * q2_0 + q1_x * q2_z \\
q3_z &= q1_0 * q2_z + q1_z * q2_0 + q1_y * q2_x - q1_x * q2_y
\end{aligned}$$

where q1 and q2 are the parent and child quaternions, respectively, and q3 is the quaternion that represents the orientation of the child segment.

The second step necessary for deriving meaningful joint angles is that segment orientations expressed using quaternions must be converted into Euler angles. Specifically, the position of a limb in three-space may be considered as the result of one or more rotations in each of the cardinal planes. The values of the rotation angles and the accuracy of the conversion relative to the original quaternion depends on the order of rotation as well as the joint in question and even the movement being performed [25]. The conversion can be performed using each one of 12 possible combinations of the three axes of rotation, also known as *rotation sequences*. In this work, we chose the rotation sequences for each movement and joint that are most commonly used in biomechanics [22]–[24].

In addition to computing joint angles from the Kinect's quaternion stream, they can also be derived directly from the three dimensional joint locations. Specifically, the location of two joints in 3D space defines a body segment orientation. Following standard practice [26], [27], the angle of each body segment is calculated relative to the normal of the floor, giving what is defined as an *absolute angle*. The absolute angles can then be differenced to compute joint angles (also called *relative angles*).

$$\Theta_{joint} = \Theta_{parent\ segment} - \theta_{child\ segment}$$

where each segment's absolute angles in the frontal and sagittal planes can be calculated respectively as:

$$\Theta_{\mathrm{segment}_{frontal}} = \mathrm{atan}\left(y_{distal} - y_{proximal}/x_{distal} - x_{proximal}\right)$$

$$\Theta_{\mathrm{segment}_{sagittal}} = \mathrm{atan}\left(z_{distal} - z_{proximal}/y_{distal} - y_{proximal}\right)$$

where x, y, and z are the coordinates of the joint centers that define a body segment. We compared joint angles computed using this method with those derived from the quaternion measurements to determine whether there were any systematic biases or errors across subjects or movements.

3 Methods

Four subjects (three males, mean age 23) performed a series of movements while being simultaneously tracked by two immediately adjacent Kinect 2.0s and a professional-grade motion capture system (Qualisys AB, Gothenburg, Sweden). The two Kinects were used to evaluate inter-unit accuracy, and motion tracking results from both systems were compared to the gold standard Qualisys system. The movements and the recording paradigm were specifically designed to facilitate the quantification of errors in tracking joint angles and limb locations relative to all three cardinal planes of the body axis: mediolateral, vertical, and anteroposterior.

Subjects wore tight-fitting shorts and an (optional) upper body garment that allowed for placement of reflective markers in accordance with the Qualisys MOCAP full-body plug-in-gait marker set [28]. This included 39 markers, placed on the head, arms, wrists, trunk, pelvis, legs and feet. All acquisitions were performed in a dedicated motion tracking laboratory which houses a 12-camera Oqus passive marker measurement system. Before each session, the Qualisys system was calibrated and then the two Kinect sensors were placed on tripods between 2m and 4m in front of the subject. The exact Kinect sensor locations were determined by following the manufacturer recommendations and by verifying that the subject was completely and optimally in the field-of-view, thus, optimizing the performance of the proprietary body tracking algorithm. The experimental setup is shown in Figure 1.

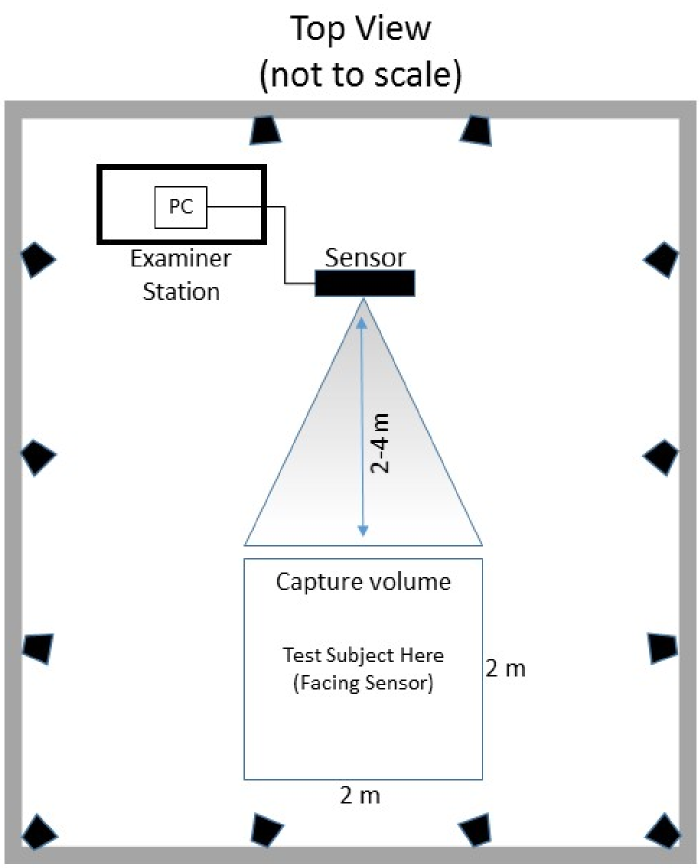

Figure 1: Experimental capture volume block diagram. Oqus cameras are represented by black boxes along the perimeter. The Kinect is labeled "Sensor."

The four subjects were asked to perform two trials each of a series of different moving postures. Each trial was preceded with a large movement such as a T-pose or an overhead reach to facilitate time-synchronization of the Qualisys and Kinect systems; these movements were not scored or otherwise included in the results. Three subjects performed a battery of *standard* clinical tests of dynamic posture, whereas the fourth subject performed the *stereotyped* postures in which movement was intentionally restricted to a single plane.

Table 1: Dynamic Postures

Standard	**Posture/Movement**	**Primary Plane**	**Notes**
	Sit-to-stand	Sagittal	• five repetitions
	Timed up-and-go	Sagittal / Transverse	• stand; walk to marked position ~3m away; walk back
	Alternating barbell lunges	Sagittal	• ten repetitions
	Overhead squats	Sagittal / Frontal	• five repetitions
	Marching in place	Sagittal	• 20 seconds
	Time to stabilization	Sagittal / Frontal	• Forward hop with unilateral landing
Stereotyped	**Posture/Movement**	**Primary Plane**	**Notes**
	Shoulder Flexion/Extension	Sagittal	• Right arm start extended at 0° • Right arm flex to 90° • Right arm flex to 180° • Right arm extend to 90° • Right arm extend to 0° • Repeat on left side
	Shoulder Ab/Adduction	Frontal	• Arms raised laterally (abducted) to “T” position • Arms raised laterally to overhead position • Arms lowered laterally (adducted) to “T” position • Arms lowered laterally to starting position • Repeat once
	Hip Ab/Adduction	Frontal	• Right leg raised laterally (hip abducted) to ~45° • Right leg lowered laterally (hip adducted) to 0° • Left leg raised laterally to ~45° • Left leg lowered laterally to 0° • Repeat once
	Combined Hip/Knee Flexion/Extension	Sagittal	• Right hip and knee flexed (e.g. “high knee” stepping) • Right hip and knee extended to starting position • Left hip and knee flexed • Left hip and knee extended to starting position • Repeat once
	Combined Arm Ab/Adduction & Elbow Flexion/Extension	Frontal / Sagittal	• Arms raised laterally to “T” position • Elbows flexed 90° to “goal post” position • Elbows flexed maximally • Elbows extended to “goal post” position • Elbows extended to achieve “T” position
	Trunk Leans	Sagittal / Frontal	• Lean left • Return to starting position • Lean right • Return to starting position • Lean backward • Return to starting position • Lean forward • Return to starting position

Body movement was tracked with the two systems simultaneously. The benchmark Qualisys was controlled via proprietary data acquisition software ("Qualisys Track Manager"). In order to convert the marker locations to angular kinematics, the trajectories were mapped offline onto a subject-specific rigid body model using the freely available OpenSim software tool. [29] In contrast, the two Kinects tracked body motions in 3D using single-camera sensors, Microsoft's proprietary body tracking algorithm [12], and a custom-designed software tool that converted the Kinect raw data into comma-separated-variable files for offline analysis. [30] These CSV files stored three-dimensional joint center trajectories, the three-dimensional orientations of 25 joints, and the Kinect-estimated floor plane quaternion. The data acquisition and processing pathway is summarized in Figure 2.

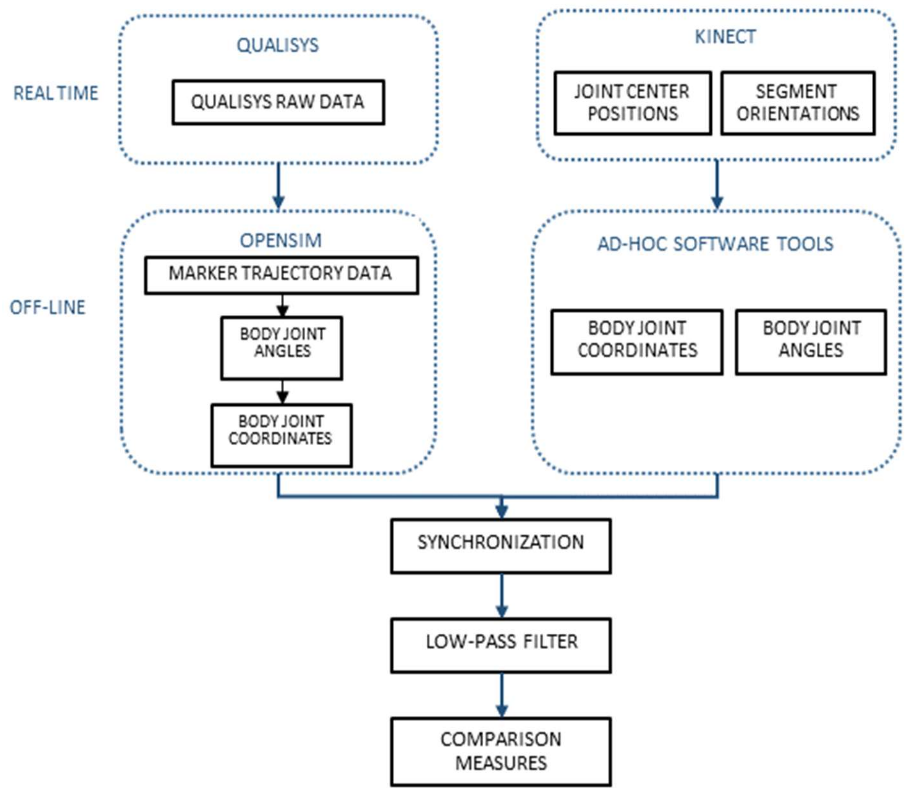

Figure 2: Signal Processing Block Diagram

Note that, while the Qualisys data were acquired at a constant frame rate of 120 fps, the Kinect data were acquired at a variable frame rate that depended heavily on the available computational and memory resources in the acquisition computer during run-time. Although the Kinect nominally collected data at 30 fps, instantaneous drops to 10-15 fps were not uncommon. For the purpose of data analysis, all Kinect data was upsampled to 120fps to match the Qualisys data.

Hardware limitations made it impossible to time-align the data streams using an electronic trigger during acquisition. Instead, data from the systems were temporally aligned by first de-trending them and then by cross-correlating them to assess the time lag that maximized their similarity [13]. To facilitate time synchronization, each pose was preceded by a large *alignment movement*, either an arms-open T-pose or an eccentric or concentric overhead press. The presence of a large alignment movement before each posture allowed the cross-correlation method to work robustly; temporal alignments were manually reviewed and found to be accurate to within a single frame. The alignment movement also served the dual purpose of initiating Kinect body tracking, which requires movement for optimal body detection.

After synchronization, data from both systems were low-pass filtered to reduce noise and acquisition artifacts. Since human movements are rarely faster than a few hundred milliseconds (eye blinks are typically 100-150ms) [31], motion capture systems do not need frequencies higher than a few Hertz. In this work, as in other manuscripts of this nature, all data was low-pass filtered using a 15^{th} order Butterworth low-pass filter with a 3 dB cut-off frequency of 6.3 Hz [2], [32]. Finally, in order to calculate joint displacement and compare Qualisys and Kinect data, movement from each joint was zeroed relative to its initial position.

4 Results

In order to validate the Kinect-based MOCAP system, we compared its performance to a gold standard 12-camera 3D Qualisys system, that was used to concurrently evaluate subjects' movements. Subsequently, the similarity between the two sets of data was assessed by measuring both the cross-correlation values and the average absolute errors between corresponding time series, joint by joint and motion by motion, to elucidate any systematic biases that appear in some dimensions but not others. Since no statistical difference (Student's t-test, $p>0.05$) was found between measurements from the two side-by-side Kinect sensors, we report only their average measurements. Three separate error metrics were used to describe the performance of the Kinect system relative to the benchmark Qualisys system. First, we calculated cross-correlation coefficients, which effectively describe how much information one signal can yield about another, but that is generally blind to errors of constant or near-constant offset or bias. Secondly, we calculated the root-mean-squared errors (RMSEs) between the various output signals. RMSE measures constant or near constant differences between signals but is blind to signal correlation. Finally, we propose a novel "summary measure" which seeks to combine the cross-correlation and RMSE errors in a manner that is relevant to the context of Kinect-based motion tracking.

When comparing data between the two adjacent Kinect sensors, small deviations were noted between the two. However, these differences were not statistically significant (Student's t-test, $p>.05$). For brevity, only the mean values between the two sensors are presented here.

Figure 3 shows representative joint center displacements of head, the middle of the spine, left hip, and right hip, as measured for a single subject during a sit-to-stand test; data from both Qualisys and Kinect are displayed. This figure illustrates similarities between the joint displacement data from the two motion capture systems. This figure also underscores the need for multiple similarity metrics, since it is possible to have a high cross correlation but also a high root mean squared error. The poorest cross-correlation scores were generally obtained with respect to those axes along which the observed motion was negligible (mediolateral in the case of sit-to-stand). Note also that, in general, tracking between the two systems was less robust in the anteroposterior plane (representing 'depth' away from the Kinect sensor), than in the vertical plane. A more detailed summary of these results is seen in Tables 2 and 3, and in the Appendix.

Figure 4 shows representative joint angles (lumber extension, and hip flexion – left and right) for the same sit-to-stand trial as depicted in Figure 3. In the case of joint angles, we compare two sets of data to the Qualisys gold standard (blue traces). The first is joint angles derived from the Kinect quaternion data stream (red traces), whereas the second is joint angles derived directly from the Kinect's 3D joint coordinates (orange traces). We compare the Kinect-derived joint angles to each other as well as to the Qualisys benchmark. In general, the two Kinect-derived measures correlated strongly against one another and against the benchmark, although offsets and scale factors tended to negatively impact the RMSEs. Again, a more detailed summary of these results is seen in Tables 4 and 5, and in the Appendix.

A "summary metric" was devised that would combine the cross-correlation (CC) and RMSE errors into a single meaningful number. The metric was defined as the ratio of RMSE to cross-correlation value. Ideal trials with high cross-correlation (close to one) and low RMSE (close to zero) would score well (close to zero) on this scale, whereas less accurate measurements would score worse (larger values). Since the resulting metric lacks meaningful scale (which complicates interpretation), we chose to normalize the $\frac{RMSE}{CC}$ quotient by an arbitrary constant U_{ref} as follows:

$$Summary\ Metric_i = \frac{RMSE_i}{CC_i} * \frac{1}{U_{ref}}$$

where $Summary\ Metric_i$ is the $\frac{RMSE}{CC}$ quotient calculated for the i-th measurement and normalized by U_{ref}, that is given by:

$$U_{ref} = \frac{RMSE_{ref}}{CC_{ref}}$$

where $RMSE_{ref}$ was different for displacement-based and joint angle measures; and respectively chosen equal to 3 cm and 15 degrees. CC_{ref} was set to 0.75.

We chose CC_{ref} equal to 0.75 for the cross-correlation in order to make sure that the signals under observation had similar (linear) time-courses and the $RMSE_{ref}$ errors were chosen on the basis of previously reported data [33]. According to these arbitrary units and our own analysis, it was determined that summary measures ranging between 0 and 2 were ‘good’, values between 2 and 4 were approaching their limit of usability, and values greater than 4 were considered to represent measurements that Kinect cannot accurately capture.

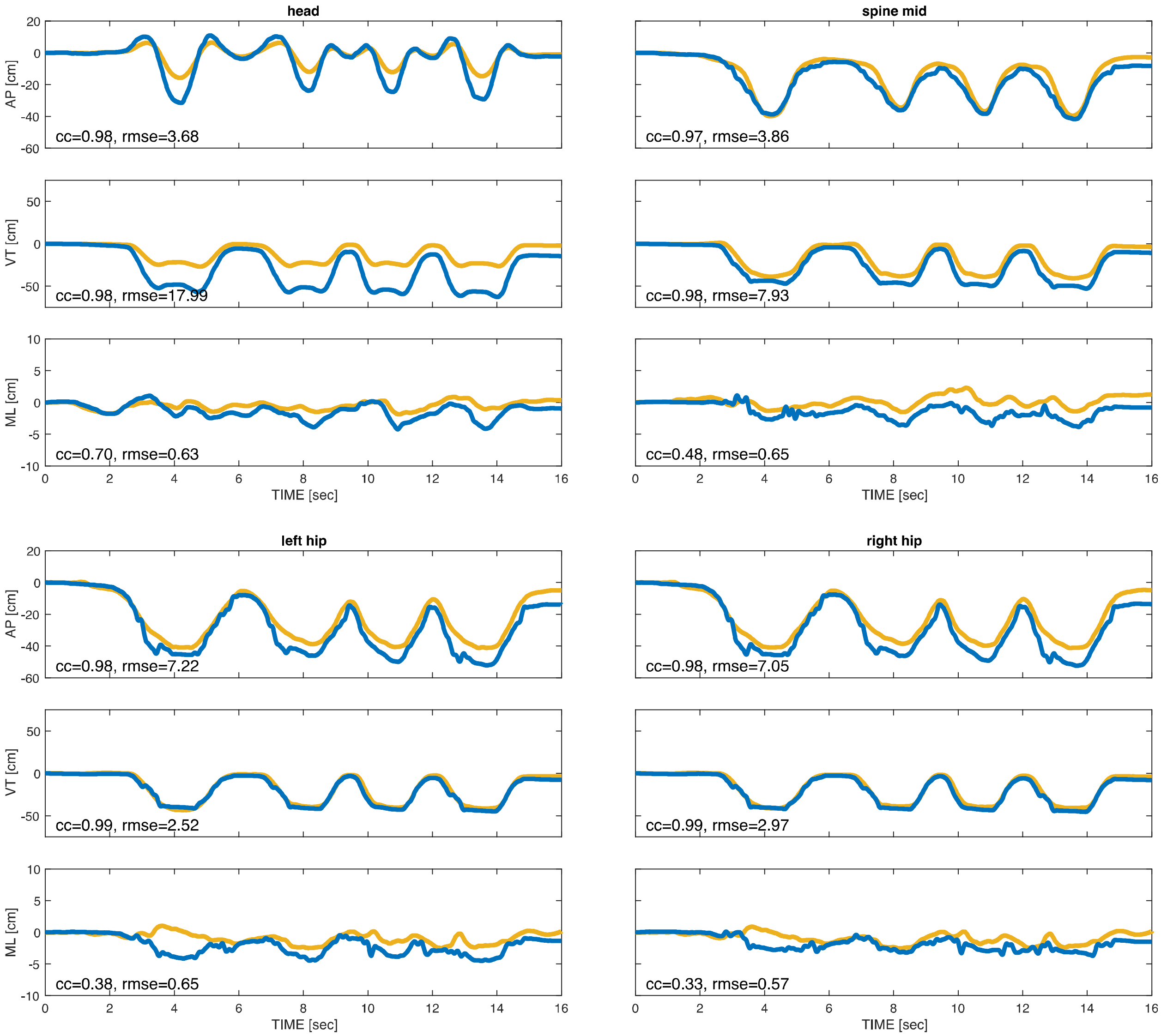

Figure 3: Head, spine middle, left and right hip joint center displacements in cm as derived from both MOCAP systems Qualisys (yellow) and Kinect (blue), during a sit to stand test. The displayed signals are for a single subject and a single trial. Values in the lower left corner of each plot show the cross-correlation coefficients and the root mean squared error calculated between the Qualisys and the Kinect displacements over time. ML = Mediolateral, VT = vertical, AP = anteroposterior

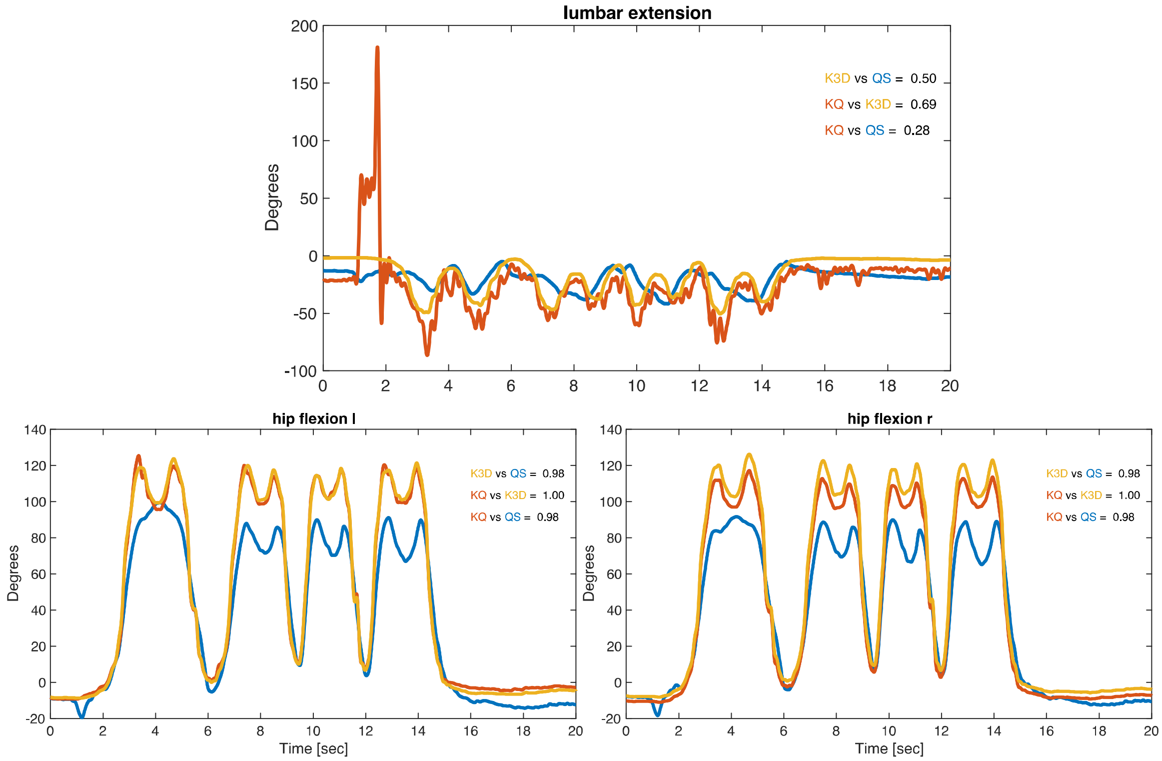

Figure 4: Joint angles for trunk extension, left and right hip flexion/extension. The blue, red and orange lines display joint angles derived using respectively Qualisys, Quaternion and coordinate data. The numbers show correlation coefficients between the different pairs of data

Table 2: Errors in tracking joint displacement. Errors are averaged over all trials of all 12 movements. AP = anteroposterior, VT = vertical, ML = mediolateral

	correlation				**error**				**summary metric**			
	AP	VT	ML	Average	AP	VT	ML	Average	AP	VT	ML	Average
head	0.93	0.98	0.93	0.95	3.85	4.99	5.58	4.80	1.59	1.32	0.72	1.21
spine top	0.73	0.78	0.68	0.73	3.17	2.42	1.75	2.45	0.68	0.69	0.35	0.57
spine mid	0.72	0.86	0.73	0.77	3.44	2.54	1.67	2.55	0.65	1.37	0.45	0.82
spine base	0.81	0.97	0.86	0.88	4.74	4.48	2.99	4.07	2.69	1.65	0.68	1.67
left shoulder	0.91	0.98	0.95	0.95	3.54	4.61	5.33	4.49	1.13	0.81	0.74	0.89
right shoulder	0.69	0.54	0.67	0.63	2.97	2.90	1.47	2.45	1.27	0.72	0.58	0.86
left elbow	0.66	0.54	0.70	0.63	3.45	3.37	1.41	2.74	1.84	1.16	0.96	1.32
right elbow	0.75	0.77	0.68	0.73	3.08	2.51	1.73	2.44	1.35	1.23	1.02	1.20
left wrist	0.94	0.71	0.88	0.84	2.57	2.12	1.27	1.99	1.02	1.28	1.54	1.28
right wrist	0.62	0.60	0.63	0.62	7.30	3.70	1.82	4.27	0.94	1.19	1.42	1.18
left hand	0.78	0.87	0.75	0.80	3.22	2.82	1.94	2.66	1.01	1.38	1.67	1.35
right hand	0.80	0.62	0.75	0.73	2.19	2.49	1.23	1.97	0.92	1.25	1.41	1.20
left hip	0.96	0.82	0.90	0.89	6.23	4.97	2.76	4.66	1.03	1.50	0.93	1.15
right hip	0.84	0.97	0.88	0.89	4.34	4.70	3.26	4.10	1.01	0.98	0.77	0.92
left knee	0.84	0.68	0.84	0.79	3.50	2.82	1.19	2.51	0.95	2.03	0.39	1.12
right knee	0.83	0.65	0.79	0.76	3.34	3.19	1.24	2.59	0.96	1.60	0.33	0.97
left ankle	0.50	0.47	0.56	0.51	5.28	2.96	1.88	3.37	0.93	1.63	0.53	1.03
right ankle	0.52	0.46	0.59	0.52	4.41	3.48	1.95	3.28	1.12	1.92	0.45	1.16
left foot	0.93	0.98	0.95	0.96	3.50	4.86	5.30	4.55	2.59	2.81	0.75	2.05
right foot	0.94	0.98	0.93	0.95	3.81	5.36	6.08	5.08	2.35	3.34	0.75	2.14

Table 3: Errors in tracking joint displacement. Errors are averaged over all trials of all 20 tracked body points. AP = anteroposterior, VT = vertical, ML = mediolateral

Movement	**correlation** AP	VT	ML	**error** AP	VT	ML	**summary metric** AP	VT	ML
sit to stand	0.85	0.84	0.67	4.30	4.51	2.63	1.46	1.38	0.90
timed up and go	0.97	0.75	0.83	10.13	4.41	5.07	2.64	2.36	1.61
alternating barbell lunges	0.92	0.80	0.87	9.50	5.40	2.18	2.64	2.49	0.66
overhead squats	0.78	0.86	0.61	4.27	5.72	1.86	1.49	1.70	0.90
marching in place	0.88	0.80	0.92	2.17	2.05	1.86	0.62	0.63	0.50
time to stabilization	0.93	0.89	0.87	6.15	3.54	3.84	1.72	1.04	1.10
shoulder ab/adduction	0.60	0.75	0.65	1.24	1.98	0.98	0.66	0.93	0.34
shoulder flexion/extension	0.66	0.65	0.64	1.95	3.02	1.10	0.70	1.32	0.59
hip ab/adduction	0.71	0.78	0.95	1.85	2.61	2.85	0.84	0.88	0.75
combined hip/knee flexion/extension	0.85	0.87	0.97	1.58	2.24	3.88	0.50	0.64	1.00
combined arm ab/adduction	0.49	0.55	0.56	1.46	4.09	1.76	1.51	1.71	0.60
sagittal/frontal trunk leans	0.78	0.59	0.84	2.16	3.21	3.10	0.85	2.84	0.91

Table 4: Errors in tracking joint angles. Errors are averaged over all trials of all 12 movements. KQ = Kinect Quaternions, K3D = Kinect 3D-derived joint angles, QS = Qualisys, flxn = flexion, addn = adduction, extn = extension.

			correlation			error			summary metric		
			KQ vs QS	K3D vs QS	KQ vs K3D	KQ vs QS	K3D vs QS	KQ vs K3D	KQ vs QS	K3D vs QS	KQ vs K3D
arm	flxn	L	0.42	0.48	0.45	60.5	46.2	57.2	14.3	9.4	9.8
arm	flxn	R	0.40	0.48	0.53	77.9	54.3	52.7	13.1	8.3	6.5
arm	addn	L	0.65	0.77	0.77	41.9	22.3	26.5	4.1	1.7	2.4
arm	addn	R	0.64	0.75	0.75	47.7	27.7	29.4	5.3	2.1	2.4
elbow	flxn	L	0.64	0.38	0.36	27.8	41.7	28.5	2.3	6.0	4.7
elbow	flxn	R	0.69	0.44	0.42	27.5	41.3	25.3	2.0	6.8	10.4
hip	flxn	L	0.70	0.78	0.92	14.4	13.1	4.1	1.8	1.3	0.3
hip	flxn	R	0.71	0.71	0.98	13.7	14.4	2.6	2.5	1.9	0.2
hip	addn	L	0.36	0.35	0.64	6.2	6.8	9.4	4.4	1.5	2.7
hip	addn	R	0.30	0.30	0.68	5.0	7.9	4.5	1.6	2.7	1.5
knee	flxn	L	0.69	0.71	0.88	19.8	18.0	5.8	1.9	1.4	0.3
knee	flxn	R	0.66	0.68	0.97	21.0	19.7	4.0	2.3	2.5	0.1
knee	addn	L	0.25	0.40	0.45	22.0	10.0	20.8	2.9	1.5	2.3
knee	addn	R	0.57	0.44	0.70	12.5	12.3	18.3	1.7	1.8	1.5
lumbar	extn		0.38	0.51	0.40	38.0	19.9	25.2	6.1	4.4	4.5

Table 5: Errors in tracking joint angles. Errors are averaged over all trials of all 15 joint angles. KQ = Kinect Quaternions, K3D = Kinect 3D-derived joint angles, QS = Qualisys, alt = alternating, flex = flexion, ext = extension, sag/front = sagittal/frontal.

	correlation			**error**			**summary metric**		
Movement Task	KQ vs QS	K3D vs QS	KQ vs K3D	KQ vs QS	K3D vs QS	KQ vs K3D	KQ vs QS	K3D vs QS	KQ vs K3D
sit to stand	0.67	0.67	0.65	33.1	22.7	29.5	3.2	2.2	3.5
timed up and go	0.43	0.50	0.54	34.6	30.8	22.3	7.1	5.2	4.3
alt. barbell lunges	0.58	0.53	0.71	64.4	57.8	38.1	5.9	6.4	4.6
overhead squats	0.65	0.55	0.64	43.5	39.3	29.1	3.8	5.0	4.3
marching in place	0.62	0.61	0.62	15.4	13.3	9.7	1.5	1.8	1.4
time to stabilization	0.57	0.57	0.61	28.8	17.0	25.4	3.1	1.8	2.8
shoulder ab/adduction	0.42	0.41	0.70	14.4	14.7	13.0	4.0	4.5	7.0
shoulder flex/ext	0.33	0.36	0.73	16.1	11.6	11.0	5.0	3.6	1.3
hip ab/adduction	0.68	0.74	0.74	15.2	11.5	11.3	1.9	0.9	1.3
comb. hip/knee flex/ext	0.59	0.65	0.75	18.6	12.5	14.4	2.3	1.3	1.8
comb. arm ab/adduction	0.35	0.33	0.65	31.2	26.1	23.7	8.7	7.3	3.2
sag./front. trunk leans	0.57	0.65	0.60	33.4	27.5	24.1	6.6	2.6	4.2

For compactness sake, Tables 2-5 summarize errors by averaging over either movement or limb/joint. A full presentation of all error combinations can be found in the Appendix. Those errors are presented in the interest of investigators seeking to optimally calibrate their own Kinect-based motion tracking systems. To simplify data interpretation, the values in Tables 10 and 11 are color-coded. Green values indicate that the Kinect-based performance was good (values ranging between 0 and 2). Yellow values indicate that the performance is approaching the limit of usability, with values ranging between 2 and 4. Red values indicate those conditions where the Kinect-based MOCAP yielded poor performance, with values larger than 4.

In the tables above, for purposes of presentation, we averaged the performance metrics across movements. This allows a single value to represent how well the Kinect-based MOCAP was capable of evaluating each joint both in terms of displacements and in terms of joint angles. Additionally, in the case of the joint displacement, we averaged metrics across joints and then across the three axes to identify which axis captured the motions with the highest accuracy. Because averaging obscures performance characteristics which may be meaningful in certain applications, the data are also presented in their original, uncollapsed form in the appendices.

5 Discussion

The overall finding of this work has been that data from the Kinect compare favorably to the gold-standard Qualisys tracking system, given the limitations of the Kinect hardware. This work has quantified, for the first time, the specific limitations of a Kinect-based motion tracking system for general applications with respect to a set of representative clinical movement tests. Furthermore, whereas others have quantified Kinect's limitations either through global summary metrics or by collapsing data across movement planes, this work presents more fine-grained performance comparisons. Specifically, this data is critical for investigators who need to know the precision that can be expected when using Kinect to track motion in real-world settings.

One of the most relevant aspects of this work is to fully evaluate the potential of a Kinect-based multi-purpose MOCAP that can be useful in clinical settings. This motivated our choice to analyze system performance with respect to different clinically relevant motions, and to keep the results grouped by movement. One important finding was that some motions were better captured than others, regardless of which metrics were used in quantifying error. One hypothesis to explain the movement-based differential in tracking performance is that certain movements may be similar to those that Microsoft used when designing and calibrating the Kinect for video game play. Tables 3 and 5 show that certain motions such as hip ab/adduction, marching in place, hip/knee flexion/extension, time to stabilization and sit to stand movements yielded the highest agreement between Qualisys and Kinect. This finding suggests that a Kinect-based MOCAP system can be used more confidently when investigating the above-mentioned motions. Identifying the limitations of such a system is valuable for all those investigators and medical professionals in need of carrying out motion analysis studies using light-weight and low-cost equipment.

Another relevant observation was that there were key differences when joint angles were calculated from Kinect's quaternion stream versus being derived from the Kinect 3D coordinates. Specifically, the 3D coordinate approach was generally superior when tracking arm ab/adduction, hip flexion/extension and ab/adduction, knee flexion/extension and ab/adduction. In theory, the 3D coordinate approach should only work when the Kinect's global reference system is aligned with the subject's anatomical planes (e.g. for movements such as jumping jacks where the limbs remain in the frontal plane). To overcome this limitation, joint locations can be recomputed relative to a local rotated frame prior to computing joint angles. With this correction, only elbow flexion angles were better computed using quaternions than the 3D coordinate trigonometric method (see Tables 4 and 5).

Lower performance in the quaternion approach can be due to multiple concurrent factors. First, the Kinect sensor shows frequent errors and oscillations in evaluating joint orientations during motion. Without a strict rigid body model to be superimposed onto the Kinect raw data, it is not possible to compensate for such sensor errors. Secondly, when allowing the subjects to move in 3D space without constraining their movements to specific planes, the conventional kinematic angles cannot be easily derived from quaternions without choosing a three-axial rotation sequence. The difficulty of selecting an appropriate rotation sequence based on joint and motion type is a well-known problem in biomechanics; recommended rotation sequences for various joints have been defined [22]–[24], [34]. However, these sequences are defined relative to local reference coordinate systems that do not exist when using quaternions. It is therefore not unexpected that the same rotation sequences used as standard practice in biomechanics research are not optimal when used with Kinect quaternions. We evaluated all possible Kinect quaternion rotation sequence combinations and chose those that yielded the joint angles most closely approximating the gold-standard Qualisys kinematics. The identified rotations were then applied at a given joint irrespective of the movement being tested.

Kinect-based motion capture is not flawless, as emphasized by our results. Inaccuracies are mainly due to a combination of hardware and software limitations. From a hardware perspective, the Kinect camera is based on a combination of low-cost commodity sensors, such as a single depth sensor. With respect to software, the Microsoft body tracking algorithm is designed for gaming performance and generalization rather than tracking accuracy. The Microsoft tracking algorithm aims to detect people in the sensor field of view irrespective of their pose and body type. Consequently, for the sake of performance and usability, the Kinect system was devised to minimize the body model constraints necessary and to choose speed over accuracy. For instance, to reduce the computational time necessary to track joints, the sensor depth data stream is always processed in real-time and on a frame-by-frame basis. Although computationally efficient, it allows for predicted joint locations to jump from frame to frame depending on instantaneous sensor measurements. Consequently, it does not enforce rigid body constraints, which are a core assumption of most biomechanics studies.

We hypothesize that Kinect-based motion tracking could be improved by third-party algorithms which combine sensor data with various real-world constraints such as fixed anatomy and range of motion. Contemporary processor speeds should be in line with the types of processing demands that are necessary to implement these improvements within reasonable time frames. The combination of a low-cost, portable, expedient sensor with high-performance data modeling could yield systems whose performances are acceptable in most medical, sports, fitness and rehabilitation applications.

Although the number of subjects in this study may be a limitation, we expect that the broad extent of the movements evaluated in this work would contribute more variability to motion capture performance than would differences between subjects. Because the focus of this study was to evaluate Kinect performance for non-specific purposes, inter-subject variability was of less interest than variability in fine-grained body tracking behavior across a range of movements. In future work, we intend to build on our present findings with group-based investigations to confirm the viability of the Kinect for observing clinically relevant movement features. This will require a more narrowly focused scope with depth in sample size as opposed to experimental conditions.

6 Conclusion

The Kinect-based motion capture system can consistently track the 3D displacement of joint centers with high precision and acceptable accuracy levels. Specifically, our results show that the Kinect-based MOCAP and the Qualisys system reached high levels of agreement when tracking joint displacements, with average overall cross-correlation coefficient of 0.78, root mean squared error of 3.35 cm and a combined metric of 1.21. On the contrary, lower agreement levels were achieved when tracking joint angles with cross-correlation coefficient of 0.58, root mean squared error of 24.59 degrees and a summary metric of 3.76.

This is a promising finding, considering the ease of setup, use and cost of a Kinect-based system. The overall analysis of displacement tracking performance showed that some segments/joints are tracked with less accuracy, particularly the foot/ankle complex. Also, the accuracy levels are axis dependent, with the highest accuracy recorded along the mediolateral direction. Furthermore, the overall data analysis indicated a motion-dependent tracking accuracy, with timed up-and-go, alternating barbell lunges and combined arm ab/adduction yielding the lowest performance and largest errors. Despite some of the Kinect precision limitations, the displacement data were consistently within a threefold difference from the precision and accuracy levels that we used to normalize the performance metrics.

The data presented here suggest that Kinect-based motion capture systems may be viable alternatives to professional three-dimensional capture systems for certain applications. Our data can be used by other investigators to understand the limits of out-of-the-box Kinect motion capture accuracy with respect to various movements and planes of motion. We hypothesize that, with the addition of certain body constraints, Kinect-based tracking systems could be valuable tools in applications such as medicine, sports, rehabilitation and fitness.

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7 References

[1] Microsoft, “Kinect for Windows SDK 2.0.” [Online]. Available: https://www.microsoft.com/en-us/download/details.aspx?id=44561. [Accessed: 01-Jan-2017].

[2] B. Bonnechere, B. Jansen, P. Salvia, H. Bouzahouene, L. Omelina, F. Moiseev, V. Sholukha, J. Cornelis, M. Rooze, and S. Van Sint Jan, “Validity and reliability of the Kinect within functional assessment activities: Comparison with standard stereophotogrammetry,” *Gait Posture*, vol. 39, no. 1, pp. 593–598, 2014.

[3] R. A. Clark, Y. H. Pua, K. Fortin, C. Ritchie, K. E. Webster, L. Denehy, and A. L. Bryant, “Validity of the Microsoft Kinect for assessment of postural control,” *Gait Posture*, vol. 36, no. 3, pp. 372–377, 2012.

[4] B. F. Mentiplay, L. G. Perraton, K. J. Bower, Y. H. Pua, R. McGaw, S. Heywood, and R. A. Clark, “Gait assessment using the Microsoft Xbox One Kinect: Concurrent validity and inter-day reliability of spatiotemporal and kinematic variables,” *J. Biomech.*, vol. 48, no. 10, pp. 2166–2170, 2015.

[5] B. Galna, G. Barry, D. Jackson, D. Mhiripiri, P. Olivier, and L. Rochester, “Accuracy of the Microsoft Kinect sensor for measuring movement in people with Parkinson’s disease,” *Gait Posture*, vol. 39, no. 4, pp. 1062–1068, 2014.

[6] M. Eltoukhy, A. Kelly, C.-Y. Kim, H.-P. Jun, R. Campbell, and C. Kuenze, “Validation of the Microsoft Kinect® camera system for measurement of lower extremity jump landing and squatting kinematics.,” *Sports Biomech.*, vol. 3141, no. February, pp. 1–14, 2016.

[7] D. Lim, C. Kim, H. Jung, D. Jung, and K. Chun, “Use of the microsoft kinect system to characterize balance ability during balance training,” *Clin. Interv. Aging*, vol. 10, pp. 1077–1083, 2015.

[8] S. Phommahavong, D. Haas, J. Yu, S. Krüger-Ziolek, K. Möller, and J. Kretschmer, “Evaluating the microsoft kinect skeleton joint tracking as a tool for home-based physiotherapy,” *Curr. Dir. Biomed. Eng.*, vol. 1, no. 1, pp. 184–187, 2015.

[9] A. Pfister, A. M. West, S. Bronner, and J. A. Noah, “Comparative abilities of Microsoft Kinect and Vicon 3D motion capture for gait analysis.,” *J. Med. Eng. Technol.*, vol. 1902, no. August, pp. 1–7, 2014.

[10] E. E. Stone, M. Butler, A. McRuer, A. Gray, J. Marks, and M. Skubic, “Evaluation of the Microsoft Kinect for screening ACL injury,” *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. EMBS*, pp. 4152–4155, 2013.

[11] R. A. Clark, S. Vernon, B. F. Mentiplay, K. J. Miller, J. L. McGinley, Y. H. Pua, K. Paterson, and K. J. Bower, “Instrumenting gait assessment using the Kinect in people living with stroke: reliability and association with balance tests.,” *J. Neuroeng. Rehabil.*, vol. 12, p. 15, 2015.

[12] J. Shotton, A. Fitzgibbon, M. Cook, T. Sharp, M. Finocchio, R. Moore, A. Kipman, and A. Blake, “Real-time human pose recognition in parts from single depth images,” *Stud. Comput. Intell.*, vol. 411, pp. 119–135, 2013.

[13] R. A. Clark, K. J. Bower, B. F. Mentiplay, K. Paterson, and Y. H. Pua, “Concurrent validity of the Microsoft Kinect for assessment of spatiotemporal gait variables,” *J. Biomech.*, vol. 46, no. 15, pp. 2722–2725, 2013.

[14] X. Xu, R. W. McGorry, L. S. Chou, J. hua Lin, and C. chi Chang, “Accuracy of the Microsoft Kinect™ for measuring gait parameters during treadmill walking,” *Gait Posture*, vol. 42, no. 2, pp.

145–151, 2015.

[15] E. Dolatabadi, B. Taati, and A. Mihailidis, “Concurrent validity of the Microsoft Kinect for Windows v2 for measuring spatiotemporal gait parameters,” *Med. Eng. Phys.*, vol. 38, pp. 952–958, 2016.

[16] Q. Wang, G. Kurillo, F. Ofli, and R. Bajcsy, “Evaluation of Pose Tracking Accuracy in the First and Second Generations of Microsoft Kinect,” no. November, 2015.

[17] D. J. Geerse, B. H. Coolen, and M. Roerdink, “Kinematic validation of a multi-Kinect v2 instrumented 10-meter walkway for quantitative gait assessments,” *PLoS One*, vol. 10, no. 10, pp. 1–15, 2015.

[18] Q. Wang, G. Kurillo, F. Ofli, and R. Bajcsy, “Remote Health Coaching System and Human Motion Data Analysis for Physical Therapy with Microsoft Kinect,” no. 1111965, 2015.

[19] L. F. Yeung, K. C. Cheng, C. H. Fong, W. C. C. Lee, and K.-Y. Tong, “Evaluation of the Microsoft Kinect as a clinical assessment tool of body sway.,” *Gait Posture*, vol. 40, no. 4, pp. 532–8, 2014.

[20] D. Comaniciu and P. Meer, “Mean shift: A robust approach toward feature space analysis,” *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 24, no. 5, pp. 603–619, 2002.

[21] J. Shotton, A. Fitzgibbon, M. Cook, T. Sharp, M. Finocchio, R. Moore, A. Kipman, and A. Blake, “Real-time Human Pose Recognition in Parts from Single Depth Images,” *Comput. Vis. Pattern Recognit.*, pp. 1297–1304, 2011.

[22] G. Wu, S. Siegler, P. Allard, C. Kirtley, A. Leardini, D. Rosenbaum, M. Whittle, D. D. D’Lima, L. Cristofolini, H. Witte, O. Schmid, and I. Stokes, “ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion—part I: ankle, hip, and spine,” *J. Biomech.*, vol. 35, no. 4, pp. 543–548, 2002.

[23] G. Wu, S. Siegler, P. Allard, C. Kirtley, A. Leardini, D. Rosenbaum, M. Whittle, D. D. D’Lima, L. Cristofolini, H. Witte, O. Schmid, I. Stokes, P. R. Cavanagh, and A. Mikaberidze, “Letter To The Editor: ‘Letter to the Editor,’” *J. Biomech.*, vol. 35, no. 4, pp. 543–548, 2002.

[24] G. Wu, F. C. T. Van Der Helm, H. E. J. Veeger, M. Makhsous, P. Van Roy, C. Anglin, J. Nagels, A. R. Karduna, K. McQuade, X. Wang, F. W. Werner, and B. Buchholz, “ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion - Part II: Shoulder, elbow, wrist and hand,” *J. Biomech.*, vol. 38, no. 5, pp. 981–992, 2005.

[25] A. Cappozzo, U. Della Croce, A. Leardini, and L. Chiari, “Human movement analysis using stereophotogrammetry: Part 1: theoretical background,” *Gait Posture*, vol. 21, no. 2, pp. 186–196, 2005.

[26] J. Hamill and W. S. Selbie, “Three Dimensional Kinematics,” in *Research Methods in Biomechanics*, D. G. E. Robertson, G. E. Caldwell, J. Hamill, G. Kamen, and S. N. Whittlesey, Eds. Champaign, IL: Human Kinetics Publishers, 2004.

[27] D. Winter, *Biomechanics and motor control of human movement.* Wiley & Sons, 2009.

[28] R. B. Davis, S. Õunpuu, D. Tyburski, and J. R. Gage, “A gait analysis data collection and reduction technique,” *Hum. Mov. Sci.*, vol. 10, no. 5, pp. 575–587, 1991.

[29] D. SL, A. FC, A. AS, L. P, H. A, J. CT, G. E, and T. DG, “OpenSim: Open source to create and analyze dynamic simulations of movement,” *IEEE Trans. Biomed. Eng.*, vol. 54, no. 11, pp. 1940–1950, 2007.

[30] A. Napoli, C. R. Ward, S. M. Glass, C. Tucker, and I. Obeid, “Automated Assessment of Postural Stability System,” in *Conference proceedings : Annual International Conference of the IEEE Engineering in Medicine and Biology Society.*, 2016, pp. 6090–6093.

[31] K.-A. Kwon, R. J. Shipley, M. Edirisinghe, D. G. Ezra, G. Rose, S. M. Best, and R. E. Cameron, “High-speed camera characterization of voluntary eye blinking kinematics.,” *J. R. Soc. Interface*, vol. 10, no. 85, p. 20130227, 2013.

[32] R. A. Clark, A. L. Bryant, Y. Pua, P. McCrory, K. Bennell, and M. Hunt, “Validity and reliability of the Nintendo Wii Balance Board for assessment of standing balance,” *Gait Posture*, vol. 31, no. 3, pp. 307–310, 2010.

[33] R. A. Clark, Y. H. Pua, C. C. Oliveira, K. J. Bower, S. Thilarajah, R. McGaw, K. Hasanki, and B. F. Mentiplay, “Reliability and concurrent validity of the Microsoft Xbox One Kinect for assessment of standing balance and postural control,” *Gait Posture*, vol. 42, no. 2, pp. 210–213, 2015.

[34] M. Šenk, L. Chèze, G. Wu, F. C. T. Van Der Helm, H. E. J. Veeger, M. Makhsous, P. Van Roy, C. Anglin, J. Nagels, A. R. Karduna, K. McQuade, X. Wang, F. W. Werner, and B. Buchholz, “Rotation sequence as an important factor in shoulder kinematics,” *J. Biomech.*, vol. 38, no. 5, pp. 981–992, 2005.

8 Appendix

Table 6: Average Cross-Correlation Coefficients of Joint Center Displacements measured across two separate trials from four different subjects (each subject repeated the tests twice) and grouped by movement types.

	SIT TO STAND			TIMED UP AND GO			ALTERNATING BARBELL LUNGES			OVERHEAD SQUATS			MARCHING IN PLACE			TIME TO STABILIZATION		
JOINT DISP	AP	VT	ML	AP	VT	ML	AP	VT	ML	AP	VT	ML	AP	VT	ML	AP	VT	ML
head	0.99	0.99	0.92	0.98	0.98	0.76	0.98	0.98	0.93	0.98	0.99	0.83	0.98	0.98	0.99	0.99	0.97	0.94
spine top	0.97	0.99	0.37	0.99	0.97	0.88	0.98	0.98	0.87	0.78	0.85	0.49	0.56	0.65	0.91	0.89	0.96	0.79
right shoulder	0.56	0.39	0.65	0.95	0.21	0.85	0.83	0.17	0.65	0.72	0.58	0.33	0.96	0.90	0.92	0.89	0.73	0.91
left shoulder	0.99	0.99	0.95	0.98	0.98	0.81	0.98	0.99	0.95	0.97	0.99	0.90	0.98	0.98	0.98	0.99	0.97	0.99
right elbow	0.97	0.99	0.34	0.99	0.97	0.88	0.98	0.98	0.86	0.69	0.90	0.54	0.80	0.37	0.92	0.88	0.95	0.77
left elbow	0.71	0.40	0.68	0.97	0.31	0.90	0.79	0.14	0.89	0.71	0.62	0.48	0.96	0.93	0.95	0.83	0.87	0.75
right wrist	0.48	0.97	0.36	0.90	0.97	0.77	0.94	0.99	0.85	0.78	0.87	0.37	0.53	0.23	0.81	0.88	0.79	0.66
left wrist	0.91	0.99	0.83	0.98	0.98	0.93	0.95	0.99	0.94	0.86	0.89	0.72	0.94	0.53	0.96	0.99	0.97	0.91
right hand	0.97	0.99	0.75	0.98	0.98	0.89	0.95	0.99	0.95	0.84	0.91	0.64	0.88	0.68	0.94	0.94	0.93	0.89
left hand	0.92	0.99	0.34	0.98	0.98	0.64	0.94	0.98	0.91	0.53	0.91	0.58	0.71	0.74	0.94	0.96	0.98	0.91
spine mid	0.91	0.98	0.53	0.99	0.98	0.78	0.90	0.99	0.87	0.69	0.97	0.52	0.81	0.78	0.95	0.92	0.98	0.85
spine base	0.95	0.99	0.56	0.98	0.98	0.70	0.97	0.98	0.91	0.76	0.97	0.50	0.97	0.95	0.96	0.97	0.95	0.95
right hip	0.93	0.99	0.76	0.98	0.98	0.79	0.93	0.98	0.88	0.70	0.97	0.39	0.97	0.95	0.97	0.97	0.96	0.96
left hip	0.97	0.98	0.78	0.98	0.97	0.97	0.98	0.99	0.96	0.98	0.97	0.79	0.93	0.87	0.93	0.99	0.92	0.95
right knee	0.94	0.62	0.87	0.98	0.30	0.84	0.98	0.85	0.88	0.91	0.84	0.91	0.99	0.93	0.88	0.92	0.82	0.77
left knee	0.95	0.61	0.88	0.98	0.37	0.93	0.97	0.87	0.94	0.94	0.84	0.89	0.99	0.88	0.94	0.92	0.86	0.91
right ankle	0.54	0.45	0.55	0.90	0.11	0.81	0.71	0.17	0.62	0.43	0.59	0.42	0.82	0.80	0.67	0.89	0.53	0.77
left ankle	0.41	0.51	0.49	0.93	0.07	0.82	0.74	0.09	0.76	0.32	0.61	0.24	0.81	0.82	0.74	0.73	0.74	0.74
right foot	0.99	0.99	0.93	0.98	0.98	0.75	0.97	0.98	0.91	0.98	0.99	0.78	0.98	0.98	0.99	0.99	0.96	0.96
left foot	0.99	0.99	0.95	0.98	0.98	0.81	0.98	0.99	0.93	0.98	0.99	0.88	0.98	0.99	0.99	0.99	0.97	0.99

	SHOULDER AB/ADDUCTION			SHOULDER FLEXION/ EXTENSION			HIP AB/ADDUCTION			COMBINED HIP/KNEE FLEXION/ EXTENSION			COMBINED ARM AB/ADDUCTION			SAGITTAL/FRONTAL TRUNK LEANS		
JOINT DISP	AP	VT	ML	AP	VT	ML	AP	VT	ML	AP	VT	ML	AP	VT	ML	AP	VT	ML
head	0.96	1.00	1.00	0.98	0.99	0.99	0.90	0.98	0.94	0.91	0.99	0.95	0.75	0.94	0.95	0.77	0.98	0.93
spine top	0.15	0.95	0.60	0.35	0.90	0.12	0.68	0.70	0.97	0.89	0.85	0.96	0.60	0.54	0.32	0.94	0.07	0.87
right shoulder	0.37	0.59	0.33	0.42	0.36	0.34	0.84	0.87	0.94	0.86	0.93	0.94	0.29	0.31	0.36	0.54	0.42	0.84
left shoulder	0.89	1.00	1.00	0.99	0.99	0.99	0.78	0.97	0.98	0.85	0.98	0.99	0.69	0.94	0.96	0.82	0.98	0.96
right elbow	0.16	0.95	0.50	0.52	0.80	0.15	0.50	0.81	0.97	0.85	0.92	0.98	0.67	0.45	0.29	0.94	0.18	0.93
left elbow	0.34	0.53	0.33	0.31	0.24	0.35	0.86	0.91	0.91	0.81	0.98	0.98	0.12	0.20	0.28	0.53	0.34	0.94
right wrist	0.55	0.19	0.30	0.20	0.33	0.45	0.52	0.14	0.94	0.42	0.53	0.98	0.28	0.45	0.35	0.91	0.76	0.69
left wrist	0.92	0.78	0.76	0.96	0.31	0.75	0.91	0.53	0.96	0.95	0.35	0.99	0.89	0.66	0.77	0.98	0.55	0.99
right hand	0.32	0.54	0.69	0.75	0.25	0.41	0.61	0.36	0.97	0.89	0.46	0.99	0.90	0.25	0.66	0.59	0.12	0.26
left hand	0.80	0.97	0.67	0.68	0.91	0.85	0.73	0.83	0.97	0.94	0.94	0.99	0.22	0.35	0.17	0.97	0.90	0.98
spine mid	0.24	0.97	0.20	0.56	0.94	0.60	0.45	0.60	0.97	0.92	0.84	0.99	0.27	0.54	0.48	0.93	0.78	0.98
spine base	0.70	0.99	0.99	0.94	0.98	0.97	0.65	0.98	0.96	0.94	0.98	0.99	0.14	0.91	0.83	0.79	0.98	0.96
right hip	0.73	0.99	0.99	0.98	0.98	0.98	0.65	0.96	0.97	0.95	0.98	0.99	0.39	0.89	0.93	0.89	0.96	0.92
left hip	0.96	0.49	0.84	0.97	0.77	0.87	0.90	0.42	0.96	0.96	0.86	0.99	0.86	0.69	0.82	0.99	0.90	0.99
right knee	0.62	0.80	0.64	0.52	0.33	0.77	0.92	0.86	0.95	0.88	0.93	0.94	0.33	0.42	0.13	0.95	0.09	0.96
left knee	0.46	0.84	0.59	0.66	0.61	0.63	0.94	0.87	0.94	0.91	0.97	0.97	0.43	0.31	0.51	0.93	0.10	0.98
right ankle	0.39	0.34	0.27	0.30	0.24	0.44	0.22	0.87	0.90	0.63	0.94	0.94	0.18	0.25	0.28	0.18	0.26	0.37
left ankle	0.45	0.16	0.24	0.25	0.17	0.23	0.46	0.92	0.90	0.55	0.98	0.97	0.06	0.08	0.16	0.36	0.44	0.41
right foot	0.97	1.00	1.00	0.98	0.99	0.99	0.91	0.98	0.95	0.93	0.99	0.96	0.90	0.95	0.96	0.75	0.97	0.92
left foot	0.96	1.00	1.00	0.99	0.99	0.99	0.79	0.97	0.97	0.91	0.98	0.99	0.74	0.95	0.97	0.90	0.98	0.97

Table 7: Average Cross-Correlation Coefficients of Joint Angles measured across the same trials used in Table 6 and grouped by movement.

	SIT TO STAND			TIMED UP AND GO			ALTERNATING BARBELL LUNGES			OVERHEAD SQUATS			MARCHING IN PLACE			TIME TO STABILIZATION		
JOINT ANGLES	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ
arm flexion r	0.50	0.56	0.50	0.13	0.26	0.19	0.41	0.41	0.87	0.41	0.24	0.58	0.32	0.62	0.40	0.30	0.46	0.61
arm flexion l	0.86	0.44	0.44	0.19	0.65	0.15	0.67	0.49	0.72	0.58	0.43	0.26	0.56	0.70	0.45	0.47	0.48	0.33
arm adduction r	0.62	0.61	0.50	0.22	0.68	0.21	0.93	0.98	0.93	0.75	0.81	0.86	0.65	0.95	0.65	0.47	0.48	0.58
arm adduction l	0.44	0.61	0.60	0.18	0.70	0.24	0.70	0.74	0.85	0.69	0.70	0.89	0.81	0.92	0.87	0.46	0.58	0.61
elbow flexion r	0.64	0.67	0.49	0.82	0.51	0.57	0.82	0.46	0.43	0.83	0.55	0.41	0.56	0.41	0.36	0.90	0.38	0.46
elbow flexion l	0.63	0.65	0.36	0.72	0.23	0.36	0.69	0.32	0.24	0.69	0.36	0.41	0.55	0.37	0.53	0.76	0.55	0.45
hip flexion r	0.98	0.98	1.00	0.91	0.90	0.93	0.62	0.64	1.00	0.94	0.95	1.00	0.92	0.92	1.00	0.82	0.80	0.99
hip flexion l	0.98	0.98	1.00	0.89	0.90	0.94	0.66	0.65	0.99	0.92	0.94	0.99	0.93	0.93	1.00	0.87	0.90	0.97
hip adduction r	0.69	0.42	0.57	0.27	0.35	0.40	0.20	0.27	0.61	0.45	0.13	0.22	0.40	0.54	0.44	0.28	0.54	0.54
hip adduction l	0.40	0.56	0.80	0.34	0.43	0.50	0.16	0.24	0.73	0.35	0.36	0.86	0.51	0.47	0.53	0.39	0.31	0.27
knee flexion r	0.96	0.96	1.00	0.47	0.47	1.00	0.90	0.93	0.96	0.75	0.76	1.00	0.84	0.85	1.00	0.85	0.86	0.99
knee flexion l	0.96	0.96	1.00	0.50	0.54	0.94	0.92	0.93	1.00	0.74	0.74	1.00	0.79	0.80	0.99	0.86	0.92	0.94
knee adduction r	0.87	0.53	0.58	0.56	0.41	0.63	0.43	0.27	0.58	0.77	0.22	0.17	0.64	0.32	0.62	0.50	0.39	0.65
knee adduction l	0.25	0.59	0.25	0.11	0.36	0.31	0.27	0.36	0.53	0.20	0.36	0.39	0.55	0.13	0.30	0.32	0.36	0.20
lumbar extension	0.33	0.56	0.66	0.19	0.11	0.75	0.35	0.21	0.24	0.69	0.65	0.58	0.25	0.15	0.16	0.28	0.46	0.53

	SHOULDER AB/ADDUCTION			SHOULDER FLEXION/ EXTENSION			HIP AB/ADDUCTION			COMBINED HIP/ KNEE FLEXION/ EXTENSION			COMBINED ARM AB/ADDUCTION			SAGITTAL/FRONTAL TRUNK LEANS		
JOINT ANGLES	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ
arm flexion r	0.22	0.30	0.83	0.96	0.90	0.90	0.60	0.81	0.57	0.45	0.53	0.42	0.11	0.23	0.31	0.40	0.49	0.25
arm flexion l	0.17	0.23	0.76	0.91	0.75	0.82	0.33	0.80	0.57	0.20	0.44	0.29	0.11	0.08	0.40	0.05	0.23	0.21
arm adduction r	0.96	0.97	0.96	0.27	0.35	0.98	0.98	0.98	0.99	0.95	0.96	0.97	0.13	0.35	0.62	0.78	0.82	0.79
arm adduction l	0.98	0.89	0.89	0.38	0.43	0.98	0.95	0.97	0.98	0.88	0.97	0.94	0.56	0.90	0.62	0.78	0.87	0.78
elbow flexion r	0.28	0.14	0.09	0.35	0.12	0.22	0.72	0.71	0.74	0.68	0.57	0.52	0.74	0.18	0.23	0.97	0.57	0.57
elbow flexion l	0.21	0.13	0.19	0.51	0.10	0.42	0.79	0.65	0.55	0.55	0.33	0.29	0.69	0.59	0.24	0.84	0.24	0.22
hip flexion r	0.26	0.36	0.98	0.24	0.22	0.96	0.91	0.91	1.00	0.85	0.76	0.97	0.36	0.36	0.98	0.71	0.74	0.98
hip flexion l	0.68	0.67	0.96	0.20	0.39	0.86	0.95	0.95	1.00	0.45	0.83	0.78	0.31	0.40	0.94	0.55	0.86	0.66
hip adduction r	0.13	0.14	0.94	0.03	0.06	0.91	0.68	0.49	0.68	0.17	0.23	0.88	0.25	0.26	0.99	0.09	0.17	0.96
hip adduction l	0.15	0.13	0.60	0.13	0.28	0.73	0.59	0.68	0.78	0.59	0.29	0.85	0.18	0.22	0.73	0.55	0.24	0.32
knee flexion r	0.48	0.46	0.94	0.07	0.08	0.91	0.87	0.88	1.00	0.72	0.83	0.96	0.21	0.23	0.99	0.79	0.89	0.95
knee flexion l	0.52	0.40	0.66	0.15	0.38	0.40	0.90	0.88	1.00	0.84	0.86	0.94	0.36	0.25	0.74	0.72	0.86	0.88
knee adduction r	0.59	0.28	0.69	0.28	0.35	0.97	0.37	0.48	0.64	0.84	0.83	1.00	0.17	0.25	0.91	0.87	0.88	0.99
knee adduction l	0.17	0.21	0.55	0.22	0.26	0.77	0.13	0.47	0.29	0.24	0.49	0.90	0.34	0.28	0.74	0.17	0.92	0.17
lumbar extension	0.46	0.79	0.42	0.22	0.65	0.15	0.40	0.40	0.27	0.37	0.77	0.51	0.75	0.39	0.25	0.26	0.97	0.30

Table 8: Average Errors in Kinect-based MOCAP Joint Center Displacement estimation across two separate trials from four different subjects (each subject repeated the tests twice) and grouped by movement types

	SIT TO STAND			TIMED UP AND GO			ALTERNATING BARBELL LUNGES			OVERHEAD SQUATS			MARCHING IN PLACE			TIME TO STABILIZATION		
JOINT DISP	AP	VT	ML	AP	VT	ML	AP	VT	ML	AP	VT	ML	AP	VT	ML	AP	VT	ML
head	4.8	4.1	8.3	7.2	4.5	8.5	8.4	8.5	1.9	3.2	4.2	1.6	3.3	2.2	3.6	3.5	3.2	6.7
spine top	7.7	3.4	1.3	5.8	3.8	2.8	7.8	3.4	2.0	5.6	7.4	3.7	1.7	0.8	1.7	3.2	1.4	2.0
right shoulder	2.3	2.3	0.8	11.2	2.2	2.6	10.3	3.0	3.4	2.8	4.4	1.1	1.5	4.3	0.8	2.7	2.5	1.1
left shoulder	3.9	3.8	8.3	8.7	5.0	10.6	7.7	8.0	2.7	3.0	4.1	0.9	3.0	2.2	4.2	3.3	3.2	9.5
right elbow	7.1	2.6	1.3	5.3	4.2	3.2	7.4	4.5	2.1	5.7	7.8	3.7	1.5	0.9	1.6	3.5	1.1	2.1
left elbow	1.9	2.4	0.4	11.8	2.4	3.3	10.8	3.1	2.0	2.1	4.7	1.0	1.1	4.1	0.8	8.8	12.5	4.0
right wrist	17.8	8.5	0.8	23.9	6.5	3.7	8.4	6.5	2.4	8.9	9.9	1.2	1.6	0.7	1.5	18.0	1.3	2.5
left wrist	2.8	5.3	0.6	6.1	3.9	2.0	8.3	2.5	1.0	3.0	4.2	0.7	0.6	0.4	1.1	3.2	2.8	2.4
right hand	2.7	5.9	0.7	6.7	4.8	2.4	5.3	2.6	1.1	2.7	4.2	0.9	0.9	0.5	1.2	2.8	2.8	2.1
left hand	2.5	3.7	1.2	7.7	3.7	4.0	10.4	4.6	1.1	3.5	7.2	4.3	1.8	1.3	1.0	3.4	1.8	2.3
spine mid	2.5	4.9	1.5	8.4	4.4	5.4	9.9	2.9	1.5	3.9	3.8	1.3	2.4	1.1	0.9	4.5	2.1	2.2
spine base	5.2	2.4	2.7	6.5	4.3	8.1	10.4	12.0	2.2	8.9	6.8	2.3	4.9	2.0	3.6	3.1	2.3	2.2
right hip	3.4	3.0	5.7	7.3	5.2	8.6	11.4	11.8	1.7	11.3	4.8	2.8	4.6	3.5	3.3	2.1	2.8	5.3
left hip	3.7	16.2	0.5	22.1	9.6	3.5	10.5	6.5	2.2	2.4	16.5	0.6	0.8	0.2	1.8	25.0	3.6	4.2
right knee	3.2	2.8	0.6	7.3	2.7	2.6	10.2	4.5	3.1	3.6	4.6	1.7	2.5	2.4	1.0	2.8	5.2	1.3
left knee	3.8	2.9	0.6	7.4	2.8	3.0	12.0	5.3	1.5	3.6	5.4	2.1	2.4	2.3	0.8	4.9	3.6	2.1
right ankle	2.4	3.7	1.0	15.2	3.5	3.5	12.8	3.9	3.9	2.7	3.7	1.7	2.1	3.3	1.6	4.5	2.8	2.4
left ankle	2.2	3.5	0.6	16.0	2.3	4.2	12.7	3.3	2.9	2.9	4.4	1.3	1.9	3.0	1.5	16.7	8.3	5.7
right foot	3.1	4.5	8.9	8.0	6.2	8.9	8.1	6.1	2.2	2.7	3.2	2.6	2.6	3.0	2.6	3.8	3.5	7.2
left foot	3.0	4.3	6.8	9.8	6.3	10.8	7.0	5.1	2.5	2.9	3.0	1.7	2.4	2.8	2.4	3.0	4.0	9.6

	SHOULDER AB/ADDUCTION			SHOULDER FLEXION/EXTENSION			HIP AB/ADDUCTION			COMBINED HIP/KNEE FLEXION/EXTENSION			COMBINED ARM AB/ADDUCTION			SAGITTAL/FRONTAL TRUNK LEANS		
JOINT DISP	AP	VT	ML	AP	VT	ML	AP	VT	ML	AP	VT	ML	AP	VT	ML	AP	VT	ML
head	1.6	3.2	3.3	5.6	10.5	2.6	1.5	2.2	6.5	1.7	1.8	7.1	1.5	12.6	6.4	3.9	3.0	10.5
spine top	0.8	1.4	0.3	0.7	0.7	1.2	0.7	1.6	2.0	1.0	1.7	2.1	1.3	0.8	0.6	1.9	2.7	1.3
right shoulder	0.5	1.4	0.2	0.3	1.1	0.1	2.2	5.7	0.7	1.1	5.3	6.2	0.2	1.0	0.1	0.6	1.4	0.4
left shoulder	1.6	2.8	2.1	3.9	5.8	2.9	1.0	3.5	5.4	1.6	1.9	4.7	2.0	12.9	5.0	2.9	2.0	7.6
right elbow	0.8	1.8	0.3	0.7	0.9	1.2	0.8	1.1	1.7	1.1	1.7	1.8	1.2	0.9	0.6	1.8	2.6	1.4
left elbow	0.5	1.5	0.1	0.2	1.0	0.1	2.3	4.0	0.7	1.1	2.3	3.8	0.3	0.7	0.2	0.5	1.7	0.3
right wrist	1.2	3.5	0.4	0.8	1.3	0.5	0.8	1.5	2.6	2.0	1.2	1.7	1.7	1.2	0.2	2.5	2.4	4.4
left wrist	1.2	0.5	0.3	0.5	0.6	0.6	0.5	0.4	2.5	2.7	0.8	2.5	0.4	0.3	0.4	1.5	3.9	1.3
right hand	0.8	2.1	0.4	0.7	0.7	0.5	1.0	0.6	2.2	1.0	1.4	1.6	0.8	0.7	0.2	0.9	3.5	1.5
left hand	0.8	1.5	0.6	1.3	2.1	0.9	0.9	1.4	2.9	1.7	1.2	3.2	2.7	1.3	0.6	1.8	3.9	1.1
spine mid	1.6	2.3	0.5	1.1	1.1	0.7	1.4	1.3	2.5	1.1	1.5	2.3	2.6	1.2	0.4	1.8	3.7	1.0
spine base	2.9	2.9	2.1	4.7	3.7	2.0	1.6	2.2	3.0	2.0	2.9	2.5	2.2	6.8	3.6	4.4	5.3	1.4
right hip	1.7	2.1	1.5	2.0	4.8	1.1	1.3	3.6	1.9	2.1	2.6	2.1	2.9	7.2	2.9	2.0	5.0	2.2
left hip	1.0	0.4	0.5	1.0	0.2	0.4	2.2	0.5	4.3	1.7	0.6	8.4	0.5	0.2	0.3	3.7	5.0	6.4
right knee	1.1	2.0	0.4	1.5	3.3	0.3	3.8	3.8	1.0	1.6	2.8	2.1	0.8	0.9	0.2	1.5	3.3	0.7
left knee	1.1	1.7	0.3	0.6	1.2	0.4	2.9	3.6	1.1	1.4	1.9	1.7	0.7	0.7	0.2	1.1	2.7	0.5
right ankle	1.2	2.0	0.5	1.1	1.7	0.5	4.1	5.7	1.0	1.9	5.6	6.6	3.0	3.4	0.2	1.9	2.4	0.5
left ankle	0.8	1.1	0.3	1.0	1.2	0.2	4.6	2.7	1.0	1.9	2.8	4.2	0.9	1.5	0.1	1.7	1.5	0.6
right foot	2.0	2.6	3.2	6.7	12.2	3.5	1.7	2.8	7.5	1.4	2.0	7.5	1.4	13.7	7.9	4.0	4.7	11.0
left foot	1.4	2.9	2.2	4.7	6.1	2.3	1.6	4.1	6.7	1.7	2.7	5.6	2.0	13.8	5.2	2.5	3.4	8.0

Table 9: Average Errors in Joint angles measured across the same trials as Table 8 and grouped by movement.

	SIT TO STAND			TIMED UP AND GO			ALTERNATING BARBELL LUNGES			OVERHEAD SQUATS			MARCHING IN PLACE			TIME TO STABILIZATION		
JOINT ANGLES	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ
arm flexion r	97	52	92	52	41	72	171	152	37	164	102	77	17	20	22	89	10	93
arm flexion l	88	12	77	66	25	58	140	184	91	97	126	83	38	17	30	68	12	61
arm adduction r	85	37	53	33	13	35	89	62	37	98	65	52	10	7	8	42	10	47
arm adduction l	52	6	50	37	8	40	141	108	34	81	61	38	9	6	7	51	6	49
elbow flexion r	37	54	32	31	43	17	61	94	54	31	50	32	16	16	9	37	52	18
elbow flexion l	33	70	37	34	54	24	67	90	71	32	24	37	19	22	10	33	65	34
hip flexion r	4	4	1	7	7	3	33	32	1	9	10	2	13	12	1	27	32	5
hip flexion l	9	8	3	11	11	4	28	34	9	13	12	4	18	17	3	13	8	5
hip adduction r	4	12	8	5	11	7	6	9	5	6	14	10	4	5	2	5	17	14
hip adduction l	5	15	16	7	10	14	8	9	12	9	21	18	6	4	8	5	5	5
knee flexion r	12	13	3	37	38	3	36	21	17	26	26	4	14	14	2	8	7	2
knee flexion l	16	14	5	28	29	6	18	18	9	28	23	9	16	14	4	9	9	3
knee adduction r	7	16	22	26	31	18	11	26	31	8	16	21	9	15	13	7	7	12
knee adduction l	25	13	29	32	32	22	21	18	25	19	14	28	22	13	13	22	5	22
lumbar extension	22	15	14	113	109	11	135	11	138	31	28	20	19	18	13	15	10	11

	SHOULDER AB/ADDUCTION			SHOULDER FLEXION/ EXTENSION			HIP AB/ADDUCTION			COMBINED HIP/KNEE FLEXION/ EXTENSION			COMBINED ARM AB/ADDUCTION			SAGITTAL/ FRONTAL TRUNK LEANS		
JOINT ANGLES	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ
arm flexion r	32	50	30	14	16	22	20	16	30	42	16	49	127	97	52	109	81	56
arm flexion l	29	53	70	46	15	50	34	16	35	30	19	37	51	48	53	39	28	42
arm adduction r	10	10	7	18	19	8	13	8	11	21	10	14	82	33	52	71	60	29
arm adduction l	9	8	6	17	17	7	16	9	11	27	8	19	32	11	24	32	20	31
elbow flexion r	8	11	15	9	10	11	14	20	12	22	28	14	28	70	59	37	48	29
elbow flexion l	8	8	12	7	8	7	17	18	12	23	33	17	26	54	49	33	55	33
hip flexion r	10	11	1	11	12	1	14	15	1	11	12	1	9	10	1	15	16	13
hip flexion l	11	10	1	12	11	1	17	16	2	15	11	5	9	9	2	16	10	10
hip adduction r	5	5	0	5	5	1	4	4	2	5	5	1	5	5	0	6	4	4
hip adduction l	4	1	5	4	1	4	6	3	8	6	4	7	4	3	6	9	5	11
knee flexion r	22	22	1	23	24	2	15	16	2	14	13	2	20	20	1	26	25	9
knee flexion l	21	19	2	23	21	3	19	16	3	16	11	6	21	19	4	24	23	14
knee adduction r	14	6	19	13	5	17	11	5	15	16	7	15	14	6	16	14	10	19
knee adduction l	21	2	20	21	3	19	18	3	16	18	6	15	18	3	17	25	10	24
lumbar extension	13	6	7	18	7	10	10	7	8	14	4	14	23	6	20	44	19	37

Table 10: Normalized summary metric of accuracy in evaluating joint displacement accuracy in a Kinect-based MOCAP in comparison with a gold standard 3D Qualisys system.

	SIT TO STAND			TIMED UP AND GO			ALTERNATING BARBELL LUNGES			OVERHEAD SQUATS			MARCHING IN PLACE			TIME TO STABILIZATION		
JOINT DISP	AP	VT	ML	AP	VT	ML	AP	VT	ML	AP	VT	ML	AP	VT	ML	AP	VT	ML
head	1.0	4.1	0.2	5.7	2.5	0.9	2.7	1.6	0.6	0.6	4.3	0.2	0.2	0.1	0.5	6.3	1.0	1.1
spine top	0.8	1.3	0.2	1.6	1.0	0.5	2.2	0.6	0.3	0.9	1.2	0.2	0.2	0.2	0.3	0.8	0.7	0.7
right shoulder	0.7	1.3	0.7	2.1	1.1	1.7	2.8	0.7	0.4	1.4	1.0	0.6	0.7	0.4	0.2	1.2	0.5	0.7
left shoulder	0.7	0.9	0.9	2.0	0.9	1.7	2.8	1.2	0.3	1.7	2.0	1.9	0.6	0.5	0.3	0.9	0.5	0.6
right elbow	0.9	0.8	1.9	1.9	1.3	2.7	3.0	3.0	0.5	4.0	1.2	1.8	1.2	0.9	0.9	0.5	0.7	1.4
left elbow	1.4	0.6	1.2	1.7	1.1	3.0	2.7	3.1	0.6	2.9	1.8	1.2	1.2	0.5	0.9	0.8	0.6	0.6
right wrist	1.0	1.0	2.2	2.2	1.3	3.3	2.0	2.0	0.7	0.8	1.0	0.3	0.8	0.6	1.1	0.8	0.8	2.4
left wrist	1.2	1.0	2.3	1.8	1.1	2.8	2.1	2.2	0.5	0.8	1.1	0.5	0.9	0.6	0.9	0.9	0.8	1.8
right hand	0.8	1.1	1.8	2.5	1.6	3.3	1.8	1.3	0.7	0.7	0.7	0.5	0.6	0.7	0.6	0.8	1.0	2.4
left hand	0.8	1.1	2.4	2.0	1.6	3.0	2.1	1.6	0.6	0.7	0.8	0.8	0.7	0.8	0.7	1.0	0.9	1.9
spine mid	0.7	1.5	0.2	1.7	1.2	0.7	1.4	0.7	0.3	0.8	1.2	0.3	0.3	0.2	0.3	0.7	0.8	0.6
spine base	9.4	2.2	0.5	6.7	1.7	1.2	2.2	1.6	0.7	2.8	2.9	0.8	0.7	0.7	0.5	5.1	0.4	1.0
right hip	1.8	0.6	0.9	1.3	1.1	0.9	1.9	1.2	0.6	2.1	2.2	1.7	0.5	0.6	0.4	1.0	0.3	0.7
left hip	2.0	0.9	0.9	1.5	1.0	0.8	2.0	0.9	0.6	1.8	2.2	1.9	0.7	0.3	0.5	0.9	0.4	0.7
right knee	1.0	1.2	0.2	1.9	1.9	0.8	3.1	1.5	0.4	1.0	1.6	0.6	0.6	0.6	0.2	1.3	1.0	0.6
left knee	0.8	1.1	0.2	1.9	2.9	0.8	2.6	1.3	0.9	1.0	1.4	0.5	0.6	0.6	0.3	0.8	1.6	0.4
right ankle	0.7	1.5	0.2	3.1	2.0	0.9	3.4	5.6	0.6	0.8	1.9	0.5	0.3	1.1	0.2	2.7	3.6	1.3
left ankle	1.0	1.6	0.3	3.0	3.3	0.8	3.1	4.5	1.3	1.0	2.0	1.1	0.4	1.2	0.2	0.8	0.9	0.3
right foot	1.4	1.7	0.3	4.3	9.2	1.3	4.3	9.5	1.0	2.3	1.8	1.4	0.6	0.9	0.5	5.8	2.8	2.0
left foot	1.1	2.1	0.5	4.2	9.3	1.1	4.7	5.6	1.7	1.6	1.7	1.2	0.7	1.0	0.6	1.3	1.3	0.8
Average per axis	1.5	1.4	0.9	2.6	2.4	1.6	2.6	2.5	0.7	1.5	1.7	0.9	0.6	0.6	0.5	1.7	1.0	1.1
Average	1.2			2.2			1.9			1.4			0.6			1.3		

	SHOULDER AB/ADDUCTION			SHOULDER FLEXION/EXTENSION			HIP AB/ADDUCTION			COMBINED HIP / KNEE FLEXION/EXTENSION			COMBINED ARM AB/ADDUCTION			SAGITTAL / FRONTAL TRUNK LEANS		
JOINT DISP	AP	VT	ML	AP	VT	ML	AP	VT	ML	AP	VT	ML	AP	VT	ML	AP	VT	ML
head	0.3	0.2	0.1	0.3	0.1	0.1	0.6	0.3	1.1	0.4	0.2	2.1	0.1	0.1	0.1	0.9	1.4	1.6
spine top	0.3	0.2	0.1	0.1	0.4	0.2	0.1	0.2	0.6	0.7	0.6	0.6	0.1	0.1	0.1	0.4	1.8	0.3
right shoulder	1.6	0.6	0.6	0.5	0.3	0.3	0.8	0.6	0.6	0.3	0.4	0.6	2.5	0.6	0.2	0.5	1.2	0.2
left shoulder	0.3	0.4	0.2	0.5	0.6	0.3	0.3	0.4	0.7	0.4	0.3	0.8	3.0	0.9	0.8	0.5	1.1	0.3
right elbow	0.6	0.5	0.4	0.5	1.2	0.3	0.5	0.9	0.5	0.6	0.7	0.5	1.9	2.1	0.8	0.5	1.3	0.6
left elbow	1.1	0.7	0.5	1.3	1.0	0.5	0.6	0.6	0.8	0.5	0.8	0.6	6.6	1.9	1.2	1.4	1.3	0.4
right wrist	0.5	0.7	0.5	1.0	1.5	0.7	0.3	0.9	1.4	0.5	0.5	1.2	0.7	3.5	1.3	0.9	0.5	2.0
left wrist	0.4	0.8	0.8	1.4	2.7	0.6	0.4	0.6	1.7	0.5	0.4	1.9	0.5	3.4	1.7	1.3	0.8	2.8
right hand	0.4	0.7	0.5	1.2	1.5	0.6	0.5	1.1	1.7	0.5	0.7	1.4	0.7	3.7	1.3	0.7	0.9	2.1
left hand	0.5	0.6	0.8	1.7	3.1	0.9	0.5	0.7	2.0	0.4	0.5	2.0	0.4	3.7	2.1	1.4	1.2	3.0
spine mid	0.6	1.0	0.2	0.2	0.7	0.3	0.4	0.5	0.6	0.3	0.7	0.4	0.2	0.7	0.1	0.4	7.3	1.4
spine base	0.5	4.5	0.4	1.0	1.0	0.3	0.4	2.7	0.7	1.2	0.6	0.4	1.5	0.7	0.1	0.7	0.8	1.6
right hip	1.6	0.5	0.2	0.3	0.3	2.0	0.4	0.3	0.4	0.3	0.5	0.5	0.5	0.5	0.5	0.5	3.7	0.4
left hip	1.4	0.4	0.1	0.5	0.2	3.7	0.3	0.6	0.5	0.3	0.5	0.5	0.5	0.4	0.5	0.5	10.4	0.4
right knee	0.6	0.5	0.1	0.2	0.5	0.2	0.8	1.0	0.3	0.4	0.5	0.4	0.4	0.8	0.1	0.3	8.0	0.1
left knee	0.5	0.6	0.2	0.7	2.6	0.1	1.0	1.1	0.3	0.4	0.7	0.6	0.6	0.6	0.4	0.4	9.7	0.2
right ankle	0.4	0.7	0.1	0.2	1.8	0.1	0.7	1.1	0.2	0.3	0.6	1.0	0.7	1.8	0.2	0.3	1.3	0.1
left ankle	0.3	0.6	0.2	0.2	0.8	0.2	0.7	1.6	0.2	0.3	1.4	1.6	0.1	0.8	0.1	0.3	0.8	0.1
right foot	0.5	2.8	0.3	0.9	4.5	0.3	2.6	0.7	0.3	0.9	0.7	1.1	3.3	4.4	0.3	1.2	1.0	0.4
left foot	0.8	1.6	0.4	1.3	1.6	0.3	4.8	1.6	0.3	0.8	1.5	1.8	5.7	3.8	0.1	4.1	2.4	0.4
Average per axis	0.7	0.9	0.3	0.7	1.3	0.6	0.8	0.9	0.7	0.5	0.6	1.0	1.5	1.7	0.6	0.9	2.8	0.9
Average	0.6			0.9			0.8			0.7			1.3			1.5		

Table 11: Normalized summary metric of accuracy in evaluating joint angle accuracy in a Kinect-based MOCAP in comparison with a gold standard 3D Qualisys system.

	SIT TO STAND			TIMED UP AND GO			ALTERNATING BARBELL LUNGES			OVERHEAD SQUATS			MARCHING IN PLACE			TIME TO STABILIZATION		
JOINT ANGLES	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ
arm flexion r	9.9	4.8	9.0	17.9	6.8	14.1	20.1	17.9	2.3	16.3	16.4	7.4	3.2	1.8	3.3	13.7	1.5	7.1
arm flexion l	5.3	1.9	9.1	18.8	1.7	19.8	10.5	18.6	6.7	8.7	14.7	19.6	3.7	1.3	3.8	6.9	1.6	10.1
arm adduction r	6.9	3.0	5.8	6.7	1.0	7.0	4.8	3.2	2.0	5.6	3.2	3.7	1.0	0.4	0.7	4.3	1.3	3.8
arm adduction l	5.9	0.6	4.4	9.1	0.8	7.7	9.7	7.1	2.1	6.1	4.0	2.9	0.8	0.3	0.6	5.4	0.7	3.9
elbow flexion r	3.1	4.2	3.8	1.4	3.0	1.4	3.5	11.8	6.9	1.7	3.2	3.2	1.4	2.3	2.0	2.0	6.7	2.1
elbow flexion l	2.9	5.4	5.4	1.8	8.6	3.0	4.6	15.2	13.4	1.8	2.2	3.3	1.9	3.3	1.2	2.2	6.0	3.9
hip flexion r	0.6	0.6	0.1	2.4	2.6	0.2	2.6	1.6	1.0	1.4	1.4	0.2	0.7	0.7	0.1	1.1	1.2	0.2
hip flexion l	0.7	0.7	0.3	2.2	2.0	0.5	1.3	1.4	0.4	1.5	1.4	0.4	1.0	0.8	0.2	0.7	0.5	0.3
hip adduction r	0.4	2.5	1.9	1.6	3.4	1.6	1.4	5.8	2.8	0.7	9.3	7.6	0.5	1.5	0.6	1.0	1.4	1.1
hip adduction l	3.0	1.8	4.2	11.3	3.0	2.6	3.6	2.8	2.7	3.8	4.1	3.1	1.4	2.3	1.5	2.2	0.8	3.0
knee flexion r	0.6	0.6	0.2	2.4	2.6	0.2	2.1	2.0	0.1	1.4	1.4	0.2	0.8	0.8	0.1	1.1	1.2	0.2
knee flexion l	0.7	0.7	0.2	2.2	2.0	0.4	1.4	1.8	0.5	1.5	1.4	0.4	1.0	0.9	0.1	0.7	0.5	0.2
knee adduction r	0.4	2.3	2.0	1.4	2.7	1.9	1.6	1.7	0.9	0.6	7.3	7.9	0.6	1.2	0.8	0.7	1.2	1.2
knee adduction l	3.2	1.8	5.2	4.9	2.8	3.9	3.0	1.8	1.1	3.0	3.6	3.7	1.1	3.1	1.6	2.0	1.0	4.1
lumbar extension	3.9	1.6	1.1	23.0	35.6	0.7	18.4	2.5	26.8	2.7	2.1	1.7	3.8	5.7	3.9	2.7	0.9	1.1
Average per axis	3.2	2.2	3.5	7.1	5.2	4.3	5.9	6.4	4.6	3.8	5.0	4.3	1.5	1.8	1.4	3.1	1.8	2.8
Average	2.9			5.6			5.6			4.4			1.5			2.6		

	SHOULDER AB/ADDUCTION			SHOULDER FLEXION/ EXTENSION			HIP AB/ADDUCTION			COMBINED HIP / KNEE FLEXION/ EXTENSION			COMBINED ARM AB/ADDUCTION			SAGITTAL / FRONTAL TRUNK LEANS		
JOINT ANGLES	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ	KQ vs QS	K3D vs QS	K3D vs KQ
arm flexion r	12.2	13.7	2.3	1.0	1.1	1.5	3.1	1.0	4.0	4.6	2.1	6.2	46.9	27.0	5.7	8.8	5.1	15.3
arm flexion l	11.9	21.3	8.2	3.6	1.4	4.6	6.0	1.5	3.9	8.8	3.3	8.9	29.2	39.0	8.4	57.8	6.7	14.5
arm adduction r	0.8	0.7	0.5	6.4	4.5	0.4	1.0	0.5	0.6	1.1	0.5	0.7	22.9	6.4	1.9	1.9	1.0	1.5
arm adduction l	0.7	0.7	0.7	3.5	3.1	0.4	1.3	0.5	0.9	1.5	0.5	1.0	2.9	0.8	1.7	2.5	1.0	2.2
elbow flexion r	1.6	14.6	85.0	1.9	7.8	3.6	1.6	2.5	1.5	1.6	2.8	1.8	2.1	18.5	10.6	1.9	4.3	2.8
elbow flexion l	3.3	3.4	3.2	0.8	5.5	1.0	1.4	2.2	1.6	2.0	4.9	3.5	2.0	2.8	9.8	2.4	12.1	6.7
hip flexion r	1.7	1.7	0.1	14.4	7.3	0.1	0.9	0.9	0.1	0.9	0.8	0.1	2.7	2.6	0.1	1.1	1.1	0.2
hip flexion l	1.4	1.7	0.2	6.5	2.6	0.4	0.9	0.7	0.2	1.5	0.7	0.4	1.6	1.8	0.2	1.5	1.0	0.5
hip adduction r	3.6	2.4	0.5	4.6	3.2	0.4	0.9	0.6	0.5	1.2	0.9	0.4	2.6	0.9	0.4	1.4	0.8	0.5
hip adduction l	11.7	0.4	1.2	3.8	0.4	0.8	4.2	0.2	1.8	2.4	0.5	0.8	2.1	0.4	0.9	3.7	0.7	9.2
knee flexion r	3.5	2.7	0.0	8.5	11.3	0.1	1.0	1.0	0.1	0.8	0.8	0.1	4.6	4.2	0.0	1.2	1.2	0.4
knee flexion l	1.8	1.8	0.1	5.2	2.1	0.2	0.8	0.7	0.1	1.4	0.7	0.3	4.7	3.7	0.1	1.4	1.0	0.6
knee adduction r	1.0	0.5	0.7	7.3	2.2	0.5	0.8	0.5	1.0	1.1	0.5	0.5	2.0	0.7	0.5	3.3	1.1	0.4
knee adduction l	2.4	0.7	1.1	3.0	0.5	0.8	3.6	0.2	1.5	3.3	0.8	0.8	2.6	0.4	0.8	3.0	0.6	3.3
lumbar extension	1.6	0.5	1.0	4.6	0.7	4.1	1.2	0.8	1.4	2.6	0.2	1.4	2.3	1.0	6.6	6.4	0.9	4.5
Average per axis	4.0	4.5	7.0	5.0	3.6	1.3	1.9	0.9	1.3	2.3	1.3	1.8	8.7	7.3	3.2	6.6	2.6	4.2
Average	5.1			3.3			1.4			1.8			6.4			4.4		

Effects of Concussion History on Center of Mass Motion During Modified Balance Error Scoring System (BESS) Testing in Women

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Introduction

Concussion and mTBI continues to account for a substantial proportion of the military healthcare burden.[1] Concussion is commonly associated with balance deficits, which are likely related to impaired processing of sensory information.[2] These deficits, in turn, have the potential to impact activities of daily life, job performance, and risk of re-injury as balance is considered a foundational component of nearly all motor behaviors. Impaired balance may present clinically as increased postural sway, particularly in the absence of posture-relevant sensory information.

It has been reported in athletics and in the armed services that women are concussed at comparable rates,[3] experience more severe concussion-related symptoms and limitations, and have longer recovery times when compared with men.[4] Despite these discrepancies in epidemiology, data concerning female-specific neuromotor effects of concussion/mTBI are lacking.[5,6] This poses unnecessary additional risk to brain-injured women as clinical assessment and decision-making may disproportionately rely on knowledge that was developed through the observation of male research subjects.

Previous work has demonstrated sex differences in movement behaviors[7] as well as the relevance of these differences to injury and injury recovery. It is reasonable therefore to suspect that the postural control effects of concussion/mTBI in females are distinct and should be considered separately. The purpose of this research was to identify neuromotor deficits (specifically, balance) between service-age healthy women (CTRL) and women with a history of concussion/mTBI (mTBI). We hypothesized that that history of concussion would be associated with increased postural sway motion and velocity.

Methods

Thirty-one healthy women and 24 women with a history of concussion/mTBI were performed 3 20-second balance trials. Procedures for balance testing were based on the modified Balance Error Scoring System (BESS[8]) protocol and featured 1 trial each of Double Leg (DS), Single Leg (SS), and Tandem (TS) stance. Each testing condition required subjects to stand barefoot with eyes closed and hands-on-hips. DS was performed in bilateral stance, SS was performed standing on the non-dominant limb with a slight bend in the hip and knee of the non-standing leg, and TS was performed with feet inline heel-to-toe (non-dominant limb behind dominant limb). Participants were instructed 1) to remain as motionless as possible throughout a given trial, and 2) to return to the testing pose quickly should the testing position be lost.

Video, infrared, and depth data were acquired using a Microsoft Kinect 2.0™ at a variable frame rate (maximum 30 Hz, not under direct control of the user). These raw data are used to estimate 3D joint center time histories through an on-board classification algorithm. Joint center displacement histories were stored to a local machine running a custom C# software interface. This data was used then used offline to define segment end points, from which the 3D center of mass (COM) displacement time series was estimated using established methods.

Mean velocity (VEL) and standard deviation (SD) of displacement were used to summarize COM motion for each trial in the anteroposterior (AP) and mediolateral (ML) directions. Group performance (CTRL vs. mTBI) was then compared using one-sided Welch's independent samples t-tests for each outcome/stance combination. The *a priori* significance level was $\alpha = 0.05$.

Results

Significant group effects were observed (CTRL < mTBI) in the DS condition for all outcomes (**VEL_{ML}**: CTRL = 0.93 ± 0.72 cm/s, mTBI = 2.83 ± 2.77 cm/s, $t = -3.17_{(25.41)}$, $p < 0.01$; **VEL_{AP}**: CTRL = 1.55 ± 2.58 cm/s, mTBI = 3.21 ± 2.64 cm/s, $t = -2.07_{(40.44)}$, $p < 0.02$; **SD_{ML}**: CTRL = 0.49 ± 0.50 cm, mTBI = 1.79 ± 1.88 cm, $t = -3.18_{(25.50)}$, $p < 0.01$; **SD_{AP}**: CTRL = 0.89 ± 1.72 cm, mTBI = 1.89 ± 1.60 cm, $t = -1.97_{(39.14)}$, $p < 0.03$).

Significant group effects were observed (CTRL < mTBI) in TS condition for **VEL_{ML}** (CTRL = 2.51 ± 0.95 cm/s, mTBI = 4.55 ± 3.71 cm/s, $t = -2.38_{(21.50)}$, $p < 0.01$) and **SD_{ML}** (CTRL = 1.60 ± 0.78 cm, mTBI = 3.53 ± 3.40 cm, $t = -2.47_{(21.01)}$, $p < 0.01$).

No effects were observed in the SS condition ($p > 0.05$).

Conclusion

These data support the conclusion that, relative to healthy female controls, postural control in women with a history of concussion/mTBI is characterized by increased variability and velocity of the COM. The effects we report appear to be specific to the DS and TS conditions. The null finding in the SS condition was unexpected as, among the three, this stance is frequently associated with the poorest balance outcomes.[8] While this pattern of findings may be anomalous, it is also possible that single leg postural control is not effective in discriminating healthy controls from previously concussed individuals in this population. Previous research has demonstrated sex differences in baseline/uninjured balance outcomes wherein females were observed to have better postural control than males using similar experimental tasks.[9] This could suggest that factors related to sex contribute to the presently observed pattern of group effects (healthy vs. concussion/mTBI history), which may be unexpected owing to underrepresentation of females in prior work. If the effects we report are true, post brain-injury balance testing in women may be more appropriately limited to DS or TS conditions.

Further research is warranted to investigate sex-specific effects of concussion/mTBI on balance behaviors prospectively and in direct comparison with comparable male samples. Future work should also consider mechanisms that might account for differential baseline and post-injury behaviors between men and women, such anthropometrics and lower extremity alignment.

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The authors have no conflicts of interest to disclose.

References

1. Taylor BC, Hagel Campbell E, Nugent S, et al. Three Year Trends in Veterans Health Administration Utilization and Costs after Traumatic Brain Injury Screening among Veterans with Mild Traumatic Brain Injury. *J Neurotrauma.* 2017;34(17):2567-2574.
2. Haran FJ, Slaboda JC, King LA, Wright WG, Houlihan D, Norris JN. Sensitivity of the balance error scoring system and the sensory organization test in the combat environment. *J Neurotrauma.* 2016;33(7):705-711.
3. Laker SR. Epidemiology of Concussion and Mild Traumatic Brain Injury. *PM&R.*3(10):S354-S358.
4. Berz K, Divine J, Foss KB, Heyl R, Ford KR, Myer GD. Sex-specific differences in the severity of symptoms and recovery rate following sports-related concussion in young athletes. *Phys Sportsmed.* 2013;41(2):58-63.
5. Costello JT, Bieuzen F, Bleakley CM. Where are all the female participants in Sports and Exercise Medicine research? *Eur J Sport Sci.* 2014;14(8):847-851.
6. Dye JL, Eskridge SL, Tepe V, Clouser MC, Galarneau M. Characterization and Comparison of Combat-Related Injuries in Women During OIF and OEF. *Military Medicine.* 2016;181(suppl_1):92-98.
7. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *The American journal of sports medicine.* 2005;33(4):492-501.
8. Riemann BL, Guskiewicz KM. Effects of mild head injury on postural stability as measured through clinical balance testing. *Journal of athletic training.* 2000;35(1):19.
9. Howell DR, Hanson E, Sugimoto D, Stracciolini A, Meehan III WP. Assessment of the postural stability of female and male athletes. *Clin J Sport Med.* 2017;27(5):444-449.