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Accuracy of the Microsoft Kinect sensor for measuring movement in people with Parkinson's disease

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ABSTRACT

Background: The Microsoft Kinect sensor (Kinect) is potentially a low-cost solution for clinical and home-based assessment of movement symptoms in people with Parkinson's disease (PD). The purpose of this study was to establish the accuracy of the Kinect in measuring clinically relevant movements in people with PD.
Methods: Nine people with PD and 10 controls performed a series of movements which were measured concurrently with a Vicon three-dimensional motion analysis system (gold-standard) and the Kinect. The movements included quiet standing, multidirectional reaching and stepping and walking on the spot, and the following items from the Unified Parkinson's Disease Rating Scale: hand clasping, finger tapping, foot, leg agility, chair rising and hand pronation. Outcomes included mean timing and range of motion across movement repetitions.
Results: The Kinect measured timing of movement repetitions very accurately (low bias, 95% limits of agreement <10% of the group mean, ICCs >0.9 and Pearson's $r > 0.9$). However, the Kinect had varied success measuring spatial characteristics, ranging from excellent for gross movements such as sit-to-stand (ICC = .989) to very poor for fine movement such as hand clasping (ICC = .012). Despite this, results from the Kinect related strongly to those obtained with the Vicon system (Pearson's $r > 0.8$) for most movements.
Conclusions: The Kinect can accurately measure timing and gross spatial characteristics of clinically relevant movements but not with the same spatial accuracy for smaller movements, such as hand clasping.

1. Introduction

Parkinson's disease (PD) is a multi-system neurodegenerative disorder that impairs postural control and mobility, leading to reduced community ambulation [1] and increased risk of slips, trips and falls [2]. Accurate assessment of movement allows clinicians and researchers to monitor disease progression as well as response to intervention. Conventional three-dimensional video-based motion analysis systems allow for comprehensive kinematic and kinetic analysis of movement in PD. These systems require relatively large spaces, are expensive and require considerable expertise, limiting their use in the clinic and the home. Conversely, clinical assessment tools such as the Unified Parkinson's Disease Rating Scale (UPDRS) can be administered in daily clinical practice without any expensive equipment [3]. However, clinical assessment tools can be less comprehensive and often require subjective input. Trained professionals are needed for both conventional three-dimensional motion analysis and clinical assessment tools, requiring the patients to travel to the clinic or laboratory, or the clinician to travel to the patient's home. The time and cost of assessment often precludes frequent testing which would be useful when measuring within day fluctuation of movement symptoms (e.g. medication fluctuations).

The Microsoft Kinect is a camera-based sensor primarily used to directly control computer games through body movement. The Kinect tracks the position of the limbs and body without the need for handheld controllers or force platforms. Use of a depth sensor also allows the Kinect to capture three-dimensional movement patterns. We propose that this system has the potential for remote assessment of movement symptoms in people with PD, especially

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hypokinetic symptoms (reduced size and speed of movement). Early reports suggest the Kinect can identify pose [4–6], simple stepping movements [7] and postural control [8] in healthy adults, although some have raised concerns about the accuracy of the skeleton model estimation during unconventional body postures or when using wheelchairs or walkers [9].

There is also growing evidence for the use of exercise-based computer games (exergames) to retrain motor function in people with PD [10], although evidence of their safety and efficacy are yet to be established [11]. Exergaming as a therapeutic tool incorporates functional, purposeful and engaging exercise in a quantifiable and reliable way that also encourages high volumes of practice and potentially improved motivation and adherence [12–14]. A player's movement can be recorded whilst playing a game using the Kinect, allowing clinicians to ensure their patients perform exercises correctly.

To date, the accuracy of the Kinect to measure movement has not been established in people with PD. The aim of this project was to assess the accuracy of the Kinect to measure functional and clinically relevant movements in people with PD. To achieve this aim, we compared movement in a group of people with PD captured concurrently with a Vicon three-dimensional motion analysis system (gold standard) and a Kinect sensor. Because the accuracy of the Kinect has not been fully established in control participants, we also tested a group of healthy adults to extend previous reports of the accuracy of the Kinect system in measuring upper and lower body kinematics.

2. Methods

Nine people with mild-to-moderately severe PD were recruited through local movement disorders clinics. Inclusion criteria for people with PD were: diagnosis of idiopathic PD (by a consultant neurologist with a specialist interest in movement disorders), absence of any other neurological problem or any severe co-morbidity likely to affect gait, absence of dementia, adequate sight and hearing (with glasses or hearing aid if required), independently mobile indoors without a walking aid and no severe dyskinesias or prolonged off periods. People with PD were tested on the peak dose of their anti-Parkinson's medication. In addition, we also recruited a convenience sample of ten healthy controls. Inclusion criteria for controls were: absence of any neurological problem or any severe co-morbidity likely to affect movement, absence of dementia, adequate sight and hearing with glasses or hearing aid if required and independently mobile indoors without a walking aid. We did not attempt to match the control and PD group for age and sex, as a between group comparison was not the focus of this study.

2.1. Microsoft Kinect system

The Kinect is a motion sensor that can measure three-dimensional motion of a person. Microsoft's 'Kinect for Windows SDK', was used to provide an Application Programmer's Interface (API) to the Kinect hardware. The API was used to interface with the Kinect sensor and its skeletal tracking software, providing an estimate for the position of 20 anatomical landmarks at a frequency of 30 Hz and spatial and depth resolution of 640×480 pixels (Fig. 1A). We used default smoothing parameters (correction factor of 0.5, smoothing factor of 0.5, jitter radius 0.05 m, maximum deviation radius of 0.04 m and future prediction of 0 frames).

2.2. Vicon motion analysis system

We used a 10 MX3+ infrared camera Vicon system (Vicon Motion Systems, Oxford, United Kingdom) as a gold standard to establish the accuracy of the Kinect. The Vicon tracked reflective markers placed on participants according to the industry standard 'plug-in-gait full body" marker set (Fig. 1A). Two additional markers were placed on the fingernail of the thumb and index finger to measure hand motion. The Vicon was calibrated to measure marker position to within 2 mm accuracy at a frequency of 100 Hz. Vicon data were filtered using a 20 mm^2 Woltering filter.

2.3. Procedure

Participants performed a series of clinically functional movements whilst being concurrently monitored with the Kinect sensor and a Vicon system. Participants stood directly facing the Kinect sensor at a distance of 3 m, which is adequate to collect accurate data [15]. The Kinect sensor was positioned 1 m from the ground, with the lens perpendicular to the floor and pointing towards the participant (along the x axis of the Vicon system). A researcher stood beside the Kinect to demonstrate the movements and ensure the participant's safety. The movements included standing still, reaching forward and sideways, stepping forward and sideways and walking on the spot. We also measured the accuracy of the following motor items on the UPDRS (Section 3): hand clasping, finger tapping, foot tapping and leg agility, sit-to-stand from a chair and hand pronation. Data from the systems were screened and time-synced visually prior to data extraction. As we wanted to examine the absolute accuracy of the Kinect system, the data were neither spatially nor temporally normalised. We used the original time stamped data as we did not want to introduce noise by up-sampling the Kinect data or lose resolution of the Vicon data by down-sampling (see Fig. 1 for an example trace of Vicon and Kinect data). Ethical approval was obtained from the North East – Sunderland Research Ethics Committee and all participants signed an informed consent form prior to this study.

2.4. Data processing and analysis

The movements and associated outcome measures are described in Table 1. Given the differences between the Kinect skeleton and Vicon plug-in-gait models, we simplified the comparison of the two systems by using either range of motion of a single marker or two-dimensional sagittal and frontal plane kinematics where appropriate. The mean range of motion and timing of each repetition were used as outcomes except for sit-to-stand which was expressed as the total duration of the test in keeping with standard clinical reporting, and mean trunk flexion which was calculated over 10 s of still standing. To avoid redundancy, we analysed the right limb only for unilateral movements. The Kinect skeletal model did not allow for measurement of forearm pronation/supination directly; therefore we measured the vertical displacement of the wrist for each repetition as a proxy measure for the timing and magnitude of forearm pronation/supination.

We assessed mean bias between the two systems (Kinect–Vicon) using a series of repeated-measure two-sided *t*-tests. Pearson's *r* correlation was used to assess relative agreement between the two systems. Absolute accuracy was measured using intra-class correlation ($ICC_{2,1}$) and 95% limits of agreement. Limits of agreement were expressed both in absolute terms and as a proportion of the group mean. Bland and Altman plots were used to inspect the error scores between the two systems in respect to the mean scores [16]. Analysis for control and PD participants was conducted separately. A $p < 05$ was used to guide interpretation.

3. Results

The ten control participants (Mean (sd); Age: 27.5y (5.0); 5 females, 5 males) and nine people with PD (Age: 68.2y (8.3); 6 females, 3 males) completed the testing session without incident. People with PD were all community-dwelling and had mild-moderate symptoms (Activities-specific Balance Confidence (ABC) Scale: 87.3

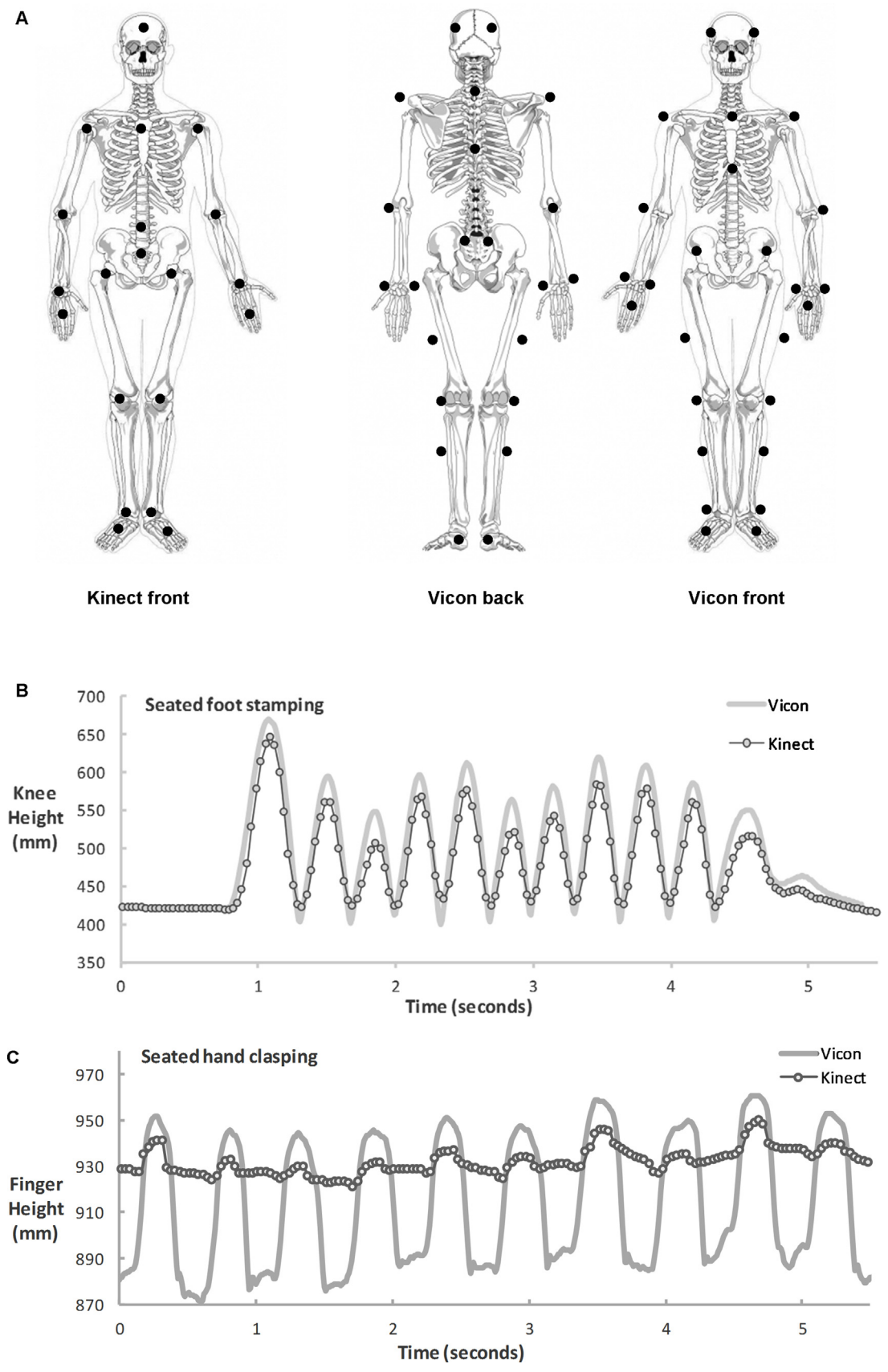

Fig. 1. Panel A illustrates the marker locations for the Kinect skeleton model and Vicon "plug-in-gait" model. Panel B shows an example trace of vertical knee displacement during the leg agility test in a person with PD. The Kinect system (black circles) tracks the Vicon system (grey line) with the same pattern but under scaled magnitude. Panel C shows an example of seated hand clasping in a person with PD, whereby the Kinect (black circles) was used to detect the timing of hand clasping but did not track the spatial scaling of the Vicon system (grey line) accurately.

Table 1
Description and measurement of different movements performed by participants.

Movement	Movement/instruction	Measurement with Vicon	Measurement with Kinect	Number of repetitions/ duration
Sit to stand	Stand up and sit down from a chair as fast and safely as possible	Vertical displacement of the head markers (mean position of left and right front markers)	Vertical displacement of the head marker	5× as quickly as possible
Standing trunk flexion	Stand as still as you can	Sagittal plane angle between the C7 and T10 markers relative to vertical	Sagittal plane angle between the shoulder centre and spine relative to vertical	10 s
Lateral trunk flexion	Lean sideways as far as is comfortable and return to standing straight	Frontal plane angle between the C7 and T10 markers relative to vertical	Frontal plane angle between the shoulder centre and spine relative to vertical	5× each side
Forward stepping	Take a large step forward and return to comfortable standing	Sagittal plane orientation of the thigh and knee markers relative to vertical	Sagittal plane angle of the hip and knee relative to vertical	5× with the right leg
Side stepping	Take a large step sideways and return to comfortable standing	Frontal plane orientation of the thigh and knee markers relative to vertical	Frontal plane angle of the hip and knee relative to vertical	5× with the right leg
Shoulder flexion	Raise your arm in front of you to eye level and lower it back to your side	Sagittal plane orientation of the shoulder and elbow markers relative to vertical	Sagittal plane orientation of the shoulder and elbow relative to vertical	5× with the right arm
Shoulder abduction	Raise your arm to the side until it is level with the ground and lower it back to your side	Frontal plane orientation of the shoulder and elbow markers relative to vertical	Frontal plane orientation of the shoulder and elbow relative to vertical	5× with the right arm
Elbow flexion	Flex your elbow as far as you can so your hand is in front of you and straighten your elbow again	Sagittal plane angle between the shoulder, elbow and wrist (mean of radial and ulnar wrist markers)	Sagittal plane angle between the shoulder, elbow and wrist	5× with the right arm
Hand clasping	With your palm facing forward, open and close your hand as far and fast as possible (whilst sitting)	Vertical displacement of the index finger marker	Vertical displacement of the hand	30 s with right hand
Pronation supination	With your arm in front of you, elbow slightly flexed and hand open, move your palm from facing up to facing down and up again as fast as possible (whilst sitting)	Vertical displacement of the medial wrist marker	Vertical displacement of the wrist	30 s with right arm
Leg agility	Raise and lower your foot on the ground as far and fast as possible (whilst sitting)	Vertical displacement of the knee marker	Vertical displacement of the knee marker	10× with the right leg
Walking on the spot	Walk on the spot at your comfortable pace	Vertical displacement of the knee marker	Vertical displacement of the knee marker	30 s

(22.5); UPDRS III (motor examination): 18.9 (7.9); Hoehn and Yahr stage I: 3, II: 5, III: 1). We were not able to obtain clean signals of hand clasping for four PD participants. In addition, the Kinect system was not able to produce usable data for toe-tapping and finger tapping movements for a majority of the participants therefore no results are presented for these two movements.

3.1. Temporal accuracy

The Kinect was able to accurately measure the timing of each of the movements (Table 2). Bland and Altman plots suggest that there was no relationship between the error of the Kinect sensor and the mean timing of movements (supplementary material 1). There was no significant bias between the two systems, apart from a tendency for the Kinect to underestimate the duration of the sit-to-stand by 0.5% and overestimate stride time for walking on the spot by 2.1% for controls, and overestimate elbow flexion duration by 1.3% for the PD group. Limits of agreement were under 10% of the group mean, indicating very good absolute agreement for all movements apart from hand clasping and pronation/supination for both groups and lateral trunk flexion for controls. Pearson's and intra-class correlations were excellent, above 0.9 for all movements.

3.2. Spatial accuracy

The magnitude of error was not related to the magnitude of the movement, apart from sit-to-stand, whereby the Kinect tended to underestimate for shorter distances and overestimate for larger distance (supplementary material 2). The Kinect significantly underestimated range of motion for lateral flexion, hip kinematics during forward stepping and side stepping, vertical knee height during leg agility movements, and overestimated arm kinematics for shoulder flexion and abduction, and elbow flexion movements (Table 3). Relative 95% limits of agreement under 10% were only found for sit-to-stand and arm abduction, with particularly poor absolute agreement for hand clasping and walking on the spot. The generally poor absolute agreement was reflected in lower ICCs. Despite the poor absolute agreement, there was a strong positive linear correlation between Kinect and Vicon measurement apart from standing trunk flexion and hand clasping. Poor Pearson's correlations and ICCs were also noted for arm pronation for people with PD but not controls.

4. Discussion

To the best of our knowledge, this is the first study to establish the accuracy of the Kinect in people with PD. We found that the Kinect was able to accurately measure timing of clinically relevant movements in people with PD and, to a lesser extent, the range of motion of those movements. These results contribute to the eventual goal of developing the Kinect as a low-cost system for monitoring PD movement symptoms in the home.

Our findings concur with those of Clark et al. [8] who showed good agreement between the Kinect and Vicon for measuring trunk and lower limb kinematics during standing balance tests in 20 healthy adults. In addition, we have been able to extend what is known about the accuracy of the Kinect system for measuring upper and lower body kinematics. A case study by Fernández-Baena et al., reported the Kinect underestimated sagittal knee and hip range of motion during a forward step in one young adult by less than 10° [7]. Similarly, we found the Kinect system underestimated hip flexion by 5° during a forward step and hip abduction by 4° during a side step, in addition to reasonably small (<10°) 95% limits of agreement.

We also investigated the accuracy of upper limb kinematics with the Kinect, because PD can have a significant effect on reaching and grasping [17]. Upper limb motion may also be a viable method of controlling exergames for people with PD who are unable to stand safely for extended periods. We found the timing of repetitive shoulder and elbow kinematics was measured very accurately by the Kinect system. Although the range of motion was overestimated by the Kinect, the relative agreement was still very good. This suggests that the Kinect measures gross upper limb

Table 2
Temporal accuracy of the Kinect system compared to the gold standard Vicon three dimensional analysis system.

Movement	Mean		Bias (Kinect–Vicon)	p	$LoA_{95\%}$	$LoA_{95\%}$ (%)	Pearson r	ICC
	Vicon	Kinect						
Controls (n = 10)								
Sit to stand (s)	8.00 (1.72)	7.96 (1.48)	−.037	.024	.085	1.1%	.999	.961
Lateral trunk flexion (s/rep)	3.80 (.79)	3.78 (.84)	−.013	.871	.491	13.0%	.955	.957
Forward stepping (s/rep)	2.84 (.40)	2.88 (.37)	.034	.196	.152	5.3%	.983	.978
Side stepping (s/rep)	2.65 (.37)	2.76 (.43)	.117	.001	.161	6.0%	.990	.940
Shoulder flexion (s/rep)	2.79 (.54)	2.80 (.53)	.117	.166	.058	2.1%	.999	.998
Shoulder abduction (s/rep)	2.87 (.61)	2.86 (.60)	−.006	.820	.159	5.5%	.991	.992
Elbow Flexion (s/rep)	2.69 (.56)	2.68 (.55)	−.003	.845	.086	3.2%	.997	.997
Hand clasping (s/rep)	.45 (.11)	.45 (.11)	.001	.843	.031	6.9%	.989	.990
Pronation supination (s/rep)	.66 (.12)	.69 (.10)	.024	.084	.077	11.4%	.950	.919
Leg agility (s/rep)	.34 (.07)	.36 (.08)	.015	.068	.041	11.7%	.962	.946
Walking on the spot (s/rep)	1.16 (.14)	1.18 (.14)	.025	.013	.053	4.5%	.983	.968
Parkinson's disease (n = 9)								
Sit to stand (s)	15.11 (5.76)	15.09 (5.67)	−.019	.657	.238	1.6%	.999	.999
Lateral trunk flexion (s/rep)	6.37 (2.64)	6.21 (2.60)	−.157	.159	.595	9.5%	.993	.992
Forward stepping (s/rep)	3.33 (.75)	3.33 (.68)	−.001	.977	.280	8.4%	.985	.982
Side stepping (s/rep)	3.08 (.77)	3.06 (.70)	−.016	.676	.214	7.0%	.994	.990
Shoulder flexion (s/rep)	3.54 (1.16)	3.53 (1.12)	−.016	.667	.102	2.9%	.999	.999
Shoulder abduction (s/rep)	3.74 (1.40)	3.77 (1.35)	.033	.346	.193	5.1%	.998	.997
Elbow Flexion (s/rep)	3.23 (1.05)	3.28 (1.06)	.043	.023	.091	2.8%	.999	.998
Hand clasping (s/rep)[a]	.55 (.17)	.54 (.14)	−.007	.582	.072	13.2%	.981	.974
Pronation supination (s/rep)	.89 (.38)	.92 (.45)	.036	.421	.177	19.6%	.984	.982
Leg agility (s/rep)	.68 (.46)	.69 (.47)	.012	.249	.058	8.5%	.998	.998
Walking on the spot (s/rep)	1.29 (.22)	1.29 (.24)	.004	.725	.069	5.3%	.990	.990

p refers to the repeated measures t-test to assess bias between the two systems.
[a] We were unable to extract data from 4 people with PD for hand clasping because of a noisy Kinect signal; s/rep – seconds per repetition.

movement accurately enough to control games which generally do not require the same level of accuracy demanded by clinical and research applications. The Kinect may also provide quality feedback of gross upper limb performance for clinical exergaming interventions.

The UPDRS III (motor examination) is a well recognised and validated tool to measure the severity of motor disability in people with PD [3]. One of our eventual goals is to instrument the UPDRS III using the Kinect, thus providing clinicians and researchers with remote assessment of PD symptoms. Encouragingly, we found that both the timing and spatial characteristics of gross movements, such as sit-to-stand, could be captured using the Kinect and may act as good quantitative surrogates for the respective items on the UPDRS III. The Kinect was able to measure the timing of smaller movements reasonably well, such as hand clasping, but not the spatial characteristics (e.g. Fig. 1C). These difficulties measuring fine movements were illustrated by not being able to obtain clean measures of hand clasping in four participants with PD, nor could we extract meaningful data for many of the participants for toe-tapping and finger tapping. Using more precise hand models [18] than the built in skeleton model provided with the Kinect software may result in more accurate hand movements. For example, using vertical displacement of the Kinect hand marker, in the absence of a more detailed hand model is likely to have resulted in inaccuracies detecting hand clasping and finger tapping movements in this study.

The Kinect was not able to collect the spatial characteristics with the same precision as the timing characteristics. For example, ICCs for all temporal characteristics were above 0.9 but ranged from .009 to .989 for range of motion. Despite this, the relative agreement of measurements (Pearson's r correlation) were generally strong. First, this indicates the Kinect may be most useful for measuring slowness of movement in people with PD rather than the reduced size of movement. Second, although the measurement of the range of movement may not be as accurate as the Vicon, the Kinect may still be useful to track relative within-person change in movement over time, such as the worsening of movement symptoms with disease progression or improvement due to intervention. However, retest reliability of the Kinect to measure functional movements is yet to be established.

Further development is required before the Kinect can be used to measure movement symptoms in a home-based setting. First, the accuracy of the Kinect may be improved with a combination of better spatial resolution, more precise estimation of anatomical landmarks and using the optimal orientation of the Kinect relative to the person. The newer "Xbox One Kinect" sensor will have improved spatial and temporal resolution, potentially improving the accuracy of fine movements, such as hand clasping and toe tapping, and facilitate more precise anatomical models. Some of the inaccuracies of the Kinect can be explained by the limitations of the Kinect to estimate anatomical landmarks. There have been several recent advances in estimating the body position and movement using a single Kinect depth sensor [5,19–21]. It is likely that using these techniques in the current study, instead of the in-built 20-point skeleton model, would have produced more accurate results for spatial characteristics for finer movements such as hand clasping. In addition, only capturing the 'front surface' of a person, unlike conventional marker-based three-dimensional motion analysis systems also limits the accuracy of the anatomical models. Posing at a 45 degree angle in relation to the Kinect may improve the spatial accuracy of measuring standing trunk flexion, hand clasping, finger tapping, as well as distinguishing the foot from the floor and determining knee location when the leg is straight. Estimating movement whilst seated (e.g. toe tapping) may also introduce error using the Kinect, as the legs of the chair may mistakenly be identified as part of the participant [9]. Attempts have been made to combine information captured concurrently with multiple Kinect sensors to improve the accuracy of tracking movement [20]. Using more than one sensor may help improve the accuracy of the Kinect in research laboratories or clinics, however multiple sensors may not be as cost effective or practical for home-based deployment. It is also possible that slight discrepancies in the orientation of the Kinect sensor in relation to the Vicon system may have introduced additional error between the two systems however given the excellent agreement for some movements such as sit-to-stand we expect this error to be quite small.

Table 3
Spatial accuracy of the Kinect system compared to the gold standard Vicon three dimensional analysis system.

Movement	Mean range		Bias (Kinect–Vicon)	*p*	$LoA_{95\%}$	$LoA_{95\%}$ (%)	Pearson *r*	ICC
	Vicon	Kinect						
Control (n = 10)								
Sit to stand (mm) (head displacement)	454.73 (64.33)	457.18 (71.69)	2.45	.467	19.98	4%	.995	.989
Standing trunk flexion (°)	11.69 (7.98)	10.50 (5.61)	−1.19	.660	16.18	146%	.302	.301
Lateral trunk flexion (°)	98.48 (19.18)	57.34 (9.44)	−41.14	<.001	23.66	30%	.860	.146
Forward stepping (°) (hip flexion)	41.57 (10.12)	36.16 (7.45)	−5.41	.005	8.97	23%	.908	.740
Side stepping (°) (hip abduction)	31.16 (9.16)	27.92 (7.44)	−3.24	.006	5.66	19%	.961	.879
Shoulder flexion (°)	103.92 (12.27)	114.36 (11.79)	10.44	<.001	5.15	5%	.977	.710
Shoulder abduction (°)	90.37 (12.19)	99.05 (11.56)	8.68	<.001	9.82	10%	.912	.724
Elbow Flexion (°)	139.94 (15.60)	156.87 (17.45)	16.93	<.001	17.98	12%	.852	.561
Hand clasping (mm) (vertical index finger displacement)	74.15 (116.16)	51.71 (22.2)	−22.44	.134	84.36	134%	.150	.012
Pronation supination (mm)	147.08 (36.21)	139.27 (43.0)	−7.81	.450	61.29	43%	.701	.699
Leg agility (mm) (Vertical knee displacement)	139.93 (55.61)	94.27 (62.23)	−45.66	<.001	22.47	19%	.990	.760
Walking on the spot (mm) (vertical knee displacement)	148.09 (58.41)	154.84 (40.52)	6.75	.546	66.80	44%	.822	.781
Parkinson's disease (n = 9)								
Sit to stand (mm) (head displacement)	427.91 (89.02)	431.81 (92.63)	3.90	.282	19.87	5%	.997	.982
Standing trunk flexion (°)	24.16 (5.55)	12.84 (5.80)	−11.32	<.001	11.27	61%	.487	.166
Lateral trunk flexion (°)	69.42 (20.52)	37.39 (12.72)	−32.03	<.001	19.05	36%	.935	.305
Forward stepping (°) (Hip flexion)	38.53 (8.98)	33.24 (5.58)	−5.29	.002	6.89	19%	.921	.785
Side stepping (°) (hip abduction)	27.65 (6.71)	30.10 (7.39)	2.45	.132	8.57	30%	.812	.778
Shoulder flexion (°)	98.35 (9.56)	115.42 (12.01)	17.07	<.001	11.63	11%	.873	.383
Shoulder abduction (°)	82.68 (8.63)	92.94 (8.62)	10.26	<.001	6.17	7%	.933	.549
Elbow Flexion (°)	122.65 (23.41)	144.31 (25.29)	21.66	.021	44.58	33%	.566	.419
Hand clasping (mm) (vertical index finger displacement)[a]	55.76 (64.35)	36.30 (29.47)	−19.46	.106	58.17	126%	.251	.009
Pronation supination (mm)	138.20 (16.03)	123.02 (15.21)	−15.18	.036	33.72	26%	.107	.038
Leg agility (mm) (vertical knee displacement)	217.29 (87.54)	202.30 (132.45)	−14.99	.427	105.26	50%	.963	.889
Walking on the spot (mm) (vertical knee displacement)	168.64 (70.94)	124.92 (110.71)	−43.72	.071	123.37	84%	.848	.710

p refers to the repeated measures *t*-test to assess bias between the two systems.
[a] We were unable to extract data from 4 people with PD for hand clasping.

Second, because our sample of PD participants had only mild-moderately severe motor symptoms we cannot say whether the Kinect is able to measure movement accurately in people with more severe motor symptoms, such as noticeable dyskinesia, without further testing. Third, although we have shown the Kinect can measure hypokinetic symptoms in people with PD, it remains unclear whether the Kinect can measure tremor and rigidity, two additional movement symptoms of PD. Finally, user-friendly software is needed to guide people through the testing process as well as a means to transfer testing information to the clinician.

5. Conclusion

The Kinect system has potential to be a low-cost, home-based sensor to measure movement symptoms in people with PD. The Kinect can accurately measure the timing and gross spatial characteristics of clinically relevant movements but not with the same spatial accuracy for smaller movements, such as hand clasping or toe tapping. Measurement of the timing of movement will provide the most accurate and stable outcomes, however the Kinect may also be useful in tracking the relative worsening or improvement for both the timing and size of movements over time. Further development is needed to improve the tracking of smaller movements and develop user-friendly software to monitor PD symptoms in the home.

Author contributions

All authors contributed to the design and implementation of the study. DJ was responsible for technical implementation of capturing movement data using the Microsoft Kinect. GB, DM and BG were responsible for data collection and processing of the data. PO and LR provided important intellectual comment on the manuscript. All the authors contributed to the revision of the manuscript and approved the final version for publication.

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Conflicts of interest statement

The authors have no conflicts of interest to report.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gaitpost.2014.01.008.

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