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INNOVATION

Comparative abilities of Microsoft Kinect and Vicon 3D motion capture for gait analysis

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Abstract

Biomechanical analysis is a powerful tool in the evaluation of movement dysfunction in orthopaedic and neurologic populations. Three-dimensional (3D) motion capture systems are widely used, accurate systems, but are costly and not available in many clinical settings. The Microsoft Kinect™ has the potential to be used as an alternative low-cost motion analysis tool. The purpose of this study was to assess concurrent validity of the Kinect™ with Brekel Kinect software in comparison to Vicon Nexus during sagittal plane gait kinematics. Twenty healthy adults (nine male, 11 female) were tracked while walking and jogging at three velocities on a treadmill. Concurrent hip and knee peak flexion and extension and stride timing measurements were compared between Vicon and Kinect™. Although Kinect measurements were representative of normal gait, the Kinect™ generally under-estimated joint flexion and over-estimated extension. Kinect™ and Vicon hip angular displacement correlation was very low and error was large. Kinect™ knee measurements were somewhat better than hip, but were not consistent enough for clinical assessment. Correlation between Kinect™ and Vicon stride timing was high and error was fairly small. Variability in Kinect™ measurements was smallest at the slowest velocity. The Kinect™ has basic motion capture capabilities and with some minor adjustments will be an acceptable tool to measure stride timing, but sophisticated advances in software and hardware are necessary to improve Kinect™ sensitivity before it can be implemented for clinical use.

Keywords

Biomechanics, gait, kinect, vicon

History

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1. Introduction

Biomechanical analysis is used in sports medicine, athletic training, rehabilitation and treatment for motor impairments. Three-dimensional (3D) motion capture systems are widely used, accurate systems, but are costly and thus not available in many clinical settings. Alternatives include two-dimensional (2D) video cameras with analysis software, electrogoniometers, pressure sensitive mats or accelerometers to assess gait timing and alignment. Although these systems are more affordable than 3D motion capture systems, shortcomings exist; they are less accurate, may deteriorate with time, may not allow for full body motion capture and data processing may be labour intensive. Microsoft recently released the Kinect™ sensor, a video gaming device developed to track the movements of a player interacting with a game. The Kinect™ consists of an infrared (IR) light projector, an IR camera, and a RGB video camera. Reflected IR light is converted into depth data and is calibrated with RGB data to distinguish shapes [1], enabling the Kinect™ to track and record 3D human motion without using controllers or markers. The Kinect™ is simple to operate and is less than or equal to the price of 2D video analysis software. The Kinect™ has potential to be a useful biomechanics analysis tool, but its spatial and temporal motion capture abilities have not yet been fully analysed with respect to gait.

Previous studies investigating Kinect™ motion capture have addressed Kinect™ hardware sources of error [2–4], postural control [5], dance gesture recognition [6], frontal gait biometrics for surveillance [7] and gait measurements for fall risk (walking speed, stride time and stride length) [8,9]. These studies indicate that the Kinect™ can perform basic motion capture functions, but system error exists that compromises accuracy [2]. For most aspects of static postural tests the Kinect™ is reported to accurately measure angular and lateral displacement [5], but Kinect™ accuracy in stride motion tracking is not great enough to predict fall risk [8,9]. In addition to stride measurements, lower limb angular displacement and intra-limb mechanics are also very important aspects of gait analysis that assess various types of movement disorders, such as stroke, Parkinson's disease and cerebral palsy (CP) [10–14] and to assess change during rehabilitation after stroke or partial spinal cord injury [15,16].

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Kinect™ hip and knee sagittal angular displacement measurement accuracy during locomotion has not been reported.

The purpose of this study was to assess concurrent validity of the Kinect™ for Xbox 360® and a 10-camera Vicon Nexus system, a commercially available and validated gait analysis package, for sagittal plane hip and knee kinematics at three different velocities. We hypothesized no significant differences between Kinect™ and Vicon measurements.

2. Methods

2.1. Subjects

Twenty healthy adults (nine male, 11 female; 27.4 ± 10.0 years, height 169.4 ± 10.9 cm; leg length 85.6 ± 6.2 cm) were recruited from an urban university community. Subjects were healthy and regularly participated in moderate-to-vigorous activity. They were free of any physical condition or limitation that prevented them from walking or jogging on a treadmill. Subjects signed an informed consent form, approved by the institutional review board.

2.2. Instrumentation and protocol

Gait data were concurrently recorded using a 10-camera Vicon MX motion capture system (Vicon, Oxford, UK), sampled at 120 Hz using Vicon Nexus 1.7 software, and an Xbox Kinect™ (Microsoft, Redmond, WA), sampled between 30–37 Hz using Brekel Kinect™ software [17]. Joint angle measurements were extrapolated from the Kinect™ skeleton mode as reported by Brekel Kinect™ software. Each participant wore a form fitting full body Velcro suit affixed with reflective markers using the Vicon Plug-in-Gait model marker set and modelled as previously described [18]. The suits provided improved marker adherence with similar accuracy to placement of the markers using double-sided tape. At our lab, we established that Vicon 3D motion analysis demonstrated excellent instrument reliability [(ICC) (3, k) $r = 0.998$] and accuracy (SEM $= 1.83°$) in the measurement of complex dance movements, making it suitable for use as our criterion measure [19].

The Kinect™ sensor was positioned to the subject's left at a 45° angle to the T916 treadmill (Nautilus, Vancouver, WA). Unlike previous single camera systems that permit the calculation of 2D position and angles, the Kinect-based tracking system estimates 3D position. Hence, this allows positioning of the camera to optimize spatial distance from the subject rather than strictly keeping it normal to the plane of motion. Therefore, at 45°, the Kinect was able to track an ambulating human figure most continuously and this sensor position was optimal to capture sagittal plane gait data without treadmill structure obstruction (Figure 1). Subjects took between 10–40 steps per leg on the treadmill at three velocities: 3.0 mph (4.83 kph, slow walk), 4.5 mph (7.24 kph, brisk walk to slow jog) and 5.5 mph (8.85 kph, medium to quick jog). The number of steps recorded for each subject varied depending on how well the Kinect™ was able to maintain tracking for a particular individual. All recorded steps were used in analysing gait for each subject. During data collection, Vicon cameras transferred data at a rate of one gigabit s^{-1} via Ethernet protocol and Kinect™ transferred data at 480 megabits s^{-1} via USB 2.0 protocol.

2.3. Data processing

Vicon data was filtered with an FIR filter and processed using the Plug-in-Gait model in Vicon Nexus. Kinect™ data was processed through the Brekel Kinect™ software. Maximum angular displacement for hip and knee flexion and extension were determined for each step using a custom script within LabVIEW software (LabVIEW version 7.5, National Instruments Corporation, Austin, TX). Stride timing was defined as the time from peak hip/knee flexion to peak hip/knee flexion of the same limb (stride timing $= t_{\text{step } n+1} - t_{\text{step } n}$). We assumed a Kinect™ sample rate of 30 Hz when calculating the time of each step, but in

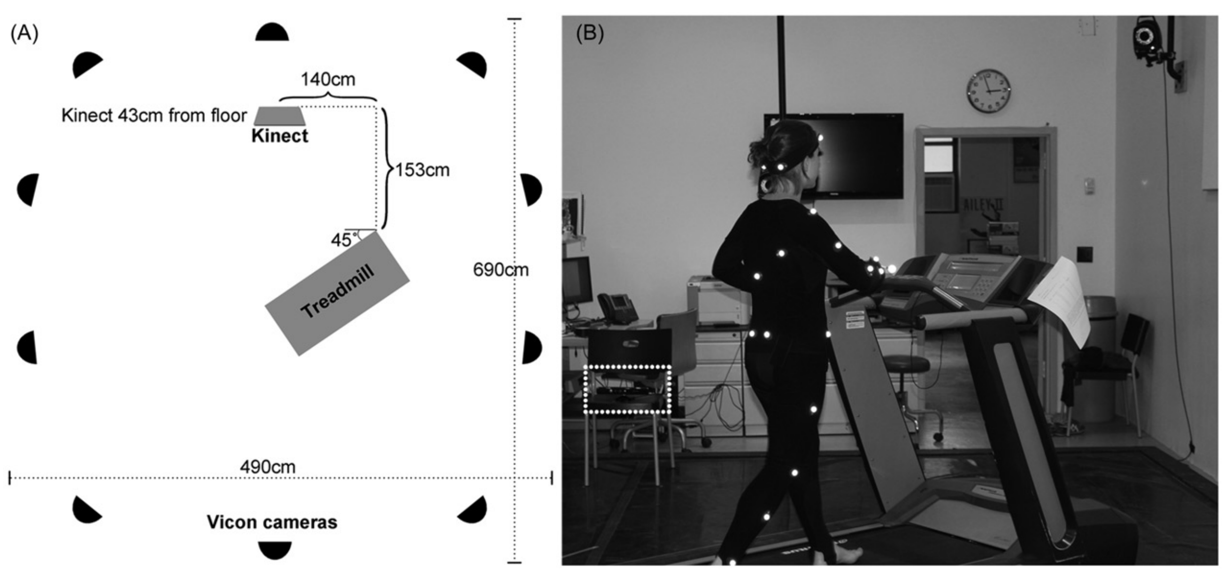

Figure 1. Treadmill and camera layout. (A) The schematic displays a bird's eye view of the equipment arrangement. The treadmill was angled at 45° with respect to the Kinect™ sensor, with the front of the treadmill positioned 140 cm to the right and at a distance of 153 cm in front of the sensor. The base of the Kinect™ sensor rested 43 cm above the floor. Vicon cameras were mounted around the perimeter of the room. The Kinect™ sensor was closest to the left of each subject. (B) The photograph of the camera and treadmill layout shows the Kinect™ sensor highlighted by the white dashed rectangle to the left of the subject.

reality the Kinect™ sample rate was constantly fluctuating between 30–37 Hz and could not be stabilized. The variable frame rate resulted from the limited memory buffer present in USB 2.0, which had difficulty managing the amount of data transmitted from the camera to consistently calculate the kinematics. The number of times the Kinect™ failed to record data for a full step (missed steps) was also counted and recorded for each trial.

2.4. Data analyses

Outliers were identified using Cook's D, lever and studentized deleted residual values and removed [20]. Mean (SD) angular displacement and timing for right and left hip and knee peak flexion and extension were calculated for each subject, at the three velocities. Separate paired two-tailed t-tests ($p < 0.05$) were used to compare average Vicon and Kinect™ peak angular displacement and stride timing among individuals at the three velocities. In addition, variability of Kinect™ and Vicon measurements were assessed by SD comparisons across individuals using two-tailed t-tests ($p < 0.05$).

To determine correlation strength between the Kinect™ and Vicon system for different measurements, average angular displacement and stride timing at each velocity were separately compared using Pearson product moment correlation coefficients. Linear regression analyses were performed to calculate the slope (m) of the relationship between Vicon and Kinect™ measurements. Agreement between Kinect™ and Vicon measurements was assessed as described by Bland and Altman [21], by determining the mean (SD) difference between paired data points. The Bland Altman mean (SD) difference will be referred to as error.

The percentage of steps missed (%missed steps) by the Kinect™ system for each subject at each joint was calculated (number missed steps/total number steps). Mean (SD) of %missed steps for the right and left hip and knee were determined and %missed steps between joints and limbs were compared using two-tailed t-tests. To determine whether the Kinect™ sensor tracked subjects of a particular size more accurately, %missed steps were compared to three aspects of body size: height, leg length and body ratio (height/leg length). Pearson product-moment correlation coefficient calculations were used to identify linear relationships between %missed steps and size.

3. Results

3.1. Angular displacement

The Kinect™ recorded angular displacements providing basic gait characteristics, but Kinect™ displacements were often more variable than Vicon displacements (Figure 2). Kinect™ peak flexion angular displacements were smaller than those measured by the Vicon system in every case ($p < 0.004$), except for the right hip at 3.0 mph (Figure 3A). Kinect™ peak extension measurements were consistently greater than that of Vicon (Figure 3B); Specifically, Kinect™ and Vicon extension differed for the right hip at all velocities and for both knees at 4.5 and 5.5 mph ($p < 0.04$). Kinect™ SD

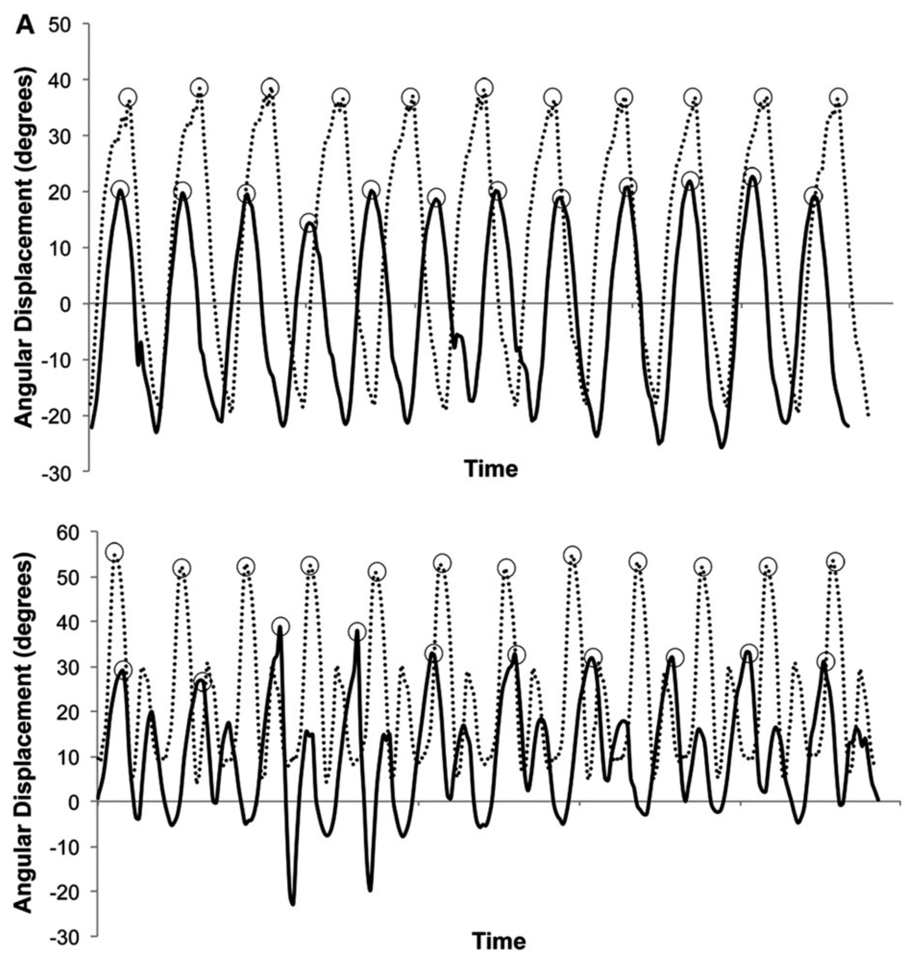

Figure 2. Representative gait traces for the left (A) hip and (B) knee at 4.5mph. Kinect™ gait tracings appear as solid lines and Vicon gait tracings appear as dotted lines. Small circles highlight peak flexion data measured by the Kinect™ and Vicon. For each subject the average peak flexion from all steps in the trail was compared between Kinect™ and Vicon. The same process was carried out to compare extension.

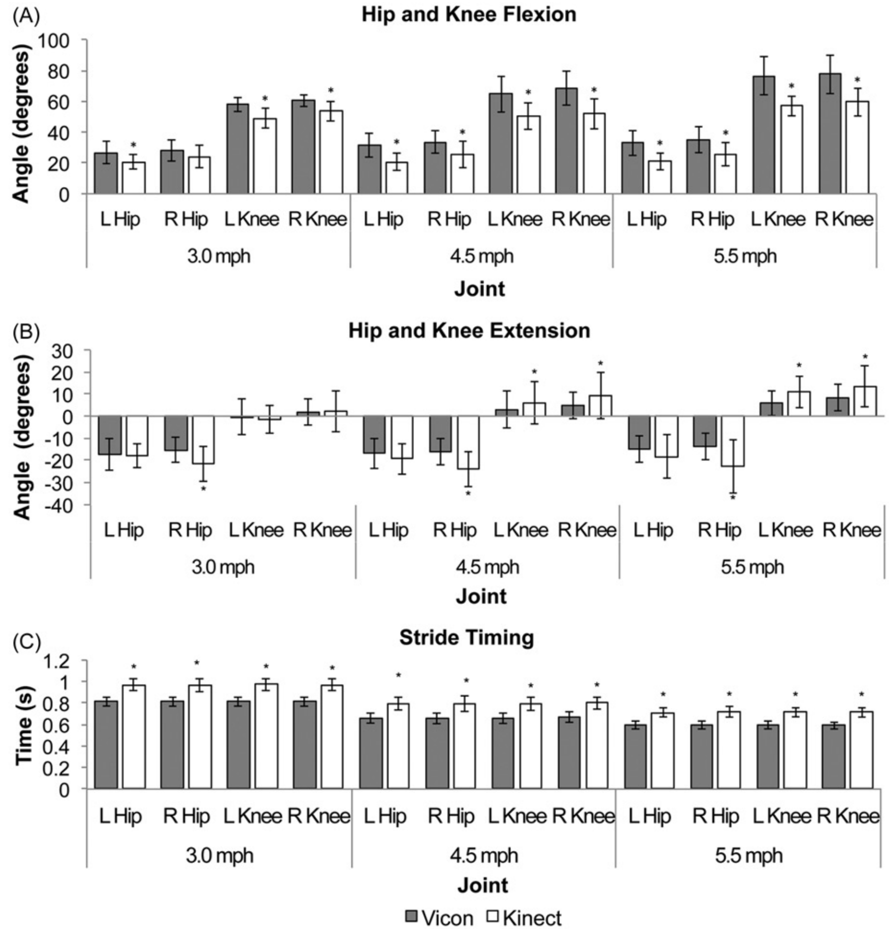

Figure 3. Mean (SD) hip and knee flexion and extension at three velocities for Vicon and Kinect. (A) In comparison to Vicon, the Kinect™ measured smaller angular displacement for peak flexion ($p < 0.004$), except at the right hip at 3.0 mph. (B) Kinect™ angular displacement measurements for extension were greater than Vicon measurements for the right hip at each velocity and for the left and right knee at 4.5 and 5.5 mph ($p < 0.04$). (C) The Kinect™ measured greater mean stride time ($p < 0.02$) than the Vicon in every case except for right knee at 4.5 mph. Vicon data is shown in grey; Kinect™ is shown in white. Asterisks (*) indicate differences between Kinect™ and Vicon pairs.

Table 1. Correlation and slope of Kinect™ vs Vicon hip and knee flexion and extension.

	3.0 mph			4.5 mph			5.5 mph		
	r	Error	*m*	*r*	Error	*m*	*r*	Error	*m*
L Hip Flexion	0.20	−6.18 ± 7.74	na	−0.06	−10.81 ± 9.95	na	−0.28	−12.26 ± 11.00	na
L Hip Extension	−0.04	−0.76 ± 9.14	na	−0.22	−2.55 ± 10.89	na	−0.04	−3.4 ± 12.08	na
R Hip Flexion	0.19	−4.1 ± 9.14	na	0.15	−8.12 ± 10.49	na	−0.20	−9.35 ± 12.55	na
R Hip Extension	0.27	−6.4 ± 8.37	na	−0.32	−7.84 ± 11.47	na	0.20	−8.6 ± 12.39	na
L Knee Flexion	0.43	−9.14 ± 6.04	na	0.79	−14.1 ± 7.05	0.61	0.55	−19.32 ± 10.20	0.29
L Knee Extension	0.69	−1.11 ± 5.93	0.53	0.78	3.07 ± 6.11	0.88	0.52	5.12 ± 6.65	0.71
R Knee Flexion	0.71	−6.93 ± 4.44	1.18	0.87	−16.73 ± 5.45	0.77	0.86	−18.11 ± 6.63	0.61
R Knee Extension	0.77	0.452 ± 6.10	1.28	0.84	4.43 ± 6.25	1.42	0.86	5.14 ± 5.24	1.33
L Hip Time	0.87	0.157 ± 0.031	1.24	0.98	0.131 ± 0.015	1.14	0.96	0.118 ± 0.012	1.10
R Hip Time	0.91	0.153 ± 0.028	1.31	0.98	0.135 ± 0.021	1.31	0.77	0.121 ± 0.032	1.09
L Knee Time	0.91	0.157 ± 0.026	1.20	0.99	0.133 ± 0.015	1.23	0.93	0.118 ± 0.016	1.10
R Knee Time	0.92	0.159 ± 0.024	1.12	0.98	0.137 ± 0.014	1.16	0.97	0.121 ± 0.014	1.25

r, Pearson product-moment correlation coefficient; Error, Bland Altman mean (SD) difference; *m*, slope; na, not applicable.

values were greater than Vicon SD ($p < 0.0002$) in every case except left and right hip and knee flexion and left knee extension at 3.0 mph. Kinect™ left hip flexion SD values were smaller than SD of the right hip at every velocity ($p < 0.03$). There were no other differences between right and left Kinect™ joint measurements.

Pearson product moment correlation coefficients (r) were poor ($r < 0.30$) for hip angular displacement and error was fairly large, greater than 5°, in every case. Linear regression slopes ($p > 0.05$) were not different from zero in any case for the hip (Table 1). Correlation strength between Kinect™ and Vicon knee angular displacements was not consistent for knee data, although high correlations ($r > 0.80$) were found for right knee flexion and extension at 4.5 and 5.5 mph. Error was somewhat smaller for knee data than hip, but values were still generally large. Positive linear regression slopes ($p < 0.05$) were found between Kinect™ and Vicon for all knee data except left knee flexion at 3.0 mph; however, the slopes were often far from unity (Table 1).

3.2. Stride timing

The Kinect™ measured longer stride times than Vicon in all cases ($p < 0.02$) (Figure 3C). Kinect™ stride timing SD

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values across individuals were greater than Vicon SD values in every case ($p < 0.03$), except 3.0 mph left hip and 4.5 mph right hip. The only difference between left and right Kinect™ SD values occurred in hip flexion at 5.5 mph ($p < 0.04$). Vicon SD values were smaller at 5.5 mph than Vicon SD at 3.0 mph ($p < 0.04$). Kinect™ right hip and left knee SD values were smaller at 5.5 mph than at 3.0 mph ($p < 0.02$).

Kinect™ and Vicon stride timing demonstrated high correlations ($r > 0.80$) for both limbs and joints at all velocities in every case except for the right hip at 5.5 mph. Error was consistently small and linear regression slopes ($p < 0.05$) were very close to a value of 1.0 in most cases (Table 1).

3.3. Tracking ability

On average, the Kinect™ missed 8–18% of steps and appeared to have difficulty most frequently when the knees crossed. Mean %missed steps did not differ significantly between left and right, hip and knee or between velocities ($p > 0.05$). Cases of missed steps greater than 30% occurred 16 times out of 240 total trials (6.6%). Correlations between %missed steps and height, leg length or body ratio were poor ($r < 0.50$).

4. Discussion

We found the Xbox 360 Kinect™ using Brekel Kinect™ software was generally able to track lower limb sagittal plane motion and produce representative gait traces (Figure 2), but accuracy varied. While the Kinect's™ ability to track a human figure is acceptable for some applications (video game movement interactions), Kinect™ measurement accuracy was not acceptable for clinical measurement analysis. The Kinect™ did not produce consistent hip measurements. Kinect™ and Vicon knee measurements were better correlated than hip but not consistent enough for clinical application. Kinect™ and Vicon stride timing measurements were often well correlated and with some slight adjustments to the software the Kinect™ may be a clinically acceptable tool to collect temporal gait measurements.

4.1. Angular displacement

The Kinect™ produced tracings representative of normal hip and knee gait, although these were never as smooth as those produced by Vicon (Figure 2). In most cases, mean Kinect™ peak flexion amplitude was less than Vicon measurements, indicating that the Kinect™ was unable to measure the full magnitude of peak flexion for the hip and knee (Figure 3A). Mean Kinect™ extension did not differ from Vicon for left hip extension at all velocities (Figure 3B). The range of motion for hip extension is less than flexion range of motion, which may have allowed for more accurate Kinect™ measurements. In comparison to Vicon, the Kinect™ hip angular displacement measurements were scattered, differing from Vicon measurements without any predictability, as indicated by poor correlation ($r < 0.30$) and insignificant regression line slopes in every case. In accordance with our findings, Raptis *et al*. [6] report that depth perception noise leads to difficulty in Kinect™ hip tracking.

Kinect™'s ability to measure knee angular displacement was somewhat better than hip. The Kinect™ was able to properly track an extended limb during right and left knee extension at 3.0 mph. However, at 4.5 and 5.5 mph, Kinect™ mean extension measurements were greater than those of Vicon, indicating that the Kinect™ often interpreted full knee extension as hyperextension during faster ambulation (Figure 3B). Although Kinect™ and Vicon right knee data were well correlated in some cases, linear regression slope values for the knees were spread over a fairly wide range and were often far from unity (Table 1), indicating that Kinect™ angular displacement measurements did not differ from Vicon by a common factor. The Kinect™'s somewhat superior ability to track the right lower limb was surprising as the right was further from the Kinect™ sensor and partially hidden behind the left (Table 1). There was greater variability in Kinect™ right hip flexion than left, but no other differences in Kinect™ variability appeared between left and right knee flexion or hip and knee extension across individuals. Slower Kinect™ sampling frequency of 30–37 Hz and insufficient smoothing algorithms may have contributed to Kinect's inability to properly capture the flexion and extension peak amplitudes.

Although the boundaries for clinical error in kinematic measurements are not concrete, generally an error less than 2° is considered clinically acceptable, an error between 2–5° may also be acceptable with appropriate interpretation, but error greater than 5° indicates that important kinematic information is missing [22,23]. Error in hip and knee measurements was greater than 5° in every case (Table 1), indicating that the Kinect™ with Brekel Kinect™ software is not sensitive enough to detect subtle changes in sagittal plane angular displacement that are required for gait analysis. Although the Kinect™ by itself is not sensitive enough for complete gait analysis, it could be useful to clinicians as a complementary tool to visual analysis. Currently, 2D Dartfish® video analysis software cannot substitute for 3D motion capture gait analysis in CP patients, but Dartfish® analysis has been shown to improve inter-rater reliability of CP gait assessment [24]. The Kinect™ could act as a similar but less expensive and less time-consuming instrument for gait assessment raters.

4.2. Stride timing

All subjects walked at 3.0 mph, some walked while others jogged at 4.5 mph depending on leg length and everyone ran at 5.5 mph. Gait became more regular during running, as indicated by less variation in Vicon timing and, consequently, Kinect™ timing measurements were also less variable. Gait kinetics and kinematics change in the transition between walking and running [25,26] and likely explain why there is less variation during running.

Kinect™ and Vicon stride timing were well correlated in nearly every case and linear regression slopes were generally reasonably close to 1 (Table 1), indicating that the Kinect™ measured stride timing more consistently than angular displacement. The consistent timing measurements show that the Kinect™ was able to track when the hip or the knee reached peak flexion, although it was not able to follow the complete motion path to capture the full extent of flexion. Error between Kinect™ and Vicon was small and consistent for different joints and velocities (Table 1); however, the differences in timing measurements may not be small enough to validate Kinect™ temporal measurements. The inconsistent and relatively slow Kinect sampling rate of 30–37 Hz also likely introduced error into stride time calculations. Adjustments to the hardware and software allowing a consistent and faster frame rate would help solve this uncertainty in the present version of the Kinect™.

Other studies validating temporal gait tools such as gyroscopes and GAITRite® reported errors of roughly 0.02–0.04 s between systems [27,28], smaller than temporal errors observed for the Kinect™ (Table 1). Stride timing is an important indicator of fall risk in older adults [29–31] and with reliable measurements the Kinect™ could be a useful tool to assess fall risk. However, Kinect™ variability was greater than Vicon in nearly every case and such variability as previously reported [9] is too high to monitor fall risk.

4.3. Tracking ability

The Kinect™ was designed to track a human figure in the frontal plane. It is possible that our hip and knee angular displacement measurements would be more accurate if the Kinect™ sensor was placed perpendicular to the subjects (e.g. frontal plane). Frontal tracking is useful for biometrics surveillance [7], but there are several practical problems that exist with frontal tracking in the clinic. Clinics, hospitals and laboratories wishing to use Kinect™ gait tracking in the frontal plane would need a treadmill without handlebars or a control panel at the front of the machine so that the Kinect™ could properly detect and track the legs without interfering structures. Such a treadmill set-up would increase the cost of the motion tracking system and could be problematic for patients needing handlebar support.

As the knees crossed during ambulation the Kinect™ intermittently confused left and right limbs, missing 8–18% of steps on average. Although the left side was fully exposed to the Kinect™ while the right was partially hidden behind the left, there were no differences in %missed steps between joints or at different velocities. Missed steps may decrease by using two or more Kinect™ sensors to capture 360° of motion. We compared %missed steps to height, leg length and body ratio, but found no indication that the Kinect™ better tracks people of a certain size or proportion.

Several aspects of the Kinect™ likely contributed to measurement error. Slower Kinect™ sampling frequency of 30–37 Hz and insufficient smoothing algorithms may have contributed to Kinect's™ inability to properly capture the flexion and extension peak amplitudes. The Kinect™ is only a single camera that does not provide true three-dimensional data, while the Vicon system provides 360° of coverage. In Vicon, the joint centres are calculated using bony landmarks to place optical markers which are tracked by the cameras, while the joint centres in Kinect™ are based on the Kinect's™ interpretation of the centre of the person and the centre of the legs. The resolution of the Kinect™ camera is another factor contributing to lack of smoothness and accuracy, but could not be increased in our study due to the limitation of the USB 2.0 frame buffer as described above. Integrating multiple Kinect™ sensors to capture more than 180° (software reportedly in development [32,33]) and introducing a marker system similar to that of Vicon could lead to major improvement in Kinect™ measurements.

Although some improvements are necessary, the Kinect™ has the basic capabilities for motion capture in gait analysis. The Kinect™ was designed to track player full body movements in interactive video games, thus it is able to track a person covering a limited distance as well as moving in place. Although it is unknown how well the Kinect™ would track joint angular displacement in freely walking individuals, Kinect™ temporal gait measurement accuracy for subjects walking freely through space [8,9] is similar to the results for subjects using a treadmill presented in this study. Before it can be implemented in the clinical setting, substantial changes are required to improve clarity and speed of the frame capture rate and kinematic measurement accuracy. When developing future kinematic rigs for Kinect™, caution should be used with respect to over-prediction of normal gait or automazation of gait parameters such as intra-limb mechanics. While this may work well for animation and game cinematics, the Kinect™ will only be beneficial to clinicians if it is capable of detecting irregularities in gait. We conducted this study before the commercial release of the Kinect™ for Windows. Some of the issues we identified may have already been solved with faster processing speed and software designed with the release of the system development kit. Kinect™ motion capture for biomechanical analysis will advance as programmes develop that improve the link between Kinect™ hardware and software. The Kinect™ is a remarkable device and, with future improvements, it may become an ideal and affordable tool for clinics and hospitals.

Declaration of interest

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of this article.

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