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Short communication

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Full-Body Motion Assessment: Concurrent Validation of Two Body Tracking Depth Sensors versus a Gold Standard System during Gait

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Short Communication

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Abstract

RGB-D cameras provide 3-D body joint data in a low-cost, portable and non-intrusive way, when compared with reference motion capture systems used in laboratory settings. In this contribution, we evaluate the validity of both Microsoft Kinect versions (v1 and v2) for motion analysis against a Qualisys system in a simultaneous protocol. Two different walking directions in relation to the Kinect (towards – WT, and away - WA) were explored. For each gait trial, measures related with all body parts were computed: velocity of all joints, distance between symmetrical joints, and angle at some joints. For each measure, we compared each Kinect version and Qualisys by obtaining the mean true error and mean absolute error, Pearson's correlation coefficient, and optical-to-depth ratio. Although both Kinect v1 and v2 and/or WT and WA data present similar accuracy for some measures, better results were achieved, overall, when using WT data provided by the Kinect v2, especially for velocity measures. Moreover, the velocity and distance presented better results than angle measures (except for the knee angle). Our results show that both Kinect versions can be an alternative to more expensive systems such as Qualisys, for obtaining distance and velocity measures as well as some angles metrics (namely the knee angles). This conclusion is important towards the non-intrusive assessment of motor function in different areas, including sports and healthcare.

Introduction

A single RGB-D camera, such as the Microsoft Kinect, is able to track the 3-D position of several body joints, without interfering with the scene or requiring calibration. Currently, there are two versions of this sensor: Kinect v1 (Kv1, released in 2010), and Kinect v2 (Kv2, released in 2014). Data provided by the Kinect includes RGB images, depth information, and 3-D position of twenty and twenty-five body joints for Kv1 and Kv2, respectively. The Kv2 further provides infrared images. These sensors are low-cost and portable, when compared with reference systems (e.g., Vicon or Qualisys) typically only available in specialized laboratories and requiring complex and time-consuming setups. To ensure that the information provided by RGB-D cameras is trustworthy for the intended application, it is important to evaluate its accuracy for a specific goal against a reference system.

An overview of the state-of-the-art using the Kinect for motion assessment is presented in Table 1, including studies related with posture and balance (Behrens et al., 2016; Clark et al., 2012; Clark et al., 2015; Wang et al., 2015), gait (Behrens et al., 2014; Clark et al., 2013; Mentiplay et al., 2015; Muller et al., 2017), movement-related diseases (Chen et al., 2017; Galna et al., 2014; Grobelny et al., 2017), rehabilitation (Capecci et al., 2016) and joint position estimation (Otte et al., 2016; Xu and McGorry, 2015; Xu et al., 2015). To our knowledge, no contribution compared both Kinects simultaneously in the context of gait.

When conducting gait analysis, researchers usually rely only on data acquired while participants walk towards the sensor (Clark et al., 2012; Galna et al., 2014; Geerse et al., 2015; Muller et al., 2017; Otte et al., 2016; Xu et al., 2015). This requires the subject to perform multiple repetitions to acquire sufficient data. If walking away from the sensor and towards it present comparable quality and usefulness, the former data could also be used, bringing benefits (reduced entropy and time) to gait-related applications.

In this contribution, we evaluate the validity of both Kv1 and Kv2 for 3-D gait analysis when compared with a reference multi-camera marker-based system (Qualisys). We aim to study the compromise in terms of accuracy when using a single RGB-D camera, mimicking a possible clinical scenario.

We acquired 3-D body joint data from twenty healthy subjects during ten trials consisting of walking towards (WT) and away (WA) from the Kinects. For each trial, we compared each Kinect version with Qualisys by obtaining the mean true and mean absolute errors, Pearson's correlation coefficient and optical-to-depth ratio, for several measures associated with all body parts (velocity, distance and angle).

Table 1.

Methods

Subjects and Experimental Setup

Our experiment was conducted at LABIOMEP (Porto Biomechanics Laboratory), with the participation of twenty healthy individuals (10 male and 10 female, age: 30.5 ± 8.07 [22–51] years, height: 1.71 ± 10.9 [1.50–1.94] m, body mass index: 23.1 ± 3.2 [17–31] kg/m^2). Results presented below are only applicable to cohorts of the same age range. None of the participants had any history of movement impairment or physical limitation. This study was conducted according to the Helsinki Declaration and approved by the Ethics Committee of Santo António University Hospital (Portugal). All participants signed an informed consent form.

The experimental setup comprised three systems: Qualisys system (Qualisys AB, Sweden), Kv1 and Kv2 (Microsoft Corporation, USA). The Qualisys system included 12 Oqus infrared cameras, and thirty-six retroreflective markers placed on the subject's body according to the marker setup used in (Rocha et al., 2018). The Kinects were placed in front of the subject, at a height of 1 m, with a tilt angle of -10º/-5º (Kv1/Kv2), as shown in (Rocha et al., 2018). The angle was chosen to maximize the practical depth range: 1.84 m (WT) and 2.06 m (WA) for Kv1; 2.71 m (WT) and 2.66 m (WA) for Kv2.

Experimental Protocol and Data Acquisition

For each participant, the experiment consisted of performing ten gait trials (20 subjects, 200 trials). Each trial included walking towards (WT) the RGB-D cameras and walking away (WA) from them, for 14 m, at a self-selected comfortable pace.

Data provided by the Kinects were acquired simultaneously at 30 Hz, using our *KinecTracker* (*KiT*) software application that enables online visualization and acquisition of the data provided by a Kinect (Cunha et al., 2016). At the same time, the 3-D position of the Qualisys markers were acquired at 200 Hz. The body joints tracked by both versions of the Kinect are shown in (Rocha et al., 2015). The joint nomenclature used in this contribution follows the Kv2 labelling (Microsoft, 2018). Body joints tracked exclusively by Kv2 were not considered.

Data Processing

Qualisys data were processed using a zero-lag low-pass fourth order Butterworth filter with a cut-off frequency of 15 Hz (values chosen based on the signals' frequency content). For both Kinects, joint data were filtered using a similar filter but with a cut-off frequency of 4 Hz. Furthermore, Kinect data were resampled to 200 Hz so that data from all systems have an identical fixed sampling rate.

The synchronization of the three systems was possible using a specific temporal event visible to all of them: dropping an extra marker at the beginning of each trial. The following measures were computed for each frame: velocity of all 20 joints; distance between symmetrical joints; angle at specific joints (Rocha et al., 2014). Trials with outliers for Qualisys data were not taken into account. Data corresponding to WT and WA trials were automatically selected based on data provided by the Kinects. Further information on data processing is presented in Supplementary Data.

System Validation

For each trial and measure, we computed the mean true error and mean absolute error, Pearson's correlation coefficient (r) and optical-to-depth ratio (ODR), between the time series obtained from each Kinect version and Qualisys.

The mean true error is the mean value for the difference between the Kinect and Qualisys values for all frames. The mean absolute error is similar, but the absolute difference value is considered.

The correlation coefficient r shows the strength and direction of the relationship between two signals. The following thresholds were set for r, according to the guidelines given by Portney and Watkins (Portney and Watkins, 2015): poor (< 0.5), moderate (≥ 0.5 and < 0.75), good (≥ 0.75 and < 0.9) and excellent (≥ 0.9).

ODR quantifies the noise behavior of the Kinect when compared with Qualisys. ODR was computed based on signal-to-noise ratio definition using (1), where var(*Qualisys*) is the variance of the measure extracted from Qualisys data and var(*Kinect − Qualisys*) is the variance of the true error of the Kinect comparing with Qualisys (Otte et al., 2016). Large negative values (< −10 dB) indicate that the Kinect data has considerably more noise than Qualisys data. An ODR value higher than 10 dB indicates that the difference between the two systems' signals is negligible (the variance of the Qualisys signal is 10 times larger than the noise variance).

$$ODR = 10\ \log_{10}\left(\frac{var(Qualisys)}{var(Kinect-Qualisys)}\right)\ dB \quad (1)$$

To verify if there are statistically significant differences between the four considered cases (Kv1+WT, Kv1+WA, Kv2+WT, Kv2+WA), we performed a one-way repeated-measures analysis of variance (ANOVA), for each measure and evaluation metric. If a significant difference was detected (p-value ≤ 0.05), a post-hoc Tukey test was then carried out to find which cases are significantly different.

All data processing and statistical analysis described in this section were performed in MATLAB (The MathWorks Inc.), except for the ANOVA and Tukey tests which were performed in the R environment (version 3.5.1) (R Core Team, 2015).

Results

Table 2 presents the mean and standard deviation values for the mean true error and mean absolute error, Pearson's correlation coefficient (*r*) and ODR, for each measure, body segment/joint, Kinect version and walking trial (WT or WA). Complete results obtained for each individual joint are available on Supplementary Tables S8 to S16. The results consider the following body segments: trunk (head, neck, spine base, spine middle), upper limbs (shoulders, elbows, wrists, hands), upper-lower limbs (upper-LL: hips and knees) and lower-LL (ankles and feet). Figure 1 illustrates the correlation coefficient results for the different measures, body segments/joints, Kinect versions and WT/WA trials.

Table 2.

Figure 1.

Discussion

Comparing the two Kinect versions, the obtained mean errors were overall lower for Kv2, which may be due to the improvements made to the tracking algorithm over Kv1. Although Wang et al. evaluated other measures and activities (Wang et al., 2015), our findings are in accordance with their results. Furthermore, the mean error for velocity and distance measures was lower for upper than lower limbs (LL) – in agreement with (Capecci et al., 2016; Xu and McGorry, 2015). This error tends to be higher for joints closer to the ground, which was expected due to the greater movement of the limbs' extremities during gait and possible interferences from infrared reflections on the floor. On the other hand, for the velocity, trunk and upper-LL have the lowest ODR values. For WT trials, correlation is excellent (upper limbs and lower-LL) or good. Analyzing the opposite direction (WA), correlation is excellent and good for the lower-LL (Kv1 and Kv2, respectively), moderate for trunk and upper-LL, and good for other segments. Velocity measures extracted from Kinects data are noisier than Qualisys data, which is reflected in lower ODR values.

As for the distance, the mean estimation errors are between 1 and 11 centimeters, which is in line with the literature (Clark et al., 2015; Galna et al., 2014) and may be acceptable for some applications. However, caution should be taken when preparing or interpreting minuteness studies. Nevertheless, correlation is excellent or good for all considered body segments, Kinect versions and walking directions. Additionally, the mean ODR values are higher for distances than for the other measures.

When analyzing angle measures, correlation ranges from moderate (hips and upper limbs) to poor, and mean ODR values are low (except for the knees, which may be due to the higher range of motion). For WA, the trunk and ankle angles have the worst mean *r* and ODR values. To the best of our knowledge, no other study analyzed upper body angles during gait.

The poor results for most joint angles, when compared with other measures, can be because the angle computation involves three joints. Thus, less accurate joint position estimations have a larger negative effect. Moreover, the physical configuration of the RGB-D sensors may not be the most adequate for measuring angles. Further studies are necessary to verify if angle measurement can be improved.

Although for some cases there are no statistically significant differences between Kv1 and Kv2 and/or between WT and WA, significant differences were found between two or more of the four considered conditions (Kv1+WT, Kv1+WA, Kv2+WT, Kv2+WA) for most measures/metrics. For the velocity measures, the best results are achieved when using the Kv2 and WT data, overall. However, for the distance and angle measures, this depends on the considered joint. Although further investigation is needed, from the present study, it seems that WA data may be used in some cases.

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In conclusion, our results show that both Kinect versions can be an alternative to more expensive and intrusive reference systems like Qualisys, for obtaining distance and velocity measures as well as some angle measures (namely the knee angles). However, as the practical depth range is larger for Kv2, using it allows acquiring more data for the same number of trials. Regarding the comparison between WT and WA, although for some joints both data can be used with similar accuracy, better results were achieved, overall, for the traditional approach of using WT (especially for velocity measures).

Data Availability

The dataset used is available with the corresponding author.

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Author Contributions Statement

JPSC, HMPC, MCVB and APR conceptualized the article. MCVB, HMPC and APR performed project administration, data curation and software development. MCVB, HMPC and APR performed the experiments, formal analysis and investigation. JMF and JPSC were the supervisors of the project. MCVB and HMPC wrote the original draft. All authors reviewed the manuscript.

Conflict of interest statement

The authors declare no competing financial interests.

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Figure Legends:

Figure 1. Overall Pearson's correlation coefficient results, for both Kinects (v1 and v2), the three types of computed measures (velocity, distance and angle), and walking towards (WT) and away (WA) from the sensor. Green stands for excellent (≥ 0.90), yellow for good (≥ 0.75 and < 0.90), orange for moderate (≥ 0.50 and < 0.75) and red for poor correlation (< 0.50). Results are indicated for the main body segments/joints with the exception of the trunk for the distance measure.

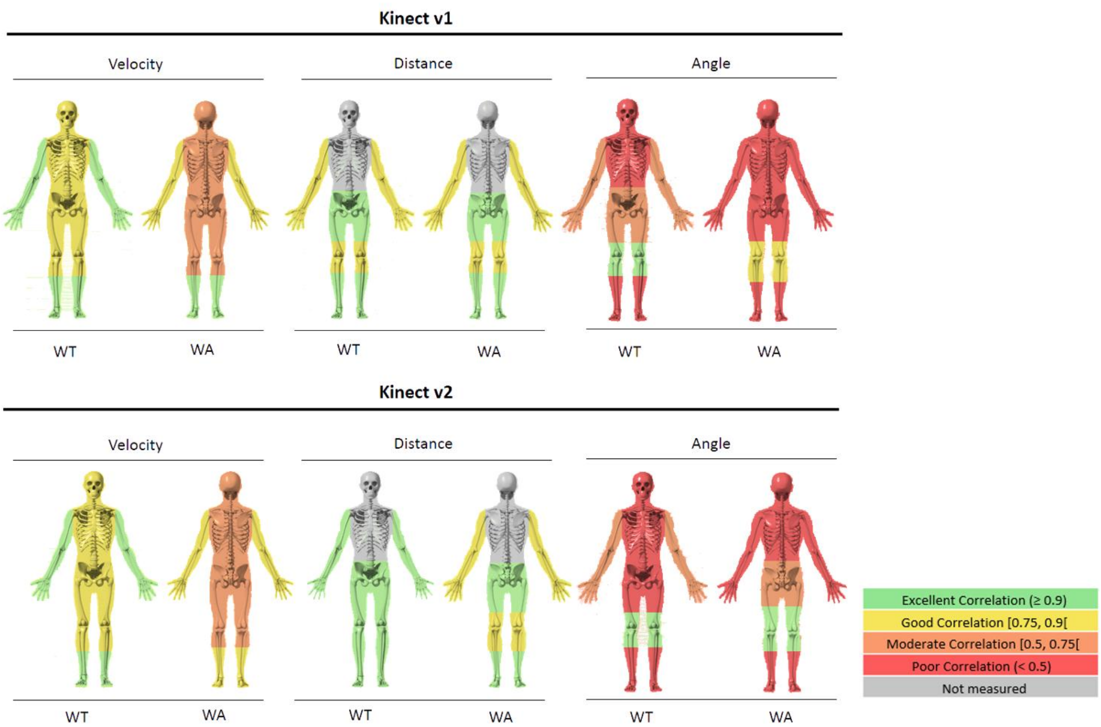

Table 1

Author, Year	Goal	Kinect version	Experimental setup	No. of subjects	Performed task(s)	Measures	Evaluation metrics	Main conclusions
Clark et al., 2012	Postural control assessment	v1	Subject at 2.5 m from Kinect	20 healthy	Three postural tasks	Joint displacement and trunk flexion angle	Pearson's correlation coefficient (*r*), ordinary least products regression, and Bland-Altman 95% limits of agreement (LoA)	The Kinect can be used to assess kinematic variables during postural control tasks.
Clark et al., 2013	Gait assessment	v1	n.d.	21 healthy	Walking (comfortable pace)	Spatiotemporal gait parameters	Bland-Altman bias and 95% LoA, percentage error, *r*, and concordance correlation coefficient (r_c)	Gait speed, step length and stride length present excellent relative and overall agreement. For the remaining variables, agreement varies between poor and excellent.
Galna et al., 2014	Movement measurement in Parkinson's disease patients	v1	1 Kinect w/ 1 m height, tilt angle of 0º; subjects at 3 m from Kinect	9 w/ Parkinson's disease + 10 healthy	Clinically relevant tasks (including walking)	Temporal and spatial measures	Bland-Altman bias and 95% LoA, *r*, and intraclass correlation coefficient (ICC)	The Kinect accurately measures timing for all movements, and spatial characteristics for gross movements.
Pfister et al., 2014	Gait assessment during treadmill walking	v1	1 Kinect w/ 43 cm height, placed 45˚ to the left of treadmill	20 healthy	Treadmill walking (three different speeds)	Stride timing; hip and knee flexion and extension angles	Bland-Altman bias, *r*	The Kinect under-estimates joint flexion, while it over-estimated joint extension. The hip angular displacement has very low correlation and a large error. The knee measurements were better correlated than the hip, but were not consistent enough for clinical applications. For stride timing, correlation was high, and error was relatively small.
Behrens et al., 2014	Feasibility of computerized versions of walking tests	v1	1 Kinect in front of subject 140 cm above ground, angled -9° towards the floor	22 w/ Multiple Sclerosis + 22 healthy	Short Maximum Speed Walk test	gait speed and degree of sway	feasibility, reliability and correlation with EDSS and the T25FW	Detection of ambulation speed via the joint hip-centre was feasible and reliable. SMSW average walking speed was a valid parameter as demonstrated by retest reliability results and the strong correlation with established clinical scores.
Xu & McGorry, 2015	Kinect's joint tracking algorithm evaluation	v1 and v2	n.d.	20 + 20 healthy	Standing and sitting postures	Joint position (time series)	Distance between joint position provided by Kinect and ground truth system	Accuracy is better for standing than sitting, and for upper than lower limb joints. The average error for all joints is slightly higher for Kinect v2 comparing with v1 (difference of 1 cm).
Clark et al., 2015	Standing balance and postural control assessment	v2	Subjects at 2.5 m from Kinect	30 healthy	Standing and dynamic balance tasks	Trunk angle range; sternum and pelvis range and path length	Bland-Altman plots with 95% LoA, and *r*	Relative agreement was excellent for trunk angle (dynamic tasks), as well as for anterior-posterior range and path length (static tasks). For the medial-lateral range an path length, the agreement varied between poor and modest for all static tasks expect one.
Xu et al., 2015	Gait assessment during treadmill walking	v1	1 Kinect in front of treadmill	20 healthy	Treadmill walking (three different speeds)	Spatiotemporal and kinematic gait parameters	Bland-Altman bias, *r* and r_c (spatiotemporal parameters); Bland-Altman bias (kinematic parameters and associated timing); root mean square error (angle at knee and hip, joint time series)	Accuracy varies across the gait parameters. The Kinect is able to follow the trend of the knee and hip joint trajectories, despite substantial error in magnitudes.
Mentiplay et al., 2015	Gait assessment	v2	n.d.	30 healthy	Walking (comfortable and fast pace)	Spatiotemporal and kinematic gait parameters	Bland-Altman plots, *r*, and r_c	Most spatiotemporal parameters presented excellent agreement, while agreement was poor to modest for kinematic parameters .
Geerse et al., 2015	Gait assessment	v2	4 Kinects alongside a walkway (first sensor at 4 m from start, and 2.5 m of inter-sensor distance) w/ 0.75 m height	21 healthy	Walking (comfortable and maximum speeds)	Joint position time series; spatiotemporal gait parameters; 10 m walking time	Bland-Altman's bias and limits of agreement, ICC	Joint location time series obtained with the multi-Kinect v2 setup agree well with those derived with a gold standard. Agreement was also high for the time to walk 10 m and all gait parameters except one.
Wang et al., 2015	Pose tracking	v1 and v2	1 Kinect w/ 1.5 m height; three different viewpoints	10 healthy	Standing and sitting tasks	Joint position (20 joints); bone length	Distance/difference between joint position/bone length provided by Kinect and ground truth system	Kinect v2 has better accuracy in joint position estimation (more robust to occlusions and body rotation).
Capecci et al., 2016	Low-back pain rehabilitation	v2	n.d.	12 healthy	Low-back pain physiotherapy exercises	Joint angle, distance, and position	Absolute and relative error for maximum and minimum value (angle and position); offset and root mean square error (distance); absolute error for time-peak distance (angle and position)	Temporal accuracy: Kinect v2 can accurately measure timing characteristics of physical exercises. Spatial accuracy: Better for tasks involving upper limbs comparing with lower limbs.
Otte et al., 2016	Clinical measurement of motor function	v2	1 Kinect w/ 1.4 m height, tilt angle of −8°	19 healthy	Sitting, standing and walking tasks	Joint position (21 out of 25 joints); spatiotemporal and kinematic measures	Distance, *r*, and signal to noise ratio (SNR) for joint position provided by Kinect and ground truth system; Bland-Altman bias and 95% LoA, *r*, and ICC, for the spatiotemporal and kinematic measures	Accuracy of Kinect v2 joint estimation is moderate to excellent, w/ larger noise for ankles and feet. Agreement is good to excellent for most spatiotemporal and kinematic measures.
Behrens et al., 2016	Visual perceptive computing (VPC) for static posturography	v1	1 Kinect w/ 1.4 m height, mean distance of 2.3 m	90 w/ Multiple Sclerosis + 59 healthy	Static stance tests in three conditions with eyes open and closed.	Body's centre of mass displacement	Clinical scores and intra-class correlation coefficients at retest	Closed stance test showed best applicability and reliability. Postural control can be reliably assessed by VPC-based static posturography in patients with MS.
Muller et al., 2017	Gait assessment	v2	6 Kinects placed pairwise in rows along 7 m	10 healthy	Walking (comfortable pace)	Spatiotemporal gait parameters	Bland-Altman bias, reproducibility coefficient, and coefficient of variation, *r*, and ICC	Kinect's joint tracking is sensitive to view angle. Better accuracy for two-sided than one-sided setup, mainly due to better lower body joint tracking. Excellent agreement for all gait parameters for two-sided setup. Temporal synchronization between Kinects is essential.
Napoli et al., 2017	Dynamic posture assessment	v2	2 Kinects placed at 2 m and 4 m in front of the subject	4 healthy	Several dynamic postures	Joint displacement (time series)	Cross correlation coefficients (CCR), root mean squared error (RMSE), and a new summary metric combining the two first metrics	High levels of agreement when tracking joint displacements, but lower agreement levels were achieved when tracking joint angles.
Grobelny et al., 2017	Gait assessment	v1	1 Kinect in front of the subjects who walked from 3.5 to 1.5 m from the camera	95 w/ Multiple Sclerosis + 60 healthy	Gait	Average speed, Speed deviation, Vertical deviation, Mediolateral deviation and 3D deviation, based on the coordinates of the "hip center joint"	Skewness and kurtosis, Mann-Whitney U test, Spearman's Rho, ICC, Standard error of measurement, smallest real difference, one-way repeated measures ANOVA, multivariate linear regressions per variable, Pearson correlation, Bland-Altman-Plot, Student's t-test, Levene's test, Welch's t-test	Average speed was the most reliable parameter. VPC-assessed walking parameters during SMSW can reliably detect gait disturbance in PwMS over very short distance

Table 1. Summary of the state-of-the-art concerning the validity of the Kinect. n.d. stands for not-disclosed.

Table 2

Measure[a] & Body segments/Joints[b]	Kinect version	Walking towards the sensor (WT)				Walking away from the sensor (WA)			
		Mean True error (m/s)	Mean Absolute error (m/s)	*r*	ODR (dB)	Mean True error (m/s)	Mean Absolute error (m/s)	*r*	ODR (dB)
Vel. Trunk	**v1**	0.06 ± 0.02	0.09 ± 0.02	0.79 ± 0.13	2.44 ± 3.19	0.10 ± 0.04	0.13 ± 0.04	0.61 ± 0.24	−1.86 ± 4.64
	v2	0.01 ± 0.01	0.06 ± 0.01	0.86 ± 0.10	6.06 ± 3.78	0.02 ± 0.02	0.08 ± 0.03	0.64 ± 0.24	−0.16 ± 5.68
Vel. UL	**v1**	0.09 ± 0.03	0.15 ± 0.04	0.90 ± 0.07	7.37 ± 2.95	0.09 ± 0.04	0.17 ± 0.07	0.83 ± 0.17	5.10 ± 3.67
	v2	0.01 ± 0.02	0.10 ± 0.07	0.92 ± 0.15	10.51 ± 3.43	0.03 ± 0.04	0.12 ± 0.09	0.82 ± 0.25	7.06 ± 5.37
Vel. Upper-LL	**v1**	0.08 ± 0.03	0.17 ± 0.03	0.82 ± 0.08	5.95 ± 2.01	0.10 ± 0.05	0.21 ± 0.06	0.74 ± 0.16	3.56 ± 2.58
	v2	0.02 ± 0.02	0.15 ± 0.05	0.84 ± 0.13	6.59 ± 2.13	0.04 ± 0.03	0.19 ± 0.07	0.74 ± 0.20	3.94 ± 3.01
Vel. Lower-LL	**v1**	0.12 ± 0.06	0.40 ± 0.12	0.92 ± 0.05	9.28 ± 2.53	0.13 ± 0.09	0.47 ± 0.17	0.90 ± 0.13	7.98 ± 2.50
	v2	0.06 ± 0.05	0.37 ± 0.16	0.92 ± 0.14	9.71 ± 2.33	0.11 ± 0.07	0.47 ± 0.23	0.89 ± 0.20	8.39 ± 2.61
Vel. Full-Body	**v1**	**0.09 ± 0.04**	**0.19 ± 0.05**	**0.87 ± 0.08**	**6.48 ± 2.73**	**0.10 ± 0.05**	**0.23 ± 0.08**	**0.78 ± 0.17**	**3.98 ± 3.41**
	v2	**0.02 ± 0.02**	**0.15 ± 0.07**	**0.89 ± 0.13**	**8.68 ± 3.02**	**0.05 ± 0.04**	**0.19 ± 0.10**	**0.78 ± 0.23**	**5.26 ± 4.41**
Dist. UL	**v1**	20.43 ± 10.96	24.42 ± 8.53	0.88 ± 0.10	5.71 ± 3.37	19.37 ± 10.92	23.25 ± 9.69	0.77 ± 0.17	3.66 ± 4.39
	v2	26.26 ± 8.31	29.13 ± 8.15	0.90 ± 0.15	7.24 ± 3.87	21.97 ± 11.14	25.40 ± 12.32	0.82 ± 0.21	5.41 ± 5.60
Dist. Knees	**v1**	18.23 ± 15.52	24.55 ± 12.41	0.89 ± 0.12	7.41 ± 3.49	45.07 ± 14.72	48.24 ± 13.60	0.84 ± 0.12	5.54 ± 3.05
	v2	13.04 ± 7.89	18.94 ± 6.50	0.93 ± 0.08	8.98 ± 2.53	26.14 ± 8.98	31.36 ± 8.89	0.88 ± 0.12	6.31 ± 3.07
Dist. Ankles	**v1**	31.35 ± 25.82	40.19 ± 24.66	0.95 ± 0.09	12.58 ± 4.47	29.02 ± 23.50	44.96 ± 21.24	0.94 ± 0.08	10.87 ± 3.50
	v2	44.44 ± 17.06	48.67 ± 21.04	0.94 ± 0.13	12.58 ± 4.58	36.24 ± 15.82	44.64 ± 21.05	0.96 ± 0.11	12.55 ± 3.62
Dist. Feet	**v1**	77.01 ± 32.76	81.88 ± 29.46	0.92 ± 0.10	9.20 ± 3.18	89.62 ± 22.49	93.83 ± 20.84	0.93 ± 0.08	9.88 ± 2.86
	v2	88.14 ± 27.03	91.25 ± 27.04	0.92 ± 0.12	9.30 ± 2.92	109.64 ± 20.32	114.0 ± 19.82	0.92 ± 0.11	8.84 ± 2.55
Dist. Full-Body	**v1**	**31.31 ± 17.83**	**36.64 ± 15.35**	**0.90 ± 0.10**	**7.72 ± 3.54**	**36.97 ± 15.58**	**42.80 ± 14.13**	**0.84 ± 0.13**	**6.21 ± 3.76**
	v2	**37.40 ± 12.82**	**41.04 ± 13.17**	**0.91 ± 0.13**	**8.76 ± 3.61**	**39.65 ± 13.09**	**44.37 ± 14.45**	**0.87 ± 0.16**	**7.32 ± 4.34**
Ang. Trunk	**v1**	3.37 ± 2.84	4.21 ± 2.54	0.23 ± 0.45	3.56 ± 3.11	8.15 ± 5.87	9.36 ± 5.27	0.08 ± 0.41	−8.30 ± 5.63
	v2	8.87 ± 3.77	9.04 ± 3.60	0.41 ± 0.44	0.36 ± 4.28	5.14 ± 5.25	5.74 ± 4.96	0.08 ± 0.44	−4.28 ± 4.39
Ang. UL	**v1**	9.09 ± 2.27	10.02 ± 1.97	0.60 ± 0.29	3.54 ± 3.29	12.50 ± 3.74	13.12 ± 3.43	0.15 ± 0.30	−0.87 ± 2.90
	v2	5.94 ± 2.05	6.90 ± 1.92	0.59 ± 0.29	4.00 ± 3.06	10.49 ± 2.84	11.16 ± 2.44	0.10 ± 0.28	−0.77 ± 2.94
Ang. Hips	**v1**	5.21 ± 2.73	6.19 ± 2.07	0.62 ± 0.23	2.14 ± 2.18	5.15 ± 2.81	7.34 ± 2.54	0.13 ± 0.42	−1.66 ± 2.74
	v2	6.32 ± 2.84	8.55 ± 2.07	0.13 ± 0.33	−2.75 ± 2.84	4.47 ± 2.62	6.60 ± 1.66	0.54 ± 0.26	−0.80 ± 2.70
Ang. Knees	**v1**	8.16 ± 2.87	9.04 ± 2.81	0.93 ± 0.11	8.42 ± 2.95	3.34 ± 2.29	7.31 ± 2.70	0.87 ± 0.18	6.79 ± 3.05
	v2	2.62 ± 1.60	5.22 ± 1.71	0.94 ± 0.10	9.47 ± 2.13	4.52 ± 2.67	7.12 ± 2.84	0.91 ± 0.20	8.17 ± 2.74
Ang. Ankles	**v1**	15.88 ± 8.91	27.21 ± 5.57	−0.18 ± 0.25	−10.12 ± 1.78	27.26 ± 7.53	33.63 ± 5.30	0.01 ± 0.24	−10.38 ± 3.06
	v2	6.61 ± 5.44	17.72 ± 2.88	−0.15 ± 0.24	−9.02 ± 1.45	20.83 ± 7.31	32.08 ± 5.89	−0.02 ± 0.21	−11.33 ± 2.35
Ang. Full-Body	**v1**	**8.47 ± 3.65**	**11.11 ± 2.82**	**0.46 ± 0.27**	**0.60 ± 3.15**	**11.48 ± 4.33**	**13.98 ± 3.78**	**0.23 ± 0.31**	**−2.55 ± 3.38**
	v2	**6.27 ± 3.02**	**9.05 ± 2.44**	**0.42 ± 0.30**	**0.96 ± 2.92**	**9.32 ± 3.92**	**12.31 ± 3.37**	**0.29 ± 0.28**	**−1.63 ± 3.01**

[a] Vel., Dist. and Ang. stand for velocity, distance and angle, respectively. [b]UL e LL stand for upper and lower limb, respectively.

Table 2. Mean and standard deviation values for the mean true and absolute errors, Pearson's correlation coefficient (*r*), and optical-to-depth ratio (ODR), for velocity, distance and angle of the considered body segments (trunk, upper limbs (UL), upper lower limbs (upper-LL), and lower lower limbs (lower-LL)), and joints (hips, knees, ankles and feet). The values are indicated for both Kinect versions (v1 and v2), and for walking both towards (WT) and away (WA) from the sensors. Results were obtained from 20 participants, 10

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trials each (200 trials in total). The presented values correspond to the mean value of: each body side (left and right for individual joints); segment' joints (for body segments); and the full-body result represent the mean values of all body segments.