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Short communication

Reliability and comparison of Kinect-based methods for estimating spatiotemporal gait parameters of healthy and post-stroke individuals

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ABSTRACT

Different studies have analyzed the potential of the off-the-shelf Microsoft Kinect, in its different versions, to estimate spatiotemporal gait parameters as a portable markerless low-cost alternative to laboratory grade systems. However, variability in populations, measures, and methodologies prevents accurate comparison of the results. The objective of this study was to determine and compare the reliability of the existing Kinect-based methods to estimate spatiotemporal gait parameters in healthy and post-stroke adults. Forty-five healthy individuals and thirty-eight stroke survivors participated in this study. Participants walked five meters at a comfortable speed and their spatiotemporal gait parameters were estimated from the data retrieved by a Kinect v2, using the most common methods in the literature, and by visual inspection of the videotaped performance. Errors between both estimations were computed. For both healthy and post-stroke participants, highest accuracy was obtained when using the speed of the ankles to estimate gait speed (3.6–5.5 cm/s), stride length (2.5–5.5 cm), and stride time (about 45 ms), and when using the distance between the sacrum and the ankles and toes to estimate double support time (about 65 ms) and swing time (60–90 ms). Although the accuracy of these methods is limited, these measures could occasionally complement traditional tools.

1. Introduction

Alterations in gait are a common sequelae after stroke (Goldie et al., 1996). Assessment of gait-related impairments is commonly performed through standardized clinical scales and tests, such as the 6-Minute Walk Test (Dunn et al., 2015), the 10-Meter Walk Test, (Bohannon et al., 1996), or the Dynamic Gait Index (Whitney et al., 2000), which are usually easy to administer and not time-consuming. In contrast, traditional tools usually provide global scores, and may have limited sensitivity and be biased.

Kinematic and spatiotemporal analysis of gait enables identification of abnormal patterns and behavior in the different phases. Most widely used solutions for gait analysis use multicamera marker-based motion tracking to detect body segments during walking (Carse et al., 2013). Kinematic and spatiotemporal parameters can also be estimated from wearable inertial sensors (Sprager and Juric, 2015) or instrumented walkways (Wong et al., 2014), respectively. Although many solutions are available, they present common limitations, such as the high cost and required space, that may limit their clinical use.

Recently, the off-the-shelf Microsoft Kinect (Microsoft, Redmond, WA), in its different versions, has enabled human motion tracking by estimating the 3D position of the main joints without using markers and with higher portability, which has motivated its use for gait analysis. Different studies have reported the reliability of different methods of estimating spatiotemporal gait parameters in healthy population with comparable results to laboratory-grade systems, with both the first (Clark et al., 2013; Pfister et al., 2014; Stone et al., 2011; Xu et al., 2015; Baldewijns et al., 2014) and second version of the Kinect (Dolatabadi et al., 2016; Mentiplay et al., 2015; Eltoukhy et al. 2017a, 2017b; Müller et al., 2017; Geerse et al., 2015). The second version of the device improves some features of the previous version. Specifically, it has wider field of view and depth range and higher camera and depth resolution. Besides, Kinect v2 has shown better global performance regarding accuracy and stable data (Gonzalez-Jorge et al., 2015). An increasing number of studies have focused on spatiotemporal gait analysis with these devices in post-stroke individuals (Vernon et al., 2015; Clark et al., 2012; Cao et al., 2017).

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However, variability in populations, measures, and methodologies prevents adequate comparison of the results. Consequently, the real strengths and weaknesses of each method remain unclear.

The objective of this study was to determine and compare the reliability of the most common methods in the literature to estimate spatiotemporal gait parameters using the Kinect v2 in healthy and post-stroke adults.

2. Methods

2.1. Participants

Individuals from 18 to 80 years old with no known musculoskeletal or vestibular disease and/or prosthetic surgery were recruited from the student body and staff of Universitat Politècnica de València. Post-stroke individuals were recruited from the outpatient service of Servicio de Neurorrehabilitación y Daño Cerebral of Hospitales Vithas-NISA. The stroke group included stroke survivors from 18 to 80 years old, able to walk ten meters and follow instructions (Mississippi Aphasia Screening Test >45) (Romero et al., 2012), with fairly good cognitive condition (Mini-Mental State Examination >23) (Folstein et al., 1975) and without fixed contracture, arthritic or orthopedic conditions in the legs.

The healthy group consisted of 45 participants (31 men, 14 women) with a mean age of 30.6 ± 7.6 years old. The stroke group consisted of 38 participants (22 men, 16 women), with a mean age of 56.1 ± 13.2 years old, a mean chronicity of 14.7 ± 8.5 months, and a mean score in the gait sub-scale of the Tinetti Performance-Oriented Mobility Assessment (Tinetti 1986) of 10.5 ± 1.5.

Ethical approval for the study was granted by the Institutional Review Board of Vithas-NISA Valencia al Mar Hospital. All eligible candidates who agreed to take part in the study provided informed consent.

2.2. Instrumentation

Position of the 25 main joints were obtained from a Kinect v2 at 30 Hz, using the Kinect for Windows Software Development Kit 2.0, and a high-performance PC that incorporated an 8-core Intel® Core™ i7-3632QM @3.60 GHz and 8 GB of RAM. A video camera Sony HXR-MC50E (Sony Corporation, Tokyo, Japan) was used to film the trials at 1920 × 1080 pixel resolution and 30 fps. A 6-m long and 1-m wide measuring walkway with an accuracy of 0.5 cm was used to estimate distances. The measuring walkway consisted of a printed vinyl with multiple transversal lines, each separated 0.5 cm from the others (Fig. 1).

2.3. Procedure

The experiment took place in a dedicated space free of obstacles and distractors. The Kinect v2 was fixed on a standing platform at 80 cm of height, oriented parallel to the floor. The measuring walkway was fixed to the floor along the sagittal axis of the Kinect v2. The video camera was fixed at 70 cm of height, also oriented parallel to the floor in a transversal axis to the measuring walkway.

All the participants were initially positioned five meters away from the Kinect v2 and were briefly introduced to the purpose of the study. Participants were required to wear close-fitting, pale, and non-reflective clothes to avoid additional tracking errors. An experimenter indicated them to walk on the walkway towards the device with a comfortable speed until they reached the standing platform. This test was repeated until three repetitions were obtained without errors. The performance of the participants was filmed with the video camera and registered with the Kinect v2.

2.4. Data analysis

Since the reliable tracking range of the Kinect v2 is restricted to 4 m (from 4.5 to 0.5 m) (Dolatabadi et al., 2016; Geerse et al., 2015; Rocha et al., 2015), the analysis of the data was limited to that space. Spatiotemporal parameters were estimated from both the recorded video and the Kinect-based data. The video was visually analyzed frame by frame and the gait events (heel strike and toe-off) were determined from the height of the ankles and toes. Spatiotemporal parameters were derived from them (Perry, 1992). Outliers of the Kinect-based data were discarded by visual inspection. After this, spatiotemporal parameters were estimated: (a) as in the video analysis; (b) from the speed of the ankles and the toes (Clark et al., 2013; Mentiplay et al., 2015); (c) from the distance between the knees (Auvinet et al., 2015); (d) from the distance between the sacrum and the ankles and toes (Zeni et al., 2008); and (e) from the height of the center of mass (Baldewijns et al., 2014) (Table 1). Spatiotemporal measures included speed, stride distance and time, step distance, time, and asymmetry, and double support and swing time. For each repetition, the average of the spatiotemporal parameters estimated using the aforementioned methods and the recorded video in all the detected steps was computed. Mean absolute and relative errors were estimated, also for each repetition, between the averaged spatiotemporal parameters derived from the methods and those from the recorded video. Absolute error was computed as the absolute value of the difference between a measure obtained with one of the methods and that obtained from the recorded video. The relative error was computed as the absolute error divided by the measure obtained with

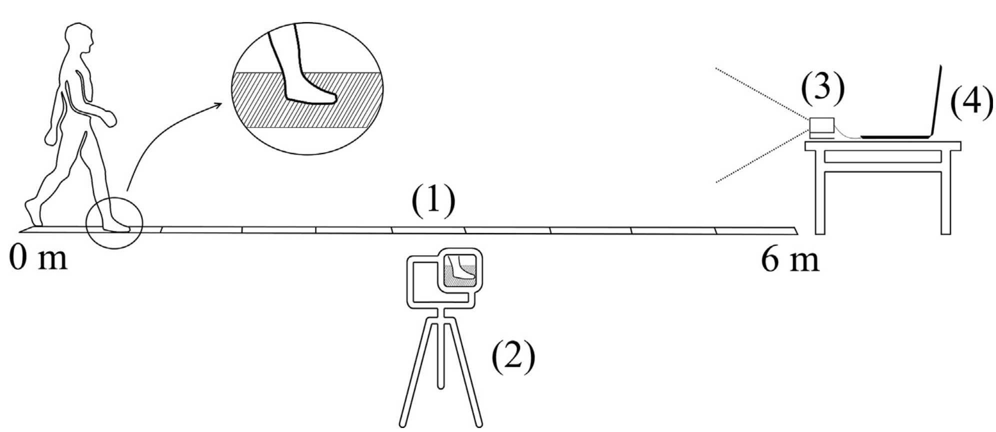
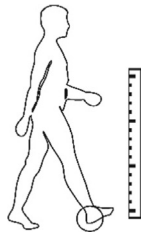
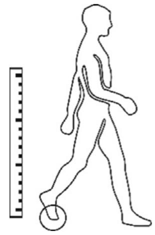
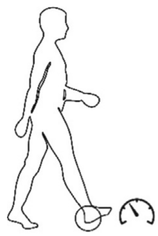
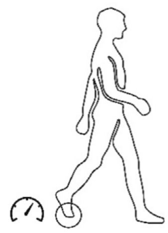
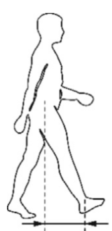
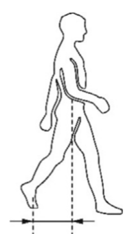
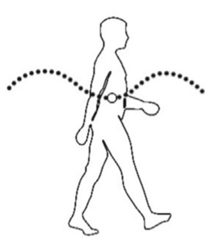


Fig. 1. Description of the setup. The setup consisted of (1) a vinyl walkaway; (2) a video camera; (3) a Kinect v2; and (4) a laptop.

Table 1
Description of the methods used to estimate spatiotemporal measures.

Method	Heel strike	Toe-off	Description
Height of ankle and toe			Heel strike is defined as the first instant when the height of the ankle reaches the minimum. Toe-off is defined as the last frame in which the height of the toe is minimum.
Speed of ankle and toe			Heel strike is defined as the instant when the speed of the ankle decreases below 1 cm/s. Toe-off is defined as the instant when the speed of the ankle increases above 1 cm/s.
Distance between the knees		–	Heel strike is defined as the instant when the distance between the knees is maximum. Toe-off cannot be estimated.
Distance between sacrum and ankles and toes			Heel strike is defined as the instant when the distance between the sacrum* and the ankle joint of leading leg is maximum. Toe-off is defined as the instant when the distance between the sacrum* and the toe joint of the rear leg is maximum. *: The spine base joint provided by the Kinect v2 was used to identify the sacrum.
Height of the center of mass		–	Heel strike is defined as the instant when the height of the center of mass reaches a local minimum. Toe-off cannot be estimated.

The table describes how heel strike and toe-off events are estimated in the existing methods.

the recorded video, and multiplied by 100. Afterwards, the average of the absolute and relative errors in all the repetitions were obtained for each participant. Finally, the mean absolute and relative errors for each method were computed.

3. Results

Mean values of each parameter, method, and population are shown in Table 2. The method based on the speed of ankles and toes was the most reliable option for estimating the speed, stride, and step measures for healthy individuals (Table 3). For post-stroke individuals, this method also provided the best results for stride time and length, and step time and length. Absolute errors with this method in healthy and post-stroke individuals were, respectively, 5.5 and 3.6 cm/s for gait speed, 5.5 and 2.5 cm for stride length, and about 45 ms for stride time in both groups. Relative errors ranged from 2.5% to 5% for all these measures but for the step asymmetry, which was remarkably high for both populations.

The method based on the distance between the sacrum and the ankles and toes resulted the most reliable option for detecting double support and swing time in both populations. Absolute errors of this method in healthy and post-stroke individuals were about 65 ms for double support time, and 60–90 ms for swing time, respectively. Relative errors for these measures ranged from 20% to 35%.

4. Discussion

In this study, the reliability of the most common methods in the literature to estimate spatiotemporal gait parameters was determined and compared in a sample of healthy and post-stroke adults, who were tracked by the Kinect v2. Although all the methods provided limited accuracy, speed, stride, and step measures were more reliably estimated using the speed of the ankles, while the

Table 2
Spatiotemporal gait parameters of healthy and post-stroke individuals.

	Healthy individuals						Post-stroke individuals					
	Camera Based	Height of ankles and toes	Speed of ankles and toes	Distance between the knees	Distance between sacrum and the ankles and toes	Height of the center of mass	Camera based	Height of ankles and toes	Speed of ankles and toes	Distance between the knees	Distance between sacrum and the ankles and toes	Height of the center of mass
Speed (m/s)	1.144 ± 0.063	1.153 ± 0.100	1.167 ± 0.072	1.182 ± 0.079	1.176 ± 0.097	1.170 ± 0.083	0.865 ± 0.050	0.845 ± 0.065	0.905 ± 0.088	0.888 ± 0.058	0.902 ± 0.063	0.878 ± 0.095
Stride length (m)	1.306 ± 0.043	1.353 ± 0.123	1.323 ± 0.063	1.324 ± 0.068	1.293 ± 0.109	1.332 ± 0.087	1.018 ± 0.036	0.984 ± 0.074	1.061 ± 0.067	1.013 ± 0.039	1.005 ± 0.043	1.041 ± 0.121
Stride time (s)	1.150 ± 0.039	1.196 ± 0.132	1.143 ± 0.053	1.133 ± 0.074	1.156 ± 0.140	1.151 ± 0.087	1.198 ± 0.045	1.182 ± 0.071	1.196 ± 0.056	1.164 ± 0.073	1.142 ± 0.066	1.206 ± 0.108
Step length (m)	0.652 ± 0.021	0.698 ± 0.061	0.661 ± 0.022	0.663 ± 0.040	0.647 ± 0.043	0.660 ± 0.057	0.509 ± 0.018	0.516 ± 0.031	0.537 ± 0.029	0.510 ± 0.019	0.508 ± 0.022	0.517 ± 0.074
Step time (s)	0.575 ± 0.020	0.596 ± 0.071	0.571 ± 0.028	0.567 ± 0.038	0.571 ± 0.055	0.576 ± 0.053	0.599 ± 0.023	0.587 ± 0.034	0.592 ± 0.035	0.578 ± 0.036	0.560 ± 0.035	0.603 ± 0.062
Step asymmetry (m)	0.031 ± 0.023	0.167 ± 0.159	0.056 ± 0.061	0.114 ± 0.090	0.061 ± 0.058	0.166 ± 0.166	0.055 ± 0.025	0.122 ± 0.119	0.092 ± 0.105	0.077 ± 0.073	0.060 ± 0.053	0.158 ± 0.110
Double support time (s)	0.191 ± 0.026	0.166 ± 0.062	0.109 ± 0.064	–	0.155 ± 0.050	–	0.402 ± 0.053	0.465 ± 0.293	0.531 ± 0.418	–	0.400 ± 0.098	–
Swing time (s)	0.384 ± 0.038	0.512 ± 0.076	0.537 ± 0.074	–	0.433 ± 0.039	–	0.801 ± 0.045	0.831 ± 0.227	0.769 ± 0.378	–	0.737 ± 0.071	–

The table shows the mean value and standard deviation of each parameter obtained using the video camera and Kinect v2-based methods.

Table 3
Reliability of Kinect-based methods for estimating spatiotemporal gait parameters of healthy and post-stroke individuals.

	Healthy individuals					Post-stroke individuals				
	Height of ankles and toes	Speed of ankles and toes	Distance between the knees	Distance between sacrum and the ankles and toes	Height of the center of mass	Height of ankles and toes	Speed of ankles and toes	Distance between the knees	Distance between sacrum and the ankles and toes	Height of the center of mass
Speed (m/s)	0.078 (6.71%)	0.055 ✓(4.79%)	0.072 (6.25%)	0.101 (8.43%)	0.069 (6.13%)	0.055 (5.73%)	0.043 (4.45%)	0.036 ✓ (4.25%)	0.047 (5.29%)	0.047 (5.44%)
Stride length (m)	0.109 (8.36%)	0.055 ✓ (4.20%)	0.069 (5.19%)	0.103 (7.50%)	0.072 (5.52%)	0.099 (8.84%)	0.025 ✓ (2.40%)	0.031 (3.12%)	0.039 (3.83%)	0.074 (7.17%)
Stride time (s)	0.095 (8.27%)	0.045 ✓ (3.96%)	0.059 (5.09%)	0.091 (8.04%)	0.061 (5.29%)	0.086 (7.16%)	0.046 ✓ (3.93%)	0.053 (4.42%)	0.065 (5.47%)	0.078 (6.60%)
Step length (m)	0.054 (8.35%)	0.020 ✓(3.16%)	0.034 (5.26%)	0.030 (4.59%)	0.041 (6.39%)	0.031 (6.13%)	0.013 ✓ (2.48%)	0.015 (3.06%)	0.016 (3.17%)	0.046 (8.75%)
Step time (s)	0.051 (8.87%)	0.023 ✓ (4.09%)	0.031 (5.43%)	0.039 (6.92%)	0.035 (6.25%)	0.046 (7.85%)	0.022 ✓ (3.77%)	0.030 (5.06%)	0.044 (7.37%)	0.043 (7.21%)
Step asymmetry (m)	0.148 (978.41%)	0.045 ✓ (253.69%)	0.099 (619.19%)	0.049 (283.69%)	0.143 (802.67%)	0.101 (325.45%)	0.083 (217.63%)	0.064 (217.02%)	0.054 ✓ (171.12%)	0.127 (516.14%)
Double support time (s)	0.106 (53.52%)	0.114 (59.22%)	–	0.064 ✓ (33.92%)	–	0.158 (79.18%)	0.356 (175.05%)	–	0.067 ✓ (34.09%)	–
Swing time (s)	0.140 (36.76%)	0.159 (40.14%)	–	0.062 ✓ (19.29%)	–	0.109 (27.59%)	0.145 (37.67%)	–	0.087 ✓ (21.20%)	–

The table shows, for each parameter, the mean absolute and relative errors (in percentage) between the corresponding method and the measure estimated by visual inspection of the performance. ✓: Minimum error for each parameter and population among methods.

distance between the sacrum and the ankles and toes provided the highest reliability to estimated shorter events, as double support and swing time.

The errors detected in our study are similar but slightly higher than those reported in previous studies that involved healthy (Baldewijns et al., 2014; Auvinet et al., 2015; Mentiplay et al., 2015; Dolatabadi et al., 2016; Eltoukhy et al., 2017b) and post-stroke individuals (Zeni et al., 2008; Clark et al., 2012), which could be explained by differences in methodologies, conditions, and data analysis. For instance, in contrast to studies focused on gait analysis on a treadmill (Eltoukhy et al., 2017a; Clark et al., 2013), participants in our study had to walk towards the Kinect v2. This implied detecting their movements with changing size and lighting conditions, which could be detrimental to the accuracy (Xu et al., 2015). Differences between populations could be explained by dissimilarities in their gait speed (Goldie et al., 1996), and have been detected previously using machine learning methods and the Kinect v2 (Dolatabadi et al., 2017).

Inaccuracies in the measures estimated with the Kinect v2 could be derived from the speed and jitter of the tracking (Lloréns et al., 2015), which has been reported to be particularly troublesome for the ankle and toe (Eltoukhy et al., 2017a). This could explain that the worst results were obtained for events of short duration and length (double support and step asymmetry) and for those that involved toe-off detection (double support and swing time). However, it is important to highlight that in events of short duration and length, even small changes may cause very high relative errors. Our results suggest, therefore, that gait analysis with the Kinect v2 should be limited to events with a certain duration and length, such as gait speed, stride and step measures. For these parameters, the use of the speed of the ankles and toes (Clark et al., 2013; Mentiplay et al., 2015) provided the best results in both populations. However, inaccuracies of the Kinect v2, which has been recently discontinued, could be overcome by new depth cameras, such as the Intel® RealSense™ Depth Camera D435 (Intel Corporation, CA, US), and improved tracking algorithms.

It is important to highlight that the reference method used in the study provided limited accuracy and might have influenced additional errors on the measurements, in comparison to laboratory-grade systems, such as multiple infrared camera-based systems or instrumented walkways (Stillman and McMeeken, 1996). However, the use of a video camera for spatiotemporal analysis is affordable, valid, and is repeatedly used in the clinical setting.

However, despite the limitations, all the methods provided spatiotemporal measures with constrained error. These characteristics, together with the low-cost, availability, and non-invasive nature of the Kinect v2, could support its use for spatiotemporal gait analysis in certain conditions to complement traditional assessment tools.

5. Conclusion

Speed of the ankles resulted in the most reliable information to estimate speed, stride, and step measures. Shorter events, as double support and swing time, were more accurately estimated from the distance between the sacrum and the ankles and toes. Although the accuracy of these methods is limited, it could occasionally complement traditional tools.

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Conflict of interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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