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Accuracy of the Microsoft Kinect™ for measuring gait parameters during treadmill walking

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ABSTRACT

The measurement of gait parameters normally requires motion tracking systems combined with force plates, which limits the measurement to laboratory settings. In some recent studies, the possibility of using the portable, low cost, and marker-less Microsoft Kinect™ sensor to measure gait parameters on over-ground walking has been examined. The current study further examined the accuracy level of the Kinect sensor for assessment of various gait parameters during treadmill walking under different walking speeds. Twenty healthy participants walked on the treadmill and their full body kinematics data were measured by a Kinect sensor and a motion tracking system, concurrently. Spatiotemporal gait parameters and knee and hip joint angles were extracted from the two devices and were compared. The results showed that the accuracy levels when using the Kinect sensor varied across the gait parameters. Average heel strike frame errors were 0.18 and 0.30 frames for the right and left foot, respectively, while average toe off frame errors were −2.25 and −2.61 frames, respectively, across all participants and all walking speeds. The temporal gait parameters based purely on heel strike have less error than the temporal gait parameters based on toe off. The Kinect sensor can follow the trend of the joint trajectories for the knee and hip joints, though there was substantial error in magnitudes. The walking speed was also found to significantly affect the identified timing of toe off. The results of the study suggest that the Kinect sensor may be used as an alternative device to measure some gait parameters for treadmill walking, depending on the desired accuracy level.

1. Introduction

Measurement of spatiotemporal gait parameters, such as step cycle time, step width, and lower extremity joint angles, are crucial for human gait analysis. These parameters have been used for different purposes including representation of diseases [1,2], quantifying rehabilitation effectiveness [3], and investigating the effect of load carrying [4]. Traditionally, gait parameters are assessed by opto-electronic- or electromagnetic-based motion tracking systems combined with force plates. However, due to cost, low portability, and the expertise needed to operate motion tracking systems, their use is mainly limited to laboratories.

The Microsoft Kinect™ sensor was originally designed for using body movement to interact with video games on the Microsoft Xbox™ platform. The Kinect sensor can track 3-D movement through its depth sensor and output the location of 20 body joints in 3-D space at 30 Hz. Because the Kinect sensor is low cost and portable, some researchers have examined the validity of the Kinect sensor [5] and the possibility of adopting it for biomechanics studies [6–8]. Some previous studies [9–12] investigated the validity of the Kinect sensor for assessment of gait parameters. In Gabel et al. [10], a machine learning algorithm was developed to identify gait events from Kinect sensor-identified locations of all major joints. In Clark et al. [11], participants walked over-ground with their body movements recorded by both a motion tracking system and a Kinect sensor. Various gait parameters were extracted from the recordings of the two devices. The results indicated that Kinect sensor validity is good for step and stride length.

While some gait studies are based on over-ground walking, a number of other studies are based on treadmill walking [13–15]. Coverage may be a factor when using the Kinect sensor to detect

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gait parameters during over-ground walking. Clark et al. [11] stated that, due to the limited coverage of the Kinect sensor, over-ground walking needed to be performed at 3.8 m to 1.3 m in front of the sensor and concluded with a sudden stop. Treadmill walking allows for continuous walking while the participant remains in a limited movement space. However, walking patterns on treadmills may differ from that of over-ground walking [16]. In a recent study [12], the accuracy of the Kinect sensor in the measurement of knee and hip joint angles was examined and the results indicated that, while the Kinect sensor can provide an approximate joint trajectory, subtle changes in the joint angles cannot be well measured. The accuracy of the Kinect sensor in other gait parameters during treadmill walking, such as the timing events, remains unclear. Therefore, the purpose of this study is to understand the capability of the Kinect sensor for the assessment of various gait parameters during treadmill walking under different walking speeds.

2. Method

2.1. Participants

Twenty healthy participants (10 females and 10 males, age: 28.5 (8.2) years old, height: 1.71 (0.09) m, mass: 70.4 (10.9) kg) without musculoskeletal disorders were recruited from local communities. The study protocol was approved by the local Institutional Review Board. All the participants provided written informed consent before taking part in the study.

2.2. Experiment setup

Participants were given a brief training session with the treadmill (Model: Pro, Woodway USA Inc, Waukesha, WI, USA) to ensure they could acclimate to treadmill walking. During the study, three trials of treadmill walking were performed by the participants at three different walking speeds (0.85 m/s, 1.07 m/s, and 1.30 m/s). Each walking trial was performed for 5 min. A two-minute break was provided between each trial. Walking speed was randomized among the three trials.

A motion tracking system (Optotrak Certus System, Northern Digital, Canada) was used to collect 3-D motion data at 60 Hz of the pelvis, upper legs, lower legs, and feet during walking by tracking marker clusters taped to those segments. Anatomical landmarks for creating the anatomical coordinate system of each body segment [17] were digitized using a probe with the participant standing upright. Simultaneously, a Kinect sensor placed in front of the treadmill recorded 20 joint locations with customized software integrating Kinect for Windows SDK 1.5. The joint location data derived from the Kinect sensor was up-sampled to 60 Hz with spline interpolation [11]. Each participant elevated their arms three times before they started walking on the treadmill; synchronization between the Kinect sensor and the motion tracking system was accomplished by time-shifting the Kinect sensor data such that the mean-square residual between the Kinect sensor-based and motion tracking system-based arm elevation angles was minimized.

2.3. Data analysis

For each walking trial, after 1 min of walking, 10 consecutive strides were taken for data analysis. The timing of heel strike (HS) and toe-off (TO) are essential in determining various spatiotemporal gait parameters. To derive the timing of HS and TO from the kinematics data, a method proposed in a previous study [18] was adopted: timing of HS was defined as when the anterior-posterior distance between the heel of the front foot and mid-PSISs reached the maximum, and for TO timing was defined as when the distance between the toe of the rear foot and mid-PSIS reached maximum. This method [18] can detect HS and TO from the kinematics data with an approximately 1/60 s error as compared with ground reaction force (GRF)-based HS and TO, the golden standard of HS and TO [19]. For motion data derived from the Kinect sensor, the mid-PSIS was replaced by "*hip center*" (Fig. 1). As the Kinect sensor only provides the location of the ankles and the center of foot, and it was observed that the center of foot location was much noisier than the ankle, the heel and toe were replaced by the ankle in the detection algorithm above.

Fig. 1. The identified joints on lower extremities by the Kinect sensor. The name of each joint is inherent in the Kinect sensor and may not have a clear anatomical meaning.

Once HS and TO were determined for each step for the two devices, the step time, stride time, swing phase, stance phase, and double limb support time were calculated. Based on the results of a preliminary test, it was found that the Kinect sensor-based HS had less error compared with TO. Therefore, step time and stride time were determined based on the timing of HS. The motion tracking system-based step width was calculated as the medial-lateral distance between heels of two successive HS, and the Kinect sensor-based step width was calculated as the distance between ankles.

For each device, using HS to define the beginning of a gait cycle, knee flexion and hip flexion/extension angles were extracted from the motion data recorded and normalized to a gait cycle. The motion tracking system-based joint angles were calculated according to the ISB recommendation [17]. Since the Kinect sensor-identified joints differ from the bony landmarks used to define the coordinate systems of body segments in the ISB recommendation, the Kinect sensor-based body segment coordinate systems were defined to best mimic the coordinate systems in the ISB recommendation. They were as follows: for the right lower leg, *Y*-axis is from "*ankle right*" to "*knee right*", *Z*-axis is perpendicular to *Y*-axis and the anterior-posterior direction of the treadmill; for the right upper leg, *Y*-axis is from "*knee right*" to "*hip right*", *Z*-axis is perpendicular to *Y*-axis and the anterior-posterior direction of the treadmill; for the pelvis, *Z*-axis is from "*hip left*" to "*hip right*" and *X*-axis is perpendicular to the plane that contains *Z*-axis and the "*hip center*". For each device, motion data derived for the left side was mirrored to the right counterpart before further analysis.

To validate the gait events derived from the Kinect sensor, differences in the number of frames between the two devices was calculated. The difference between motion tracking system-based and Kinect sensor-based step time, stride time, swing phase, stance phase, double limb support time, and step width were calculated, as well as the corresponding correlation coefficient (r) and the concordance correlation coefficient (r_c). For knee and hip angles, correlation coefficient and root-mean-square error (RMSE) between joint angles measured by the two devices over a gait cycle, the error in time to reach maximum joint angle, and the error in maximum Kinect-based joint angles were calculated. In order to understand whether proportional bias exist between the gait parameters derived from the two systems, Bland–Altman agreement analysis and ordinary least product (OLP) regression [7] were also performed.

One-way repeated measure ANOVAs were performed to investigate whether walking speed had a significant effect on gait parameter measurement error derived from the Kinect sensor. If walking speed was found to have a significant effect, a post-hoc Tukey test was performed to find the significant difference among levels of walking speed. The significance level was set to 0.05. All statistical tests were performed using SAS 9.2 (SAS, Cary, NC, USA).

3. Results

The Kinect sensor can provide a good measurement of HS timing. The distribution of events offset by the frame error (Fig. 2) indicated that for the right and left feet, average (standard deviation) HS frame errors were 0.18 (1.3) and 0.30 (1.6) frame, respectively, across all participants and all walking speeds (a positive frame error indicates the Kinect sensor-based time event occurred later than the motion tracking system-based time event); 94.3% and 92.2%, respectively, of HS extracted from the Kinect sensor were within ±2 frame error. The timing of TO, however, was not as accurate as that for HS. For the right and left feet, average (standard deviation) TO frame errors were −2.25 (3.4) and −2.61 (3.7) frames, respectively, across all the participants and all walking speeds; only 42.0% and 42.7%, respectively, of TO extracted from the Kinect sensor were within a ±2 frame error. Statistical tests further revealed that walking speed did not significantly affect average frame error of HS of the right or left foot. For TO, frame errors for 1.30 m/s walking were 1.0 frame less ($p = 0.016$) and 1.3 frame less ($p = 0.002$) than 0.85 m/s walking for right and left foot, respectively.

For the gait parameters in Table 1, the step time and stride time extracted from the Kinect sensor are close to those extracted from the motion tracking system. The average absolute errors across all participants and all walking speeds were 0.017 and 0.017 s, respectively. The Kinect sensor-based measurement errors of stance phase, swing phase, and double support time were greater. The average absolute errors were 0.060, 0.061, and 0.060 s, respectively. Bland–Altman agreement analysis and ordinary least product (OLP) regression revealed that the 95% CI of the slope in Bland–Altman plot did not exclude 0, and the 95% CI of the intercept and the slope from the OLP did not exclude 0 and 1, respectively. Therefore, no significant proportional bias was observed for those gait parameters listed in Table 1. Statistical

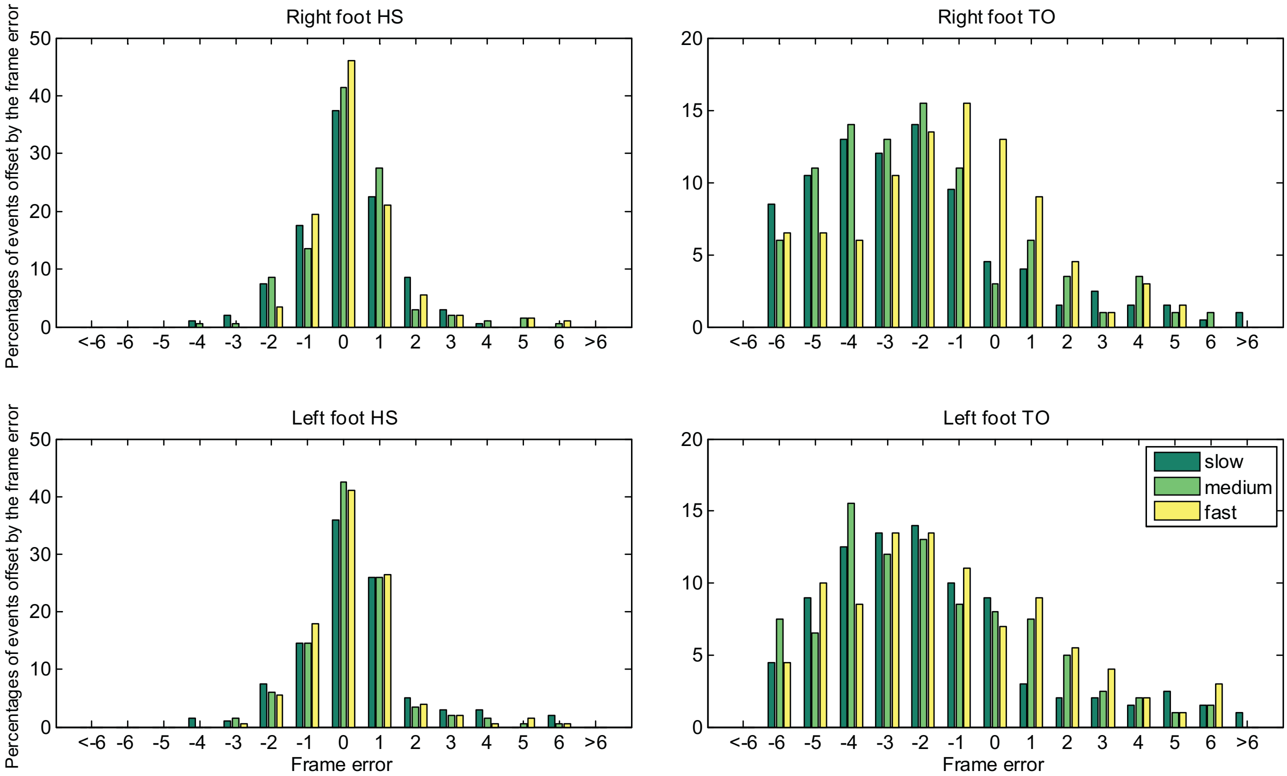

Fig. 2. The distribution of gait events offset by the frame error. The positive frame error indicates the Kinect sensor-based gait event occurs later than the motion tracking system-based gait event.

Table 1

The average value of the spatiotemporal gait parameters derived from the Kinect sensor and the motion tracking system, as well as the average of the difference between the two devices. The number in the parentheses is one standard deviation. Small letters a & b represent significant differences of the gait parameters between different walking speeds from post-hoc Tukey test. r represents Pearson correlation coefficient between gait parameters derived from the Kinect sensor and the motion tracking system. r_c represents concordance correlation coefficient.

	Walking speed														
	0.85 m/s					1.07 m/s					1.30 m/s				
	Optotrak	Kinect	Diff	r	r_c	Optotrak	Kinect	Diff	r	r_c	Optotrak	Kinect	Diff	r	r_c
Step time (s)	0.638 (0.054)	0.638 (0.062)	0.001 (0.032)	0.85	0.85	0.574 (0.032)	0.575 (0.040)	0.000 (0.026)	0.77	0.75	0.532 (0.032)	0.532 (0.036)	0.000 (0.019)	0.85	0.84
Stride time (s)	1.274 (0.101)	1.277 (0.107)	0.002 (0.033)	0.85	0.95	1.149 (0.059)	1.150 (0.063)	0.001 (0.025)	0.92	0.92	1.063 (0.060)	1.063 (0.063)	0.000 (0.019)	0.95	0.95
Stance time (s)	0.880 (0.072)	0.824 (0.093)	-0.056^a (0.060)	0.77	0.61	0.772 (0.042)	0.725 (0.066)	-0.048$^{a/b}$ (0.055)	0.57	0.37	0.706 (0.043)	0.670 (0.073)	-0.036^b (0.058)	0.60	0.45
Swing time (s)	0.397 (0.041)	0.452 (0.074)	0.054^a (0.065)	0.49	0.29	0.374 (0.027)	0.420 (0.063)	0.046^a (0.057)	0.43	0.21	0.357 (0.025)	0.392 (0.060)	0.035^b (0.057)	0.30	0.16
Double support time (s)	0.240 (0.028)	0.187 (0.066)	-0.054^a (0.065)	0.24	0.11	0.200 (0.020)	0.155 (0.055)	-0.045^a (0.054)	0.24	0.10	0.175 (0.018)	0.140 (0.058)	-0.034^b (0.057)	0.20	0.09
Step width (m)	0.138 (0.046)	0.138 (0.045)	0.000 (0.025)	0.85	0.85	0.133 (0.041)	0.132 (0.042)	-0.000 (0.025)	0.82	0.82	0.138 (0.041)	0.138 (0.045)	0.000 (0.028)	0.79	0.79

tests revealed that walking speed did not have a significant effect on the magnitude of measurement error for step time and stride time. For stance phase ($p = 0.002$), swing phase ($p < 0.001$), and double support time ($p < 0.001$), the magnitude of measurement errors were significantly reduced when walking speed increased to 1.30 m/s from 0.85 m/s. For step width, the average absolute errors across all walking speeds were 0.019 m, and walking speed did significantly influence the magnitude of step width error.

In terms of joint angles, the Kinect sensor-based knee and hip joint angles over a gait cycle can provide a similar profile as the motion tracking system-based counterpart (Fig. 3). The average r for the knee and hip joints of a gait cycle measured by the two devices were 0.81 and 0.95, respectively, across all trials; the average r_c for knee and hip joints were 0.41 and 0.71, respectively. The average RMSE error for knee and hip joints were 28.5 degrees and 11.8 degrees, respectively. The timing of maximum knee flexion, hip flexion, and hip extension measured by the Kinect sensor were 2.7% earlier of a gait cycle, 7.7% later, and 0.2% earlier, respectively, compared with those measured by the motion tracking system across all trials. The angular displacements measured from the two devices were more different (Table 2). For the knee joint, maximum knee flexion extracted from the Kinect sensor was underestimated by an average of 59% across all the trials. The 95% limits of agreement in Bland–Altman agreement analysis was from $-39.6–0.48(A)$ to $-2.1–0.48(A)$, where A is the average value derived from the two systems. The intercept and the slope in OLP equation were 27.1 and 1.51, respectively. For the hip joint, maximum hip flexion and extension were 46% underestimated and 38% overestimated on average across all trials, respectively. The 95% limits of agreement in Bland–Altman agreement analysis was from $-27.5–0.10(A)$ to $9.9–0.10(A)$. The intercept and the slope in OLP equation were 9.1 and 1.1, respectively.

4. Discussion

The goal of the current study is to evaluate Kinect sensor validity when using it to assess gait parameters during treadmill walking. The results indicated varied accuracy levels for different gait parameters.

The results suggest that the Kinect sensor had better accuracy for HS timing than for TO timing. One possible explanation is that as the Kinect sensor had less measurement error for objects closest to the sensor [5], the forward half of the treadmill belt, where HS occurs, is more easily observed than the aft half of the treadmill where TO occurs (Fig. 1). Since the current study used the position of the Kinect sensor-identified ankle location to determine the gait event, when the ankle was in an area that could not be well observed, the resultant gait event was likely to be more erroneous. Another possible reason is that the Kinect sensor is designed for video game interaction using body movements on a static ground surface; the moving treadmill belt may interfere with identification of ankle position. While the ankle of the rear foot is less easily observed, such interference, if present, may be stronger. Such speculation may also explain the effect of walking speed on TO. Within the tested range of walking speeds, the faster the walking speed, the less TO frame error. The slower the rubber strips comprising the treadmill belt moved, the easier the moving belt could be observed and, possibly, the stronger the interference introduced during identification of ankle position of the rear foot.

Due to the more accurate measurement of HS and less accurate measurement of TO, the temporal gait parameters that relied only on HS timing, such as step time and stride time, had better accuracy. The parameters that relied on timing of both HS and TO, such as stance phase, swing phase, and double support time,

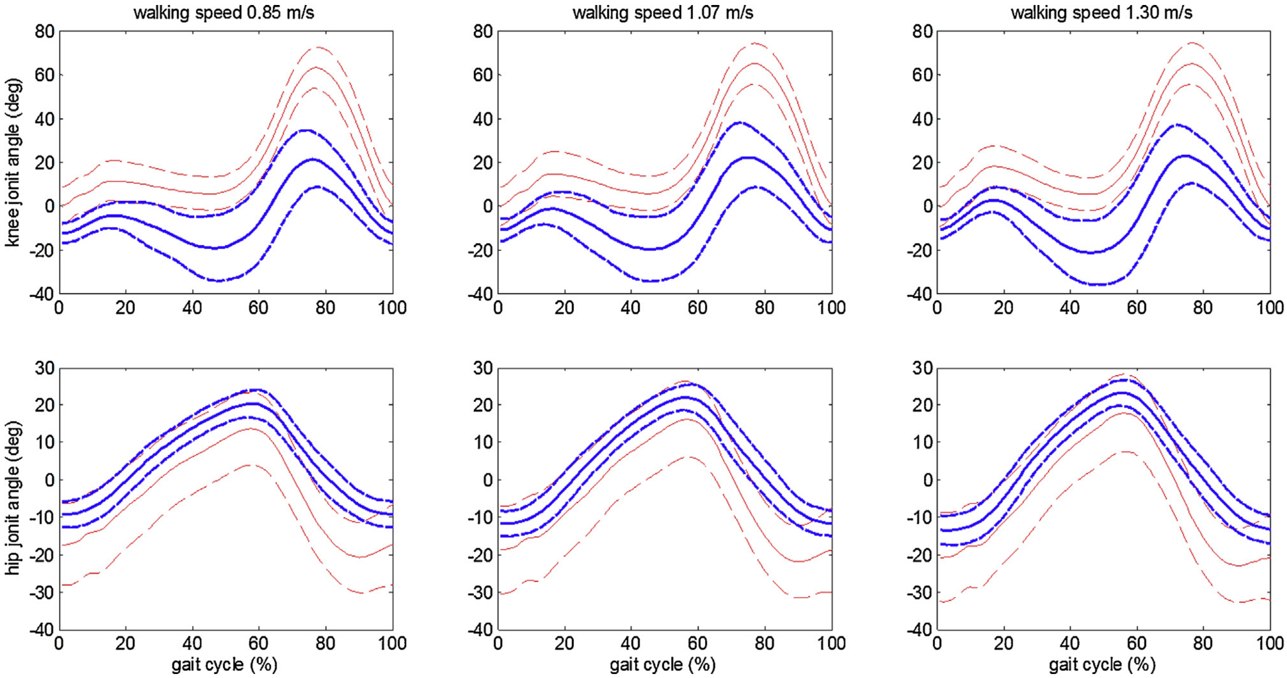

Fig. 3. The average knee and hip joint angles over a gait cycle across all the walking trials. The bold lines indicate the Kinect sensor -based joint angles, while the thin lines indicate the motion tracking system-based joint angles. The dash lines represent one standard deviation.

however, had relatively low accuracy levels and were affected by the walking speed, as TO was. In a previous study [11] where the validity of Kinect sensor-based gait parameters were examined for over-ground walking, mean error of step and stride times were −0.17 s and −0.20 s, respectively, which is greater than for the current study. One possible reason for this discrepancy is that step time and stride time were defined differently in the two studies. While the two temporal gait parameters were based on HS in this study, TO was used to define them in Clark et al. [11]. In addition, the timing of TO in Clark et al. [11] was determined based on anterior-posterior foot velocity, while it was determined by "*hip center*"-"*ankle*" distance in the current study. Therefore, how gait parameters are defined could influence the accuracy of those parameters when using Kinect sensor. Another possible reason is that the distance between participants and the Kinect sensor is approximately constant during treadmill walking, while the participants in Clark et al. [11] needed to walk towards the Kinect sensor for 2.5 m. Since the accuracy of the Kinect sensor varies with location and direction [5], the error in timing of a gait event may be influenced by participant location with respect to the Kinect sensor.

The calculation of Kinect sensor-based step width requires both the timing of HS and the relative location of the ankles in the medial-lateral direction during HS. Since most of the HS timing determined by the Kinect sensor was within ±2 frames compared with the motion tracking system, it would be expected that step width error was mainly due to misidentification of the ankle joint.

The Kinect sensor-based knee and hip joint angles measured over a gait cycle seem to follow the trend of the motion tracking system-based joint angles; however, there were substantial systematic errors in magnitude. Such results are similar to the findings in Pfister et al. [12]. Knee flexion angle reached an unrealistic negative value, indicating knee hyperextension (also observed in Pfister et al. [12]), for 61.4% of a gait cycle on average across all the trials. After manually and visually overlapping the two human body stick figures, one created by the Kinect-identified joint centers and one created by the motion tracking system-based joint centers, it was found that the Kinect sensor-based knee joint and ankle joint were posterior and anterior, respectively, compared with the motion tracking system-based joint centers. Such joint location errors result in negative knee joint angles, except in the middle of swing phase where the knee flexion angle reaches maximum. Moreover, the magnitude of the joint location error is dependent on lower extremity posture. Visual checking of the stick figures found that the Kinect sensor-based knee joint deviated most from the reference joint center around the time that the knee flexion reached maximum, with the result that most knee joint errors occurred at that time instant. Such a proportional bias was also reflected by the results of Bland–Altman agreement analysis.

The hip joint angle derived from the Kinect sensor had a smaller error when compared with the knee joint angle. Hip flexion underestimates and hip extension overestimates likely occurred because the Kinect sensor-based knee joint was backward compared with the reference. The variance of hip angle derived from the Kinect sensor was smaller than that derived from the motion tracking system (Fig. 3). Further analysis indicates that this was because the Kinect sensor did not detect inter-participant variability in pelvis anterior-posterior tilt. According to the ISB recommendation [17], the pelvic tilt is related to the relative cephalocaudal position between ASISs and the mid-PSISs. Due to morphological differences in the pelvises of participants, pelvic tilt angles could differ resulting in the observed inter-participant variability of hip joint angles. In the current study, the standard deviation of the pelvis anterior-posterior tilt angle was 8.5° across all the participants, based on the motion tracking system. For the Kinect sensor, differences in pelvis anterior-posterior tilt were not well detected. With the Kinect sensor-based pelvic coordinate system created in this study, the standard deviation of the pelvic tilt angle was 2.6°. Therefore, the underestimated inter-participant variability in pelvic tilt could result in low variability in hip angle.

There were a few limitations of this validation study that need to be addressed. First, the references HS and TO were based on the human kinematics recorded by the motion tracking system. Given that this method resulted in an approximately 1 frame error (1/60 s) compared with GRF-based HS and TO [18], the Kinect sensor accuracy may be altered slightly when GRF-based HS and TO are used as references. Second, the participants were unimpaired healthy adults. It remains unclear whether the accuracy level will be similar for pathological gait and whether the Kinect sensor is sensitive enough to observe changes in gait parameters due to pathological gait. Given that a joint angle difference greater than 5° is considered a clinically significant difference [20], the results of the current study seem to suggest that knee and joint angles measured directly with the Kinect sensor cannot be used for clinical gait analysis. However, if the gait analysis is to be based on a relative comparison between healthy and pathological groups, it would be important to know if the Kinect sensor can differentiate pathological gait parameters, and that should be further addressed in future studies. Third, in order to minimize the missing joint centers, in this study the Kinect sensor was placed in front of the participants during the treadmill walking [21]. Such placement requires customizing the treadmill by removal of the handrail. In clinical applications, the handrail may be necessary for older adults or people with abnormal gait to walk safely on the treadmill. The results of Pfister et al. [12] showed that when the Kinect sensor was placed at a 45° angle to the sagittal plane, the Kinect sensor-based joint angles were similar to those observed in the current study for missing steps. Future studies should also examine how the view angle of the Kinect sensor affects the accuracy of the gait parameters. Fourth, due to safety concerns, walking at a very fast speed was not tested in the current study. Therefore, the results should not be extrapolated to untested walking speeds.

Table 2
The average value of the maximum knee and hip joint angles derived from the Kinect sensor and the motion tracking system, along with the average magnitude and time difference of the maximum angle, as well as the average RMSE error of the knee and hip joints of a gait cycle. The number in the parentheses is one standard deviation. Small letters represent significant differences of the gait parameters between different walking speeds from post-hoc Tukey test.

Joint	Movement	Walking speed														
		0.85 m/s					1.07 m/s					1.30 m/s				
		Max angle—Optotrak (deg)	Max angle—Kinect (deg)	Diff of max angle (deg)	Diff of max angle timing (% of gait cycle)	Gait cycle RMSE error (deg)	Max angle—Optotrak (deg)	Max angle—Kinect (deg)	Diff of max angle (deg)	Diff of max angle timing (% of gait cycle)	Gait cycle RMSE error (deg)	Max angle—Optotrak (deg)	Max angle—Kinect (deg)	Diff of max angle (deg)	Diff of max angle timing (% of gait cycle)	Gait cycle RMSE error (deg)
Knee	Flexion	63.8 (9.3)	25.3 (9.3)	−38.6 (12.2)	−2.1 (5.2)	27.9 (10.0)	65.3 (9.3)	27.2 (9.8)	−38.1 (12.8)	−3.2 (9.5)	28.6 (10.8)	65.3 (9.4)	27.3 (9.6)	−38.1 (12.2)	−2.7 (8.9)	29.0 (10.3)
Hip	Flexion	21.6 (9.8)	10.3 (3.5)	−11.3^{a} (11.0)	7.5 (6.0)	11.8 (8.6)	22.9 (10.3)	12.8 (3.4)	−10.1^{b} (10.7)	8.1 (6.0)	11.7 (8.6)	24.3 (10.6)	14.3 (3.8)	−10.0^{b} (11.4)	7.3 (6.2)	11.9 (8.9)
	Extension	14.1 (9.7)	20.9 (3.6)	6.8^{a} (10.7)	0.1^{a} (3.4)		16.5 (10.0)	22.6 (3.3)	6.0^{b} (11.3)	−0.1^{a} (3.4)		18.3 (10.3)	23.6 (3.4)	5.3^{c} (11.9)	−0.7^{b} (3.2)	

5. Conclusion

In summary, the accuracy using the Kinect sensor to detect gait parameters differed across various gait parameters. The timing of HS and temporal gait parameters based purely on HS had less error than the timing of TO and temporal gait parameters based on TO. For knee and hip joints, the Kinect sensor can follow the trend of the joint trajectories but with substantial error in magnitudes. Whether the Kinect sensor is sufficient for treadmill gait analysis depends on the desired accuracy level of a specific task.

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Conflict of interest statement

All authors declare that there is no proprietary, financial, professional or other personal interest of any nature or kind in any product, service or company that could be construed as influencing the position presented in this manuscript.

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