Validation of the kinect for gait analysis using the GAITRite walkway

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Abstract— **Accurate, non-intrusive and straightforward techniques for gait quality analysis can provide important information concerning the fall risk of a person. For this purpose an algorithm was developed which can measure step length and step time using the Kinect depth image. The validity of the measured step length and time is determined using the GAITRite walkway as a ground truth. The results of this validation confirm that the Kinect is well-suited for determining general parameters of a walking sequence (a Spearmans Correlation Coefficient (SCC) of 0.94 for average step length and 0.75 for average step time per walk), but we furthermore show that determining accurate results for single steps is more difficult (SCC of 0.74 for step length and 0.43 for step time for each step), making it harder to measure more complex gait parameters such as e.g. gait symmetry.**

I. INTRODUCTION

One third of community-dwelling older adults fall at least once a year [1]. Additionally, patients suffering from neurological diseases such as a stroke, dementia and Parkinson's disease are also reported to have a high fall risk [2]. Important indicators of this elevated fall risk are gait and balance deficits [3], [4]. Moreover, it has been reported that neurological gait abnormalities have a strong predictive value for falls in older adults [5]. Gait abnormalities are therefore considered among the most consistent predictors of falls and fall prevention guidelines recommend gait evaluation and gait training to reduce the risk for future falls in both patient groups [6], [7].

To date, several methods for the assessment of gait quality exist. These include gait laboratories using marker-based motion capture systems or a pressure sensitive walkway [8]. These systems are accurate but are expensive and impractical to move. Therefore, such systems are only suitable for laboratory settings. Several research groups are developing gait assessment tools using wearable sensors such as accelerometers and gyroscopes [9], [10], [11]. Such systems are small, lightweight, mobile and less expensive and are therefore more suitable for ambulatory measurements in home settings or in the general practitioner's surgery. These sensors must, however, account for gravity, noise and signal drift [12]. Moreover, multiple sensors need to be placed on the body of the patient causing an inconvenience [13]. An accurate, non-intrusive, low-cost clinical gait analysis system can therefore be an added value to current fall prevention strategies.

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Several researchers have already proposed the Kinect's use for gait analysis [14] and previous research showed reasonably good performances of the Kinect system, when compared to a marker-based system such as the VICON system [15]. However, they only report gait parameters averaged over an entire walking path of approximately 5.2 meter. In this work, we want to evaluate the results of our approach to measure step length and step time using the Kinect sensor and the algorithms part of the Kinect Software Development Kit (SDK). To validate the results, the obtained measurements are compared with those supplied by the GAITRite system.

II. APPROACH

Since we would like to validate the use of the Kinect as a sensor for measuring gait parameters, we employ the following sequential steps using standard methods from the SDK to determine the location of the person in the depth frame (steps 1 and 2) which are followed by post-processing steps to determine the centre of mass (COM) of the subject (steps 3 and 4).

1) Determine player pixels by employing player detection algorithm from the SDK based on the depth information (sampled at 15 fps)
2) Determine binary image of the person who is walking in the field of view of the Kinect sensor
3) Use connected component analysis to remove noisy pixels from the binary image
4) Calculate centre of mass (COM) from the biggest foreground object by calculating the mean position of all the pixels within this object

Figure 1 shows the detected foreground object with the calculated bounding box and centre of mass.

To determine the step length and step time, the X- and Y-coordinates of the COM for each frame during a walking sequence are plotted (Figure 2). The different support phases (instances where both feet are connected to the ground) during the walking sequence correspond with local minima in this graph [16]. To calculate the step length the x-coordinate of the bottom right corner of the bounding box in the frame corresponding with the previous minimum of the COM is subtracted from that of the frame with the current minimum. This number is subsequently multiplied with a conversion parameter (this is the length of the walking sequence in the field of view of the Kinect divided by the width in pixels of the field of view of the Kinect) which then yields the step length (in cm). A similar operation is performed to calculate the step time. The frame number of the frame with the previous minimum of the COM is subtracted from that

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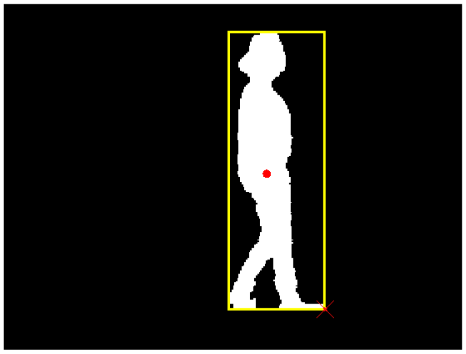

Fig. 1. Biggest foreground object with bounding box (BB) and centre of mass. The bottom right corner of the BB, marked with a red 'X' is used to calculate the step length.

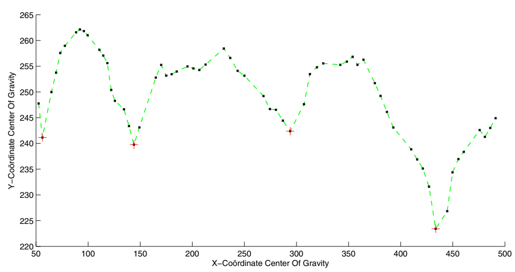

Fig. 2. X- and Y-coordinate of the centre of mass for one walking sequence [in pixels]. Each black dot corresponds with the COM coordinates of one frame. Each red cross is an automatically detected local minimum.

of the current minimum which is then divided by the number of frames per second (here 15 fps). This then yields the step time (in sec).

Figure 2 shows the X- and Y-coordinate of the COM for each frame recorded during one walking sequence. The local minima seen in this graph correspond with the different support phases during the walking cycles and are therefore used to calculate the step length and step time.

III. EXPERIMENTAL EVALUATION

A. Dataset and experimental setup

To validate our approach, we simultaneously recorded walking sequences with the Kinect, a webcam and a GAITRite [17]. The GAITRite is an electronic walkway with a length of 8 meters that has pressure sensors embedded within its length which quantifies variables such as step length, step time, walking speed, step width and cadence. The measurements of the GAITRite have already been validated in the past [17] and are therefore used as ground truth for the current measurements with the Kinect. An overview of the set-up used to record the walking sequences is given in Figure 3. The test subjects start walking on the GAITRite before they enter the field of view of the Kinect and stop after they have left the field of view. Therefore, only the steps at full walking speed are recorded with the Kinect. The webcam is used to visually check which steps registered by the GAITRite correspond with the steps registered by the Kinect. Two healthy test subjects, aged 24 and 33, were recorded while walking over a GAITRite walkway with a

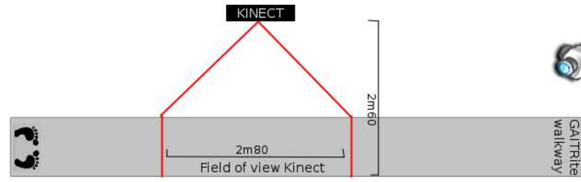

Fig. 3. Measurement set-up

TABLE I

OVERVIEW OF THE PROPERTIES OF THE MEASURED WALKING SEQUENCES

ID	Subject	Step type	Steps[a]	Length[b][cm]	Time[c][sec]
1	1	normal	3	148.74	2.37
2	1	normal	4	215.86	3.63
3	1	normal	3	173.98	2.34
4	2	normal	3	163.72	2.98
5	1	large	3	189.39	3.54
6	1	large	2	124.19	1.93
7	1	large	2	132.56	1.93
8	2	large	3	144.78	2.308
9	2	large	2	143.51	2.05
10	1	small	6	216.11	4.93
11	1	small	5	171.24	4.32
12	1	small	9	202.46	6.53
13	1	wide SB[d]	4	214.55	3.37
14	1	wide SB	4	235.40	3.33
15	1	wide SB	3	175.26	2.46
16	2	wide SB	3	166.40	4.09
17	2	wide SB	3	144.75	3.85
18	2	small SB	5	170.60	4.53
19	1	Small SB	5	170.18	3.4

Notes
[a] Number of steps detected by the Kinect system
[b] Sum of the step lengths measured with the GAITRite of the steps performed in the field of view of the Kinect
[c] Sum of the step time measured with the GAITRite of the steps performed in the field of view of the Kinect
[d] SB = Support Base

webcam and with the Kinect. The test subjects each walked 15 times across the GAITRite. Each test subject performed three walks in their usual walking pattern, three walks with a wide support base, three walks with a small support base, three walks with large steps and three walks with small steps. This resulted in 30 recorded walks. All the walks were performed in the same direction.

From the 30 performed walks 11 were discarded. This was done for the following reasons: firstly, during seven walks the Kinect was not able to detect a person in the walking sequence; secondly, in one walk the software of the GAITRite was not able to distinguish between the left and the right foot and was therefore not able to correctly assess the walking parameters; thirdly, one walk was not registered with the webcam and therefore we could not match the steps performed in the field of view of the Kinect with those measured with the GAITRite. Lastly, using visual inspection it was observed that during two walks the detection of the Kinect was very unstable, the feet were often not detected which led to a lot of incorrectly detected minima in the y-coordinate of the centre of mass and these walks were also discarded.

During 4 walks the feet or head of the participant were not detected in one frame. These walks were included in the dataset but for this frame the y-coordinate of the COM was smaller than would have been the case if the detection was

correct. Visual inspection of the graph of the coordinates of the COM determined that this caused a local minimum. The system therefore assumed a false support phase in the walking sequence and divided one actual step into two steps. The calculated data from these steps were therefore added up manually for validation purposes.

We therefore had 19 walking sequences to analyse (four with a normal walking pattern, five with a wide support base, two with a small support base, four with big steps and four with small steps) which resulted in 71 measured steps. Table I gives an overview of the characteristics of the used walking sequences.

The results of the measurements of the Kinect are first evaluated by calculating the average step length and step time per walk for each sensor. This is followed by a more in depth analysis on a step by step basis. Per walk the Mean Absolute Error (MAE) (Eq. 1) and the Mean Absolute Percentage Error (MAPE) (Eq. 2) for both step length and step time are calculated, where y_i corresponds to the measurement by the GAITRite, y'_i to the Kinect measurement and n to the number of steps in the walking sequence. An overall view is given by calculating the Spearmans Correlation Coefficient (SCC) [18], as well as summarising the MAE and MAPE for the average step length and step time, per walk as well as over all individual step measurements, i.e. with n the total number of steps in the 19 walking sequences.

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - y'_i| \quad (1)$$

$$MAPE = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{y_i - y'_i}{y_i}\right| \quad (2)$$

B. General results per walking sequence

Table II gives an overview of the average step length per walk measured with the GAITRite and with the Kinect. The error of the average step length and step time calculated with the Kinect as opposed to the measurements with the GAITRite are also included in table II.

C. Results for individual steps in a walking sequence

Table III shows the MAE and MAPE for each walk based on the error of the individual steps in the walking sequence.

D. Summary of results

Table IV gives an overall view of the agreement between the measurements performed with the Kinect to those performed with the GAITRite. This was done on a per walk basis by using the errors calculated on the average step length and step time (see III-B) and on a step by step basis where the SCC, MAE and MAPE are calculated using the steps of all walking sequences.

TABLE II
GENERAL VALIDATION OF THE KINECT WITH THE GAITRITE BASED ON THE AVERAGE STEP LENGTH AND AVERAGE STEP TIME PER WALKING SEQUENCE

	Average step length [cm]			Average step time [sec]		
ID	Kinect	GAITRite	Error	Kinect	GAITRite	error
1	44.32	49.58	5.25	0.96	0.79	0.17
2	52.94	53.93	1.03	1.17	0.91	0.26
3	58.04	57.99	0.050	1.07	0.79	0.28
4	56	54.57	1.43	1.04	0.99	0.05
5	63	63.13	0.13	1.31	1.18	0.13
6	65.19	62.09	3.09	1.37	0.97	0.40
7	66.94	66.28	0.66	1.33	0.97	0.37
8	76.13	72.39	3.74	1.03	1.15	0.12
9	77	71.76	5.25	1.27	1.03	0.24
10	33.25	36.02	2.77	1.09	0.82	0.27
11	35.87	34.25	1.63	1.25	0.86	0.39
12	23.92	22.50	1.42	1.02	0.74	0.30
13	53.81	53.64	0.18	1.12	0.84	0.28
14	53.16	58.84	5.68	1.1	0.83	0.27
15	63.58	58.42	5.16	1.16	0.82	0.34
16	58.63	55.47	3.16	1.42	1.36	0.06
17	51.046	48.256	2.79	1.49	1.28	0.21
18	37.10	34.12	2.98	1.03	0.91	0.12
19	34.83	34.04	0.79	0.93	0.68	0.25
AVG	52.88	51.96	2.48	1.17	0.94	0.24

TABLE III
VALIDATION OF THE KINECT WITH THE GAITRITE BASED ON THE MEAN ABSOLUTE ERROR (MAE) AND THE MEAN ABSOLUTE PERCENTAGE ERROR (MAPE) FOR STEP LENGTH AND STEP TIME OF INDIVIDUAL STEPS

	Step length [cm]		Step time[sec]	
	MAE	MAPE	MAE	MAPE
1	7.41 ± 0.17	9.57 ± 14.83	0.17 ± 0.23	23.23 ± 32.27
2	5.45 ± 0.31	4.67 ± 10.15	0.31 ± 0.17	36.41 ± 20.11
3	4.61 ± 0.28	2.09 ± 7.93	0.28 ± 0.14	37.52 ± 22
4	15.03 ± 0.3	4.65 ± 27.38	0.3 ± 0.06	30.48 ± 8.98
5	3.87 ± 0.22	1.88 ± 6.14	0.22 ± 0.24	21.96 ± 25.29
6	3.09 ± 0.4	2.48 ± 5.05	0.4 ± 0.45	44.47 ± 51.66
7	8.12 ± 0.37	0.93 ± 12.3	0.37 ± 0.29	39.85 ± 34.75
8	4.06 ± 0.33	5.28 ± 5.36	0.33 ± 0.17	28.26 ± 13.78
9	5.25 ± 0.24	6.11 ± 7.46	0.24 ± 0.06	23.52 ± 0.5
10	7.22 ± 0.28	7 ± 19.54	0.28 ± 0.18	33.22 ± 21.41
11	6.24 ± 0.39	4.13 ± 18.65	0.39 ± 0.17	45.59 ± 20.88
12	4.32 ± 0.3	5.04 ± 18	0.3 ± 0.21	41.16 ± 27.66
13	8.27 ± 0.28	3.15 ± 15.8	0.28 ± 0.18	33.57 ± 22.8
14	25.47 ± 0.32	7.74 ± 42.74	0.32 ± 0.15	39.05 ± 17.7
15	15 ± 0.34	10.92 ± 25.97	0.34 ± 0.12	41.25 ± 15.51
16	10.09 ± 0.16	4.33 ± 18.96	0.16 ± 0.03	12.02 ± 1.95
17	10.68 ± 0.22	8.76 ± 26.73	0.22 ± 0.18	16.69 ± 13.3
18	5.96 ± 0.22	5.01 ± 18.79	0.22 ± 0.17	25.36 ± 20.65
19	6.62 ± 0.29	3.7 ± 19.77	0.29 ± 0.13	42.03 ± 17.67
AVG	8.25 ± 5.13	16.92 ± 11.49	0.29 ± 0.17	32.40 ± 20.47

IV. DISCUSSION

The ability to automatically measure gait quality parameters such as step length and step time using a straightforward technique could benefit a variety of patient populations with a potential elevated fall risk. Providing that an overall view of the patient's gait quality is needed our results suggest that measuring these parameters with the Kinect on a walk to walk basis has a good agreement with the measurements from the GAITRite system. These results are comparable with those reported in [15].

However several technical aspects of the presented system still warrant clarification. Firstly, the choice was made to use the bottom right corner of the bounding box to calculate the step length as opposed to the y-coordinate of the COM. This was done because the x-coordinate of the COM is

TABLE IV

SCC, MAE AND MAPE OF STEP LENGTH AND STEP TIME, BOTH PER WALK AND OVER ALL STEPS

	SCC	MAE	MAPE
Average step length per walk	0.94	2.48	4.94
Average step time per walk	0.75	0.24	26.87
Step length	0.74	8.09	18.09
Step time	0.43	0.29	33.70

influenced by the posture of the person during the support phase. If a person is for instance leaning backwards during the support phase a smaller step length will be calculated. On a per walk basis the improvement in the accuracy was discernible by an improvement in the MAE and MAPE of the measurements using the coordinates of the bottom right corner of the bounding box as opposed to those using the coordinates of the COM (a MAE of 2.48 as opposed to one of 9.91 and a MAPE of 4.90 as opposed to one of 25.39).

Secondly, different stepping patterns were simulated to assess the accuracy of the algorithm with different walking patterns. This resulted in a large variability in step length and step time and in the number of steps which were performed in the field of view of the Kinect. Moreover when regarding the results in table III it can be observed that the accuracy of the step length reduces for walks with a wide support base.

Thirdly, a small delay was observed before the person was detected when the field of view of the Kinect was reached. This resulted in a variability in the length of the detected walking sequence (when the person was walking at a fast pace he was further advanced before he was detected as opposed to when the person was slower).

Moreover during 6 walking sequences the player detection algorithm was unstable and during 7 walking sequences no person was detected at all. This resulted in rendering 9 walks unusable (2 were recovered after visual inspection of the data). Therefore the implementation of a different person detection algorithm and therefore not using the Kinect SDK for this purpose should be considered.

The main limitations of the presented system are the lower accuracy of the step time based on individual step measurements (SCC of 0.43) as opposed to the average step time per walk (SCC of 0.75) and in step length (SCC of 0.74 as opposed to 0.94). To evaluate more complex gait measures, an improvement in accuracy is needed. One possibility would be to increase the sampling frequency.

V. FUTURE WORK

Future work will include the implementation of another person detection algorithm. It will also include using the depth values to distinguish the left and right foot. After this other parameters can be calculated which will include stride length, stride time, cadence, velocity, step length left, step length right, step time left, step time right, cycle time left and cycle time right. We will furthermore validate our results on a bigger dataset.

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