Comparing the gait analysis of a Kinect system to the Zeno Walkway: Preliminary results

Andrew Hynes[1], Megan C. Kirkland[2], Michelle Ploughman[2], and Stephen Czarnuch[1, 2]

[1]Faculty of Engineering, Memorial University
[2]Faculty of Medicine, Memorial University

Abstract—**Pressure sensitive walkways are a commonly used measuring device for gait analysis. However, they can be prohibitively expensive for out-of-clinic measurements. An alternative approach to gait analysis is the use of a depth sensing camera (e.g., the Kinect). Our approach is to collect lower-body gait data using a single, inexpensive Kinect camera, with a line of sight perpendicular to the walking path. Participants with MS performed walking passes on a pressure sensitive walkway and in front of the camera. The following gait metrics were measured with both systems: step length, stride length, stride width, and stride velocity. We present the preliminary results of comparing gait metrics, showing Spearman correlations ranging from 0.857 to 0.976. These preliminary results suggest that inexpensive gait tracking may be a practical reality in non-clinical settings.**

I. INTRODUCTION

Gait analysis is a common clinical practice for tracking disease progression and facilitating rehabilitation, for a variety of neurological diseases including Parkinson's [1], stroke [2], and multiple sclerosis [3]–[9]. The analysis is often performed by clinicians using observational tests, such as the Timed Up and Go [10], or with the aid of pressure sensitive walkways [11]. Because these tests need a certified clinician, they are less accessible to rural areas. Alternatively, gait analysis has been performed by computer vision systems, such as depth sensing cameras [7], [12], [13].

Pressure sensitive walkways measure important gait characteristics that a computer vision system is unable to directly evaluate, such as the force of the foot on the ground. However, both systems can measure spatiotemporal gait characteristics such as step length and stride velocity. A computer vision system can also supplement the measurements of the pressure walkway by tracking upper body parts and joint angles.

The purpose of this study is to compare our developed depth sensor tracking system to a validated pressure sensitive walkway, the Zeno Walkway, in conjunction with the ProtoKinetics Movement Analysis Software (PKMAS) [14], [15].

Participants with MS completed four walking passes on the walkway, while being simultaneously recorded by a Kinect camera from a side view. The native Kinect software development kit (SDK) is intended to track from a frontal view, as is common for its original purpose of gaming. Instead of using the SDK, we build upon our previous work [16]–[18], which developed an algorithm for tracking bodies from a side view. This allows for our method to be implemented on a generic depth sensing camera.

II. RELATED WORK

Performing gait analysis with the Kinect camera is an active area of research [3]–[7], [9], [13], [19]–[28]. The Kinect has been used to analyze gait for a number of neurological disorders [29], [30], including multiple sclerosis [3], [5]–[7], [9]. A common technique is to first track the human skeleton, either using the native software development kit (SDK) [7], [24], or with novel algorithms [28]. However, gait analysis has been accomplished without skeleton tracking, by analysing the motion of the body centre of mass [20]. The tracking abilities of the Kinect from a non-frontal view have also been examined, for general tracking [31], and for gait analysis [20], [23], [28], [31].

Gabel et al. [24] measured both stride metrics and arm kinematics. A model for walking was built using information from wearable sensors. The Kinect SDK was used to track a virtual skeleton, which was passed into this learned model. Gholami et al. [7] used the concept of dynamic time warping to develop novel gait metrics. Their study compared the gait of participants with MS to a healthy control group, and they developed a distance metric to compare dysfunctional gait to healthy gait.

Several studies have compared the gait analysis of Kinect to previously validated systems, including marker-based motion tracking [21], [26], [32], [33] and the GAITRite pressure mat [13], [20], [27]. Cippitelli et al. [23] tracked body joints from a side view, using a purpose-built algorithm. They obtained an objective score for the Get Up and Go test, and compared results to a marker-based system. Motiian et al. [27] focused on gait analysis for children, and compared results to the GAITRite pressure mat. The Kinect SDK was used to track the skeleton from a frontal view, accompanied by a side view Kinect for data visualization during the annotation phase. Dolatabadi et al. [13] tracked the walks of healthy participants with both a GAITRite mat and a frontal view Kinect using the SDK. They found strong agreement between the two systems for a number of spatiotemporal gait parameters.

To our knowledge, gait analysis with the Kinect has not yet been compared to a Zeno Walkway with the PKMAS software. However, these two systems have been used in conjunction to provide a non-immersive virtual reality for treadmill training [34].

III. METHODOLOGY

Eight walking trials were completed by two participants with MS. Each trial consisted of four passes in front of the camera, two to the left and two to the right. Data collection occurred at the Recovery and Performance Laboratory, a part of the Faculty of Medicine at Memorial University. The Kinect tracked 11 separate body parts: the head, hips, thighs, knees, calves and feet.

Four gait metrics were measured by both the Zeno walkway and the Kinect: step length, stride length, stride velocity, and stride width. For our Kinect system, only the head and foot positions are needed to calculate these gait metrics. However, tracking the full lower body is instrumental in correctly estimating the foot positions [17], [18].

A. Stride detection

During the swing phase of a normal stride, one foot remains planted on the ground, while the other moves forward. These are the stance foot and swing foot, respectively.

Using the tracked body part positions, the distance between the two feet is recorded for each frame. An example of the foot distance data can be seen in Fig. 1. There are four main sections of data, showing the different passes in front of the camera. The peaks in the data indicate instances when the feet are furthest apart in a stride.

A stride is detected with the following steps:

1) Use a peak detection algorithm to locate the peaks in the foot distance data. The MATLAB `findpeaks` function [35] was used for this implementation. The minimum peak prominence was specified as 75% of the maximum foot distance, to avoid detecting false peaks.
2) Record the frame numbers of each detected peak.
3) Cluster the peak frame numbers, so that peaks are grouped by walking pass.
4) Examine each pair of consecutive peaks that both occur in the same pass. This represents a full walking stride. The pair of frame numbers F_i and F_f are later used to calculate stride velocity.

When a stride is detected, the two peak frames are analyzed to obtain gait metrics. The distance travelled by the left foot between the two frames is calculated, as well as for the right. Ideally, one foot will move a relatively long distance while the other remains in its place. The foot which travelled a greater distance is labelled as the swing foot, and the other as the stance foot.

B. Gait metrics

Before the gait metrics are calculated, all peak foot positions are projected onto the same plane. The plane passes through the point $\begin{bmatrix}0 & y_{min} & 0\end{bmatrix}^T$, where y_{min} is the lowest y coordinate of the peak foot positions in a trial. The normal vector of the plane is $\begin{bmatrix}0 & 1 & 0\end{bmatrix}^T$. This plane is intended to model the surface of the Zeno walkway.

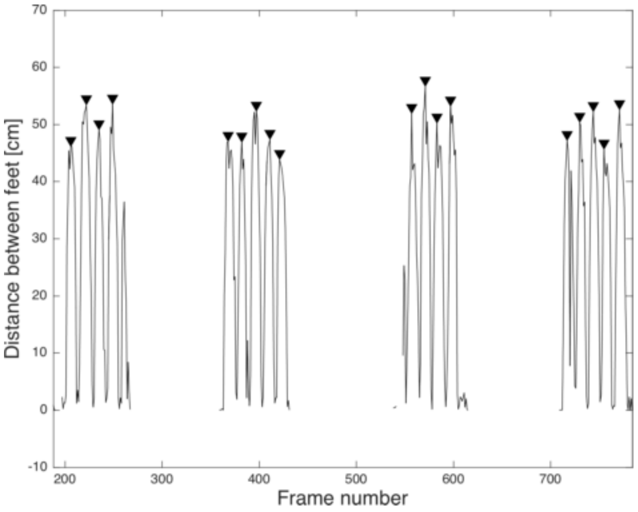


Figure 1: Foot to foot distance for each image frame in a walking trial, with detected peaks marked.

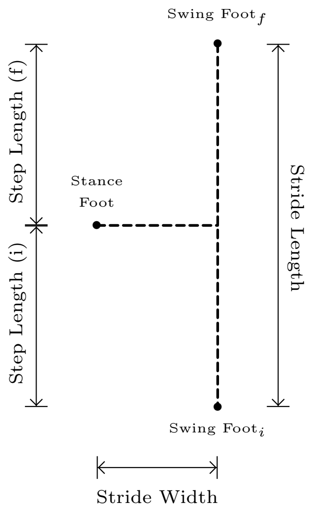


Figure 2: Diagram of step length, stride length, and stride width. During a stride, the stance foot stays stationary while the swing foot moves forward. The labels assume that the right foot is swinging.

The gait metric calculations were designed to closely match the calculations by PKMAS, as described in [8]. A diagram of a full stride is shown in Fig. 2. The swing foot moves from its initial position $\mathbf{P}_{swing,\ i}$ to its final position $\mathbf{P}_{swing,\ f}$. The swing path $\mathbf{S}$ is defined as the displacement vector between these points.

$$\mathbf{S} = \mathbf{P}_{swing,\ f} - \mathbf{P}_{swing,\ i} \tag{1}$$

The stride length is the distance between the initial and final swing foot positions.

$$l_{stride} = ||\mathbf{S}|| \tag{2}$$

The stance foot position, $\mathbf{P}_{stance}$, is projected onto the line between the two swing foot positions.

$$\mathbf{P}_{proj} = \text{proj}_{\mathbf{S}}\, \mathbf{P}_{stance} \tag{3}$$

This projected point is used to calculate step length and stride width. A full stride consists of two step lengths. The first step length is the distance from $\mathbf{P}_{swing,\ i}$ to $\mathbf{P}_{proj}$, and the second from $\mathbf{P}_{proj}$ to $\mathbf{P}_{swing,\ f}$.

$$\begin{aligned} l_{step,\ i} &= ||\mathbf{P}_{swing,\ i} - \mathbf{P}_{proj}|| \\ l_{step,\ f} &= ||\mathbf{P}_{swing,\ f} - \mathbf{P}_{proj}|| \end{aligned} \tag{4}$$

The stride width is the distance from the stance foot to its projection along the swing path.

$$w_{stride} = ||\mathbf{P}_{stance} - \mathbf{P}_{proj}|| \tag{5}$$

Finally, the stride velocity is calculated using the positions of the head. $\mathbf{P}_{head,\ i}$ and $\mathbf{P}_{head,\ f}$ are the head positions at frames F_i and F_f, respectively. Since the frame rate of the Kinect camera is 30 frames per second, the difference of frame numbers is divided by 30 to obtain a stride time in seconds. Thus, the stride velocity is

$$v_{stride} = \frac{d_{head}}{(F_f - F_i)/30} \tag{6}$$

where d_{head} is the distance from $\mathbf{P}_{head,\ i}$ to $\mathbf{P}_{head,\ f}$.

After gait metrics have been calculated for every detected stride in a trial, outliers are removed from the dataset of each gait metric. Outliers are defined as values outside of the median $\pm\ 2 \cdot$ MAD, where MAD is the median absolute deviation [36].

IV. RESULTS

A. Relative error

The mean of the gait metric measurements was calculated for each walking trial. Table I shows data from both the Kinect and Zeno systems, as well as the relative error. The Kinect measurements for step length and stride length were consistently under the Zeno measurements, resulting in negative relative errors. In general, the stride velocity has the lowest relative error magnitudes, ranging from $0\,\%$–$6\,\%$. There is a mixture of negative and positive errors. The stride width has the highest overall relative errors, ranging from $2\,\%$–$47\,\%$. For this metric, the Kinect measurements are consistently above the Zeno measurements.

B. Correlation

The Spearman correlation coefficient was used to measure the correlation of the two systems. The coefficient, also referred to as Spearman's rho, has been previously used for assessing gait analysis with Kinect [5], [30]. It does not require that the variables are normally distributed, and it is more robust to outliers than the Pearson coefficient [37].

Table II shows the Spearman coefficient for each gait metric. The Kinect measurements of step length, stride length and stride velocity are all strongly correlated with the Zeno measurements, having coefficients > 0.95.

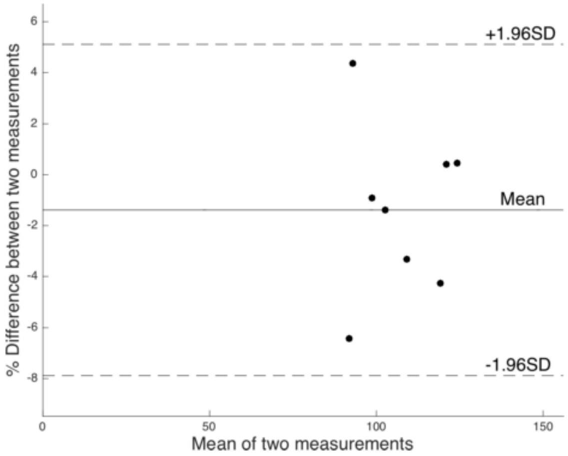


Figure 3: Bland-Altman plot for stride velocity

C. Agreement

Bland-Altman analysis [38] is a common method in medical statistics for assessing the agreement between two systems of measurement. It has been used for concurrent validity studies with the Kinect [13], [25], [33].

In a Bland-Altman plot, the difference between two measurements is plotted against the mean of the two measurements. Bland and Altman recommended that 95% of the data should lie within the lower and upper limits of agreement, which are defined as ± 1.96 standard deviations from the mean difference. The differences can also be displayed as percentages of the mean values, so that they are proportional to the magnitude of the data [39]. This is useful for comparing limits of agreement between metrics with different magnitudes, such as stride velocity and stride width. Fig. 3 shows the Bland-Altman plot for stride velocity, with differences expressed as percentages.

Table III shows the results of Bland-Altman analysis for each gait metric. The bias is the mean of differences between measurements. This bias is visible in Fig. 4. The Kinect measurements of step length have a clear negative bias, while the stride velocity is essentially unbiased.

Although the stride velocity has the lowest absolute bias, the step and stride lengths have narrower limits of agreement. A narrow range between the limits indicates strong agreement.

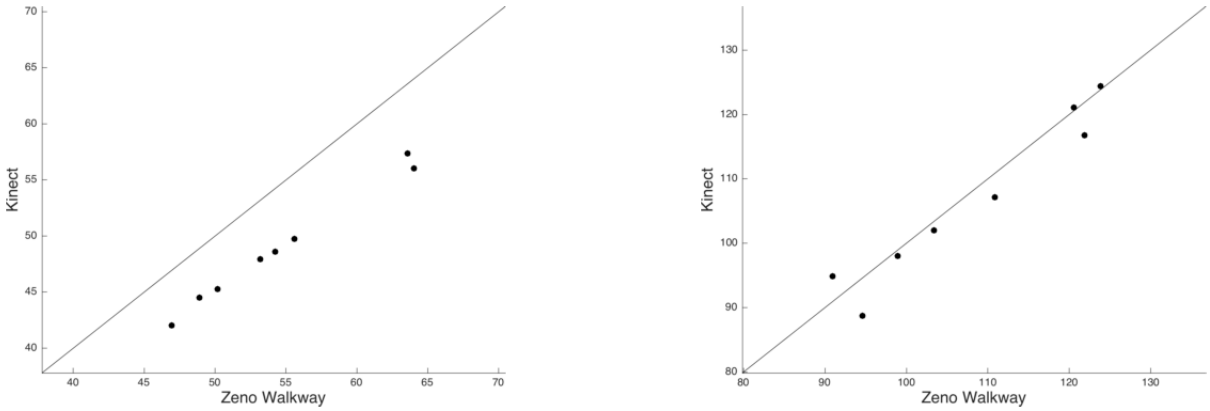
V. DISCUSSION

The results indicate that the Kinect measurements of stride velocity are highly similar to the Zeno walkway measurements, with low relative error, low bias and a narrow limit of agreement. The step length and stride length have high correlations, but there is a significant negative bias. If the source of this bias is identified and corrected, the step and stride length could be in even stronger agreement than stride velocity. The stride width metric has the least agreement between systems.

The effectiveness of this approach to gait analysis relies on correctly detecting strides from peaks in the foot distance data. During a walking pass, some image frames may only contain noise. These are deleted by our system, making them

Table I: Mean gait metrics and relative error for each trial

	Step Length [cm]			Stride Length [cm]			Stride Velocity [cm/s]			Stride Width [cm]		
Trial	Kinect	Zeno	Rel. error	Kinect	Zeno	Rel. error	Kinect	Zeno	Rel. error	Kinect	Zeno	Rel. error
1	49.8	55.6	-11%	99.9	112.6	-11%	121.1	120.6	0%	13.6	13.4	2%
2	47.9	53.2	-10%	96.8	108.0	-10%	102.0	103.4	-1%	13.1	11.4	15%
3	44.5	48.9	-9%	89.4	96.9	-8%	94.9	90.9	4%	14.6	11.2	30%
4	48.6	54.2	-10%	97.4	110.1	-12%	107.2	110.8	-3%	12.6	11.1	13%
5	45.3	50.2	-10%	90.5	100.6	-10%	98.1	98.9	-1%	12.1	9.9	23%
6	42.0	46.9	-10%	83.5	94.3	-12%	88.7	94.6	-6%	12.4	9.7	28%
7	56.0	64.1	-13%	114.3	129.0	-11%	124.3	123.8	0%	12.3	8.4	47%
8	57.3	63.6	-10%	115.5	128.0	-10%	116.8	121.8	-4%	11.0	8.1	37%



(a) Step Length [cm]

(b) Stride Velocity [cm/s]

Figure 4: Mean gait metrics of the Kinect plotted against the Zeno walkway. The line of equality shows the ideal placement of the points.

Table II: Spearman correlation between the two systems

Gait metric	ρ
Step Length	0.9762
Stride Length	0.9762
Stride Velocity	0.9524
Stride Width	0.8571

Table III: Bland-Altman results as percentage

		Limits of agreement (%)		
	Bias (%)	Lower	Upper	Range
Step Length [cm]	-10.9	-13.1	-8.6	4.4
Stride Length [cm]	-11.0	-13.8	-8.2	5.6
Stride Velocity [cm/s]	-1.4	-7.9	5.1	13.0
Stride Width [cm]	21.1	-1.3	43.4	44.7

blank. Because of this, the number of walking passes cannot be determined by simply counting the blocks of uninterrupted frames. Instead, the peak frame numbers are clustered, so that the peaks are correctly grouped by walking pass. If the number of walking passes is known beforehand, then k-means clustering is sufficient for this purpose, where k is the number of passes in front of the camera. If the number of passes is unknown or variable, the mean shift clustering algorithm is suitable, as it automatically determines the number of clusters.

VI. LIMITATIONS AND FUTURE WORK

As shown in the results, the Kinect camera system measures step and stride length with a negative bias. The cause of this bias will be addressed for future publications. Furthermore, the stride width calculation will be inspected and possibly revised to achieve a better agreement with the Zeno walkway.

The Zeno walkway measures gait metrics for the left and right sides, and for each individual stride. Future work could examine the agreement of the Kinect with these measurements.

The trials that were measured at the Recovery and Performance Laboratory by the Kinect and Zeno walkway involved a variety of walking conditions. Specifically, participants either walked normally, or were asked to engage in a cognitively challenging task while walking (dual-tasking). These different types of walks will be analyzed separately in further work.

VII. CONCLUSION

Participants with MS completed walking trials on a pressure sensitive walkway designed for gait analysis, the Zeno walkway. They were simultaneously recorded by a Kinect camera from a side view. The PKMAS software was used to calculate gait metrics from the walkway measurements.

Four gait metrics were measured by the Kinect camera and the Zeno walkway: step length, stride length, stride width, and stride velocity. The measurements from the first 8 walking trials have been presented, and the two systems have been compared. Strong agreement was found between the two systems with stride velocity, and medium to strong agreement with other gait metrics.

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