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Evaluation of an instrumented walkway for measurement of the kinematic parameters of gait

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Abstract

The purpose of this study was to compare kinematic gait parameters measured with an instrumented walkway system (GAITRite®) and a video-based system (peak performance motus 3.1®). Subjects walked across a GAITRite mat with embedded pressure sensors. Reflective markers were attached to subjects' shoes and video capture was simultaneously performed during each trial. Video data were then digitized manually using peak software. Correlation coefficients for all parameters measured with both systems were high (≥ 0.94). Significant differences between systems were found with analysis of variance (ANOVA) for two parameters, step length and stride velocity ($P = 0.003$, 0.0002). The results of this study indicate that the instrumented walkway gave comparable results for temporal parameters but further investigation is needed to evaluate the fidelity of its spatial performance.

Keywords: Gait; Motion analysis; Kinematics

1. Introduction

Observational gait analysis is a method commonly used by clinicians to estimate joint angles, muscle activity, and kinematic parameters. While visual estimates can help evaluation and treatment, they do not provide sufficient objective measures of gait. Stop watches and video recorders can be used to measure temporal and spatial parameters so that objectivity can be enhanced. However, the simplicity of these devices may sacrifice accuracy and their use may be impractical in most fast-paced clinics [1].

Sophisticated three-dimensional motion analysis systems are used to assess gait kinematics in laboratory settings. While many of the systems available are highly accurate, they may not be an optimal choice for clinical use because they are expensive, and can be time- and labor-intensive [2–7]. Such drawbacks precipitate the need for validation and use of a relatively inexpensive, user-friendly, objective gait analysis system. A system that meets these requirements can be used in a variety of clinical settings to monitor effectiveness of therapeutic interventions.

A portable computer-based instrumented walkway system (GAITRite®) has been designed to analyze gait in a clinical setting. The system includes an electronic roll-up walkway imbedded with pressure sensors. The walkway is connected to a personal computer installed with application software that calculates spatial and temporal parameters. McDonough et al. [8] compared this system with paper and chalk measures of footfall imprints and concluded that the ability to measure spatial parameters such as step length and stride length was excellent. These investigators also used a stopwatch to measure temporal parameters of gait and found that most relationships between the instrumented walkway system and the stopwatch were poor to fair. However, for future studies they recommended that temporal parameters be assessed with a standard, i.e. more accurate than a stopwatch [8].

The objective of our study was to compare the spatial and temporal gait parameters sampled concurrently with an instrumented walkway system and video-based three-dimensional motion analysis system (peak performance technologies motus 3.1®[1]) to determine the in-

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trinsic accuracy of the instrumented walkway system. This study's null hypothesis was that there would be no statistically significant differences in spatial and temporal parameters measured by the instrumented walkway system and the video-based motion analysis system. If valid, the instrumented walkway system would have sufficient accuracy for use in clinical gait analysis applications.

2. Methods

2.1. Subjects

Following the West Virginia University Institutional Review Board approval, ten healthy subjects were recruited to participate in this study. Volunteers who ambulated with assistive devices, orthotics, or braces were excluded. Written informed consent was obtained from each subject prior to data collection.

2.2. Materials

The instrumented walkway system includes an electronic roll-up walkway, i.e. 4.6 m long and is connected to a personal computer installed with application software. The walkway has six sensor pads with an active area of 61 cm wide and 366 cm long. The active area contains sensors arranged in a grid pattern (48×288) with sensors placed on 1.27 cm centers, totaling 13 824 sensors. The spatial resolution of the walkway is 1.27 cm. A serial interface cable connects the walkway to a personal computer. The sampling frequency of the system is 30 Hz.

The video-based system included a single high shutter speed Burle video camera (model #TC351 A) equipped with an infrared filter, dual infrared lights, and a 25 mm lens. The camera system collected gait parameters in the sagittal plane at 60 Hz with a shutter rate of 1000 (i.e. 1/1000 s). Data were recorded using a Panasonic S-VHS videocassette recorder. The camera was leveled and positioned on a tripod at 5 m away from the instrumented walkway.

2.3. Procedure

Subjects were required to wear dark colored shoes with low heels to aid in the standardization of data collection. Age, height (cm), body mass (kg), gender, and bilateral lower extremity lengths (distance in cm from the greater trochanter to the floor, bisecting the lateral malleolus) were recorded for each participant. Each subject was assigned an identification number to preserve confidentiality. Information from each data form was then electronically stored in the walkway system's subject data file.

Prior to ambulating across the instrumented walkway, small light reflective, spherical markers (approximately 2 cm in diameter) were attached to toe of the right shoe and heel of both shoes. A segment of video was then recorded with the subject holding a meter stick in a horizontal position. Reflective tape covered both ends of the meter stick. This segment of video was recorded and later used to calibrate the video-based system (i.e. to compare actual and recorded distances with the two pieces of reflective tape).

Each subject was required to walk at neutral or self-selected, slow, and fast paces in random order. If the randomization designated that the subject's initial trial be either fast or slow, the subject was first given a practice trial to determine the neutral or self-selected pace. Fast and slow speeds were then calculated by adding or subtracting 20% of the neutral pace from the cadence recorded by the instrumented walkway during the practice trial. A calibrated metronome was used to standardize the cadence during the trials at fast and slow speeds. Participants were given ample practice time to establish a gait pattern in which initial contact occurred simultaneously with the beat of metronome. Each ambulation trial began 4 m in front of the walkway so that a consistent gait pattern could be established prior to making contact with the walkway. This distance also allowed for coordination of initial contact with the beat of the metronome. As the individual made contact with the walkway, footfalls were detected and electronically stored by the instrumented walkway's software. The software processed each footfall to calculate kinematic parameters. The video camera was activated simultaneously with the instrumented walkway to record images of the reflective markers and foot position as the subjects traversed the walkway. Manual digitization of the camera recorded images was performed to assign X and Y coordinates and frame numbers to each reflective marker at right heel strike, left heel strike, right toe-off, and the subsequent right heel strike. The same examiner digitized all frames. These values were utilized to compute step length, step period, stride velocity, stance duration, and swing duration for the video-based system (Appendix A).

2.4. Statistical analyses

Intra-class correlation coefficients (ICC) were used to evaluate the intra-rater reliability of repeated manual digitization of eight randomly selected independent frames of video camera data.

Means and standard errors were calculated for step length, step period, stride velocity, stance duration, and swing duration in both systems. A paired t-test was used to determine the mean differences between the two systems. Pearson product moment correlation coefficients were used to quantify the relationships between

Table 1
Instrumented walkway vs. video-based system, Pearson product moment correlation coefficients for kinematic parameters

Parameter	R
Step length	0.936
Step period	0.974
Stride velocity	0.997
Stance duration	0.988
Swing duration	0.949

the instrumented walkway and video-based systems for the studied kinematic variables. Analysis of variance (ANOVA) was conducted to determine the effect of gait speed, measurement system, and the gait speed-measurement system interaction. An α-level of 0.05 was used for each analysis to determine the statistical significance.

3. Results

3.1. Subjects

The study population consisted of four males and six females between 21 and 26 years of age (average 22.1). The average height of the male and female subjects was 177.2 cm (172–184-cm range) and 168.1 cm (159–176-cm range), respectively. The average body mass of the male and female subjects was 86.1 kg (74.5–98.2-kg range) and 62.1 kg (47.7–75.5-kg range), respectively. The average neutral walking cadence of the male and female subjects were 106.78 and 117.19 steps per min, respectively.

3.2. Video-based system analysis

The largest discrepancy found between actual and predicted distances and between the two pieces of reflective tape positioned on the ends of the meter stick used for the video-based calibration was 0.2 mm. Intraclass correlation coefficients (ICC) for repeated measures of manual digitization of reflective targets positioned on subject shoes for a single frame of video data ranged from 0.92 to 0.99.

3.3. Instrumented walkway versus video-based kinematic parameters

Pearson product moment correlations of the five kinematic parameters measured simultaneously by the instrumented walkway and video-based systems ranged from 0.936 to 0.988 (Table 1). Mean differences between the instrumented walkway and video-based systems for step length and stride velocity increased with gait speed (step length, [1.8 cm at slow pace to 4.6 cm at fast pace], and stride velocity [7.1 cm/s at slow pace to 14.7 cm/s at fast pace]). However, the mean temporal parameters (step period, stance duration and swing duration) did not change with speed (Table 2). The instrumented walkway system consistently measured step length and stride velocity higher than the video-based system across all gait speeds. The mean differences in step length and stride velocity were significant ($P < 0.0001$, Table 3) and increased with speed. However, the difference in slopes of the responses were not significant enough to affect the speed-system interaction ($P = 0.5859$ for step length, $P = 0.9987$ for stride veloc-

Table 2
Mean and S.E. for kinematic parameters determined by the instrumented walkway and video-based systems at slow, neutral and fast walking speeds

Parameter	Instrumented walkway			Video-based		
	Slow	Neutral	Fast	Slow	Neutral	Fast
Step length (cm)						
Mean	63.4	75.0	81.2	61.5	71.2	76.7
S.E.	2.6	2.8	2.1	2.2	2.3	1.9
Step period (s)						
Mean	0.73	0.54	0.44	0.72	0.54	0.43
S.E.	0.03	0.01	0.01	0.02	0.01	0.01
Stride velocity (cm/s)						
Mean	91.3	143.2	191.0	84.3	132.9	176.3
S.E.	3.9	6.6	8.2	3.8	6.2	6.7
Stance duration (s)						
Mean	0.93	0.67	0.53	0.95	0.67	0.53
S.E.	0.03	0.02	0.01	0.03	0.02	0.02
Swing duration (s)						
Mean	0.52	0.41	0.34	0.51	0.40	0.35
S.E.	0.02	0.01	0.01	0.02	0.01	0.01

Table 3
Paired t-tests, mean differences in kinematic parameters determined by video-based and instrumented walkway systems for slow, neutral and fast speeds[a]

Parameter	Mean difference	t-Value	P-value
Step length (cm)	3.44	4.785	<0.0001
Step period (s)	0.01	1.195	0.2417
Stride velocity (cm/s)	10.70	11.410	<0.0001
St duration (s)	−0.01	−1.055	0.3000
Sw duration (s)	0.01	0.905	0.3731

[a] Significant at $P \leq 0.05$; St, stance; Sw, swing.

Table 4
ANOVA and instrumented walkway vs. video-based system[a]

	Subject	Speed	System	Speed* system
Step length				
F-values	13.2408	77.9652	9.8175	0.5411
P-values	<0.0001*	<0.0001*	0.0030*	0.5859
Step period				
F-values	371.1894	9.0723	0.5645	0.1976
P-values	<0.0001*	<0.0001*	0.4571	0.9930
Str velocity				
F-values	456.2305	18.0370	17.0452	0.1263
P-values	<0.0001*	<0.0001*	0.0002*	0.9987
St duration				
F-values	357.9155	8.9781	0.2192	0.1996
P-values	<0.0001*	<0.0001*	0.6424	0.9928
Sw duration				
F-values	95.2684	4.4477	0.2105	0.1580
P-values	<0.0001*	0.0005*	0.6490	0.9970

[a] Significant at $P \leq 0.05$*; speed, gait speed; system, instrumented walkway vs. video-based; Str, stride; St, stance; Sw, swing.

ity, Table 4). ANOVA also indicated that the results were significantly different for step length ($P = 0.003$) and stride velocity between the two systems ($P = 0.0002$, Table 4).

The mean values obtained by the two systems for the temporal parameters (step period, stance duration, and swing duration) at all gait speeds were not statistically different according to t-test results ($P \geq 0.2417$, Table 3) and ANOVA results ($P \geq 0.45$, Table 4).

There were significant differences between subjects ($P < 0.0001$) and gait speeds ($P = 0.0005$ for swing duration and $P < 0.0001$ for the other parameters tested, Table 4).

4. Discussion

While a number of gait analysis systems have been developed over the years, most of them are impractical for fast-paced clinical settings [2–7,9]. The present study compared with the accuracy of an instrumented walkway system to a video-based three-dimensional motion analysis system. The instrumented walkway is a gait analysis tool that is portable, easy to use and is relatively inexpensive. McDonough et al. [8] found that its ability to measure spatial parameters was excellent but these authors recommended further studies to address temporal parameters. A video-based motion analysis system such as peak was chosen as a standard which used to compare with the instrumented walkway system because it is a sophisticated motion analysis tool that is used in laboratory settings and is well documented in published literature. A single camera was used because two-dimensional precision and the accuracy are reportedly high for this system [10,11].

The present study indicates that the instrumented walkway and video-based systems are strongly correlated for all kinematic variables at the gait speeds investigated (evidenced by the Pearson product and system-speed interaction results). However, the instrumented walkway system recorded higher values for the spatial parameters than the video-based system. Both systems were closely matched at slower speeds for the spatial parameters of step length and stride velocity, but mean differences between the systems increased with increasing gait speed. These results are not surprising since stride velocity is a function of step length per unit time. The two systems were more closely matched for the measurement of temporal parameters (step period, stance duration and swing duration). The mean differences between the two systems for temporal parameters were not statistically different. In contrast to the spatial parameters, the mean differences in temporal parameters between the systems did not increase with gait speed. This difference in the two systems did not affect any of the temporal parameters because the spatial location of initial contact of the foot should not change a time-based kinematic parameter.

Though intra-tester reliability of repeated measures of digitization was high, discrepancies of spatial parameters occurred between the two systems especially at increased gait speeds. The difference in the results between spatial parameters may be due to the difference between data acquisition and processing methods used by the two systems. The instrumented walkway uses pressure transducers to automatically detect initial contact regardless of which part of the foot makes initial contact. The video-based system does not detect initial contact but rather requires visual estimation of each heel strike with subsequent digitization of a reflective marker on the heel. The intra-tester reliability of 0.92–0.99 indicated that there was repeatable digitization of reflective markers. The video-based system provides high spatial resolution and repeatable results when coupled with high intra-tester reliability, which is well suited for gait analysis [11]. The increase in discrepancy of spatial parameters with gait speed may be due to the instrumented walkway's acquisition or processing of data of the pressure sensitive transducers. This study did not investigate the instrumented walkway's calibration since the instrumented walkway system design is not intended for calibration by the end user. Further investigation of the spatial performance of the instrumented walkway with different gait speeds is needed to accurately characterize the fidelity of its spatial performance.

ANOVA analysis indicated that there was a significant difference among subjects and gait speeds. These results were expected because the neutral speed of each subject was self-selected and then individual fast and slow gait speeds were calculated from each subject's own self-selected neutral pace.

Several limitations of this study may affect the applicability of the results. First, the narrow age range used in this study may affect the ability to apply these results to a broader population. The small sample size may also be a factor. Despite this limitation, all kinematic parameters tested showed consistent patterns and the parallel relationship of the kinematic parameters between systems suggests that results would remain unchanged with a larger sample size.

5. Conclusions

The instrumented walkway and video-based systems were closely matched for the majority of kinematic variables examined in this study. Step length and stride velocity, while highly correlated, were significantly different. The instrumented walkway system is portable, requires little set-up time and gave accurate results for the temporal parameters studied. Further studies are needed to determine the spatial performance of the instrumented walkway and its clinical usefulness with various patient populations.

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Appendix A

Step length $\sqrt{[\mathrm{LHS1(X)} - \mathrm{RHS1(X)}]^2 + [\mathrm{LHS1(Y)} - \mathrm{RHS1(Y)}]^2}$

Step period $\dfrac{[\mathrm{LHS1(frame)} - \mathrm{RHS1(frame)}]}{60}$

Stride velocity $\sqrt{\dfrac{[\mathrm{RHS2(X)} - \mathrm{RHS1(X)}]^2 + [\mathrm{RHS2(Y)} - \mathrm{RHS1(Y)}]^2}{[\mathrm{RHS2(frame)} - \mathrm{RHS1(frame)}] \div 60}}$

Duration of stance $\dfrac{[\mathrm{RTO1(frame)} - \mathrm{RHS1(frame)}]}{60}$

Duration of swing $\dfrac{[\mathrm{RHS2(frame)} - \mathrm{RTO1(frame)}]}{60}$

LHS1, first left heel strike; LHS2, second left heel strike; RHS1, first right heel strike; RHS2, second right heel strike; RTO1, first right toe-off.

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