A comprehensive approach to assess walking ability and fall risk using the Interactive Walkway

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Title: A comprehensive approach to assess walking ability and fall risk using the Interactive Walkway
Issue Date: 2019-05-08

Chapter 5

Assessing walking adaptability in stroke patients

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Under review

Purpose. The ability to adapt walking is important for safe ambulation. Assessments of impairments in walking adaptability with the Interactive Walkway (IWW) may aid in the development of individualized therapy strategies of stroke patients. The IWW is an overground walkway with Kinect v2 sensors for a markerless registration of full-body kinematics which can be augmented with (gait-dependent) visual context to assess walking adaptability. This study aims to evaluate the potential of the IWW as a new technology for assessing walking adaptability in stroke patients. Materials and methods. 30 stroke patients and 30 controls performed clinical tests, quantitative gait assessments and various walking-adaptability tasks on the IWW. Outcome measures were compared between stroke patients and controls to examine known-groups validity. Pearson's correlation coefficients were calculated to assess the relationship between and within clinical test scores, spatiotemporal gait parameters and walking-adaptability outcome measures. Results. Good known-groups validity for walking-adaptability tasks was demonstrated. In addition, walking-adaptability tasks complemented clinical tests and spatiotemporal gait parameters and addressed different aspects of walking ability and walking adaptability. Conclusion. The IWW allows for a quick, unobtrusive and comprehensive quantitative assessment of walking adaptability with potential for monitoring recovery after stroke and informing neurologic therapy strategies.

Introduction

Walking speed assessed over short distances (e.g., 10-meter walking test), spatiotemporal gait parameters (e.g., step length) and clinical tests (e.g., Timed Up-and-Go test) are frequently used outcome measures of walking ability in stroke patients [1]. However, these outcome measures mainly reflect only two of the three aspects of walking ability, that is, the abilities to generate repetitive stepping and to maintain balance while walking. The third aspect of walking ability, the ability to adjust steps to one's surrounding, is largely left unaddressed, which is unfortunate as it is essential for safe and independent ambulation [2]. Walking adaptability is defined as the ability to adapt walking to meet behavioral task goals and demands of the environment [2] and includes, among others, the ability to avoid obstacles, make sudden stops, place feet accurately in a cluttered environment and walk while performing a dual task [2]. Laboratory studies showed that stroke patients generally have a reduced ability to adapt walking to environmental circumstances [3-6]. This reduced walking adaptability makes these patients more susceptible to walking-related falls due to trips, slips or misplaced steps [7-9]. Assessing walking adaptability thus seems essential to better understand and treat walking limitations. Unfortunately, there is no comprehensive clinical test of walking adaptability [2] and laboratory studies have thus far typically focused on specific aspects of walking adaptability, mainly obstacle avoidance [3-6,10,11]. As a consequence, we lack a thorough understanding of walking adaptability after stroke.

The Interactive Walkway (IWW; Figure 5.1) may help fill this void. It is an overground walkway equipped with multiple Kinect v2 sensors for markerless 3D full-body motion registration [12]. The IWW is augmented with (gait-dependent) visual context, such as suddenly appearing obstacles and stop cues (based on real-time processed gait data), to assess walking adaptability [13]. Furthermore, attention-demanding secondary tasks, such as serial-3 subtractions [11] or an auditory Stroop task [4,10], can be added to assess dual-task walking.

The aim of this study is to evaluate the potential of the IWW as a new technology for assessing walking adaptability in stroke patients. To this end, we will 1) evaluate the known-groups validity of IWW outcome measures by comparing them between stroke patients and healthy controls, 2) relate these outcome measures to clinical test scores and spatiotemporal gait parameters of unconstrained walking, and 3) examine to what extent the various walking-adaptability tasks address different aspects of walking adaptability.

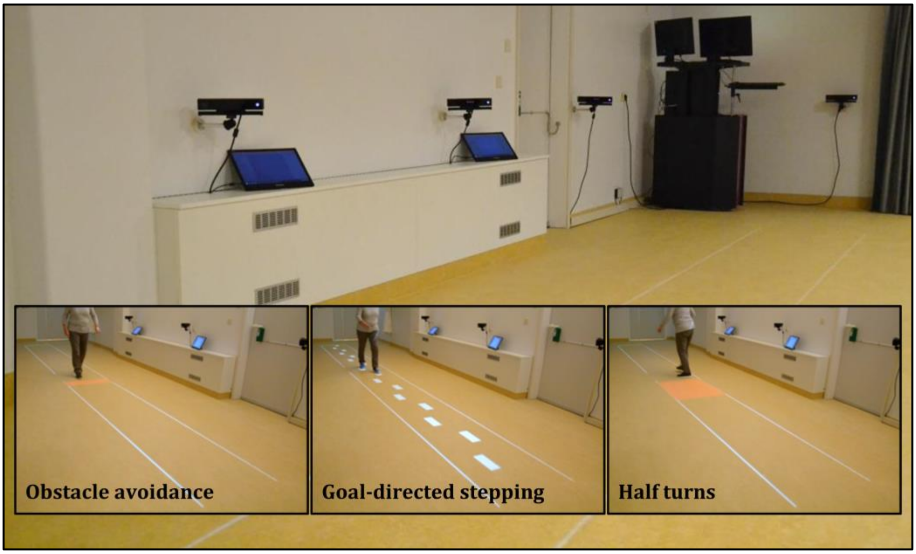

Figure 5.1 The set-up of the Interactive Walkway with various walking adaptability tasks (insets).

Methods

Subjects

In total, 30 stroke patients and 30 age- and sex-matched healthy controls (mean±std: 62.5 ± 10.1 vs. 62.9 ± 10.3 years, respectively; 18 males and 12 females) were included in this study. Stroke patients were recruited from the outpatient clinic of the Leiden University Medical Center and from a list of patients who were discharged from the Rijnlands Rehabilitation Center. Controls were recruited via advertisement. Subjects had to be 18 years or older and should have command of the Dutch language. Stroke patients had to experience residual motor dysfunction (Fugl-Meyer Assessment lower extremity score < 34), but had to be able to stand unsupported for more than 20 seconds and walk independently. Stroke patients were permitted to use walking aids, including quad canes (n = 3), canes (n = 4), ankle foot orthoses (n = 11) and functional electrical stimulation (n = 1). Controls had to have unimpaired gait, normal cognitive function (Montreal Cognitive Assessment score ≥ 23; [14]) and normal or corrected to normal vision. Exclusion criteria were (additional) neurological diseases and/or other problems interfering with gait function. Stroke patients were excluded if they were less than 12 weeks post-stroke. Stroke patients were 7.9 ± 7.3 years post-stroke, had a Fugl-Meyer Assessment lower extremity score of 19.7 ± 7.4 (possible range 0-34; higher scores indicate better motor function) and a Montreal Cognitive Assessment score of 24.4 ± 4.1 (possible range 0-30; higher scores indicate better cognitive abilities), which was not assessed in four stroke patients due to (severe) aphasia. Healthy controls had a significantly higher Montreal Cognitive Assessment score of 27.7 ± 1.4 ($p < 0.001$). Data was collected within the Technology in Motion project (protocol registered as NL54281.058.15; www.toetsingonline.nl). All subjects gave written informed consent, and the study was approved by the local medical ethics committee (P15.232).

Experimental set-up and procedure

Clinical gait and balance tests were administered. Two gait tests were included to assess mobility: the Timed-Up-and-Go test [15,16] and the 10-meter walking test at comfortable and maximum walking speed [15,17]. Longer completion times indicate worse mobility. The Tinetti Balance Assessment [18,19] has two sections that evaluate gait and balance performance, of which the combined score was used in this study (possible range 0-28; higher scores indicate better performance). Two balance tests were administered (with higher scores indicating a better balance): the 7-item Berg Balance Scale [20], to measure static and dynamic balance during specific movement tasks (possible range 0-14), and the Functional Reach Test [21,22], to determine the maximal distance one can reach forward from a standing position.

Unconstrained walking and walking adaptability were assessed on the IWW using four spatially and temporally integrated Kinect v2 sensors to obtain full-body kinematics. The IWW set-up was based on a validated IWW set-up used in Geerse et al. [12,13], with improved inter-sensor distances following recommendations of Geerse et al. [23] (Figure 5.1). The sensors were positioned at a height of 0.95 m alongside a walkway of 8 by 0.75 m. The first three sensors were placed frontoparallel (i.e., with an angle of 70 degrees relative to the walkway direction) with a distance of 1.2 m from the left border of the walkway. The last sensor was positioned frontally at the end of the walkway, since this will minimize orientation-based biases [24]. The first sensor was positioned at 3 m from the start of the walkway and the other sensors were placed at inter-sensor distances of 2.1 m. The IWW was equipped with a projector (EPSON EB-585W, ultra-short-throw 3LCD projector) to augment the entire 8-meter walkway with visual context for the walking-adaptability tasks. The coordinate systems of the sensors and projector were spatially aligned to a common coordinate system using a spatial calibration grid. IWW data were sampled at 30 Hz using custom-written software utilizing the Kinect-for-Windows Software Development Kit (SDK 2.0).

Subjects performed unconstrained walking and various walking-adaptability tasks on the IWW (Figure 5.2; see Table 5.1 for more details and Supplement 5.1 for a video of the tasks). Unconstrained walking was assessed with an 8-meter walking test. Walking adaptability was broadly assessed with the following tasks: obstacle avoidance, sudden stops-and-starts, goal-directed stepping (with symmetric and irregular stepping stones), narrow walkway, speed adjustments (speeding up and slowing down), slalom, turning (half and full turns in both directions) and dual-task walking (plain and augmented). Dual-task walking was assessed by adding an auditory Stroop task [25] in which the words high and low (in Dutch) were pronounced at a high or low pitch (i.e., congruent and incongruent stimuli) to both the plain 8-meter walking test and the augmented obstacle-avoidance task, respectively. The subject had to respond with the pitch of the spoken word. The IWW assessment comprises a total of 35 trials (Table 5.1). All tasks were performed at a self-selected walking speed.

Half of the subjects started with the block of clinical tests, the other half with the IWW assessment. With regard to the latter, subjects always started with the 8-meter walking test, which enabled us to adjust the settings of the walking-adaptability tasks to one's own gait characteristics in an attempt to obtain a similar level of difficulty for each subject (see Table 5.1). For example, available response times for suddenly appearing obstacles were controlled by self-selected walking speed during the 8-meter walking test and available response distance (ARD in Figure 5.2). Subsequently, the 8-meter walking test was performed with the dual task (i.e., plain dual-task walking), preceded by a familiarization trial in which the auditory Stroop task was practiced while sitting. The remaining IWW tasks were randomized in blocks (Table 5.1), with rest breaks in between to prevent fatigue.

Data pre-processing and analysis

Data pre-processing followed Geerse et al. [12,13], as detailed in Supplement 5.2. In total, 91 trials (4.2% of all trials) were excluded since some subjects (i.e., five stroke patients) were not able to perform the tasks or the trials were not recorded properly (i.e., incorrect recording or not all Kinect sensors were able to track the subject). The outcome measures of the IWW tasks were calculated from specific body points' time series, estimates of foot contact and foot off and step locations, as detailed in Table 5.1 and Supplement 5.2. The average over trials per task per subject was calculated for all outcome measures.

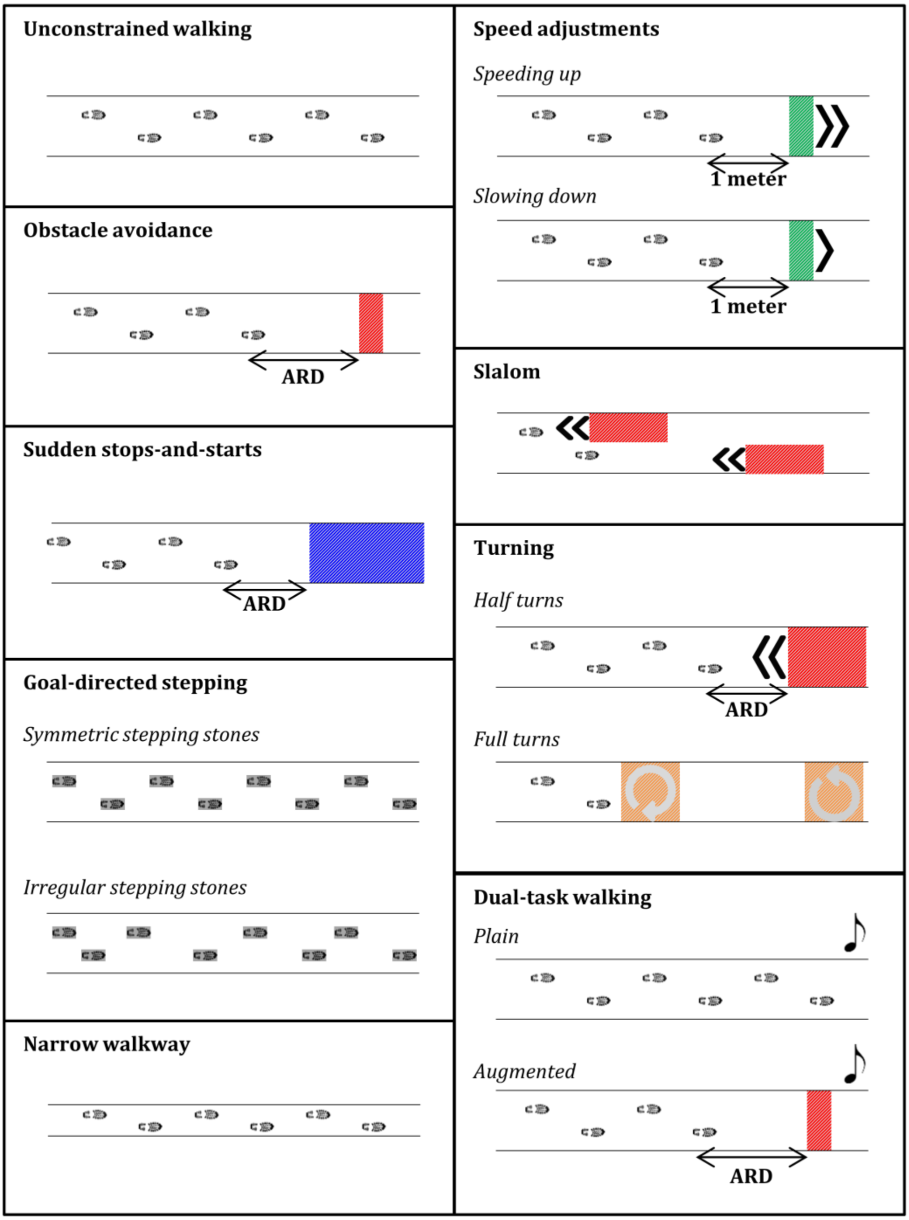

Figure 5.2 Schematics of unconstrained walking and walking-adaptability tasks on the Interactive Walkway. The available response distance (ARD) of the suddenly appearing obstacles and cues varied over subjects depending on their own gait characteristics.

Table 5.1 Interactive Walkway tasks and outcome measures of unconstrained walking and walking adaptability.

Tasks	n	Level of difficulty	Characteristics	Outcome measure	Unit	Calculation
Unconstrained walking						
8-meter walking test	2		Walking at self-selected walking speed.	Walking speed	cm/s	The distance travelled between the 0-meter and 8-meter line on the walkway divided by the time, using the data of the spine shoulder.
				Step length	cm	The median of the differences in the anterior-posterior direction of consecutive step locations.
				Stride length	cm	The median of the differences in anterior-posterior direction of consecutive ipsilateral step locations.
				Step width	cm	The median of the absolute mediolateral difference of consecutive step locations.
				Cadence	steps/min	Calculated from the number of steps in the time interval between the first and last estimate of foot contact.
				Step time	s	The median of the time interval

						between two consecutive instants of foot contact.
				Stride time	s	The median of the time interval between two consecutive ipsilateral instants of foot contact.
				Symmetry step length	%	Smallest step length (i.e., left or right) divided by the largest step length times 100%.
				Symmetry step time	%	Shortest step time (i.e., left or right) divided by the longest step time times 100%.
Walking adaptability						
Obstacle avoidance	5	ART = 1 s (three trials) ART = 0.75 s (two trials)	Avoiding suddenly appearing obstacles.	Obstacle-avoidance margins	cm	The distance of the anterior shoe edge (trailing limb) and posterior shoe edge (leading limb) of the step locations to corresponding obstacle borders during obstacle crossing.
				Success rate	%	Number of successfully avoided obstacles divided by the number of obstacles presented times 100%.

Table 5.1 Continued.

Tasks		n	Level of difficulty	Characteristics	Outcome measure	Unit	Calculation
Sudden stops-and-starts		5	ART = 1 s (three trials) ART = 0.75 s (two trials)	Stopping behind the suddenly appearing stop cues and start walking as soon as the cues disappear.	Sudden-stop margins	cm	The minimum distance of the anterior shoe edge to the corresponding stop cue border during the period in which the cue was visible.
					Success rate	%	Number of successful stops divided by the number of stop cues presented times 100%.
					Initiation time	s	The time between disappearance of the stop cue and the moment of first foot contact.
Goal-directed stepping	**SSS**	3	Average SL 75% average SL 125% average SL	Stepping as accurately as possible onto the shoe-size-matched stepping stones.	Stepping accuracy	cm	The standard deviation over the signed deviations between the center of the stepping target and the center of the foot at corresponding step locations. The center of the foot was determined using the average distance between the ankle and the middle of the shoe-size-matched targets of
	ISS	2	25% variation in SL left and right 50% variation in SL left and right				

							the calibration trials.
					Normalized walking speed	%	Walking speed divided by SSWS times 100%.
Narrow walkway		2	WW = 1.5*SW+FW WW = SW+FW	Walking between the lines of the walkway.	Success rate	%	Number of steps inside the walkway divided by the total number of steps taken times 100%.
					Normalized walking speed	%	Walking speed divided by SSWS times 100%.
					Normalized step width	%	Step width divided by the imposed step width times 100%.
Speed adjustments	**SU**	2	120% SSWS 140% SSWS	Start walking and when a speed cue appears one meter in front of the subjects it has to be followed at the imposed speed.	Success rate	%	The percentage of the time spend walking faster (or slower) than the imposed speed minus (or plus) 20% during the period in which the speed cue was visible.
	SD	2	80% SSWS 60% SSWS				
					Normalized walking speed	%	Walking speed divided by the imposed walking speed times 100%.

Table 5.1 Continued.

Tasks		n	Level of difficulty	Characteristics	Outcome measure	Unit	Calculation
Slalom		2	Symmetric distance between obstacles Variable distance between obstacles	Walking around the moving obstacles that approach the subjects with a speed of 50% SSWS.	Success rate	%	Number of successfully avoided obstacles divided by the number of obstacles presented times 100%.
					Normalized walking speed	%	Walking speed divided by SSWS times 100%.
Turning	**HT**	2	ART = 3 s ART = 2 s	Start walking and when a turning cue approaches the subject with a speed of 100% SSWS, the subject has to turn and walk back to the start.	Success rate	%	Number of successful half turns divided by the number of half turns times 100%.
					Turning time	s	Time within the turning square (for full turns) or time from appearance of the turning cue till moment walking direction was reversed (for half turns), using the data of the spine shoulder.
	FT	1		In the two presented squares the subject has to make a full turn as fast and safe as possible in the direction of the arrow.			

Dual-task walking	**PDT**	2		Walking while also performing a dual task. The dual task was an auditory Stroop task.	Normalized walking speed	%	Walking speed divided by SSWS times 100%.
	ADT	5	ART = 1 s (three trials) ART = 0.75 s (two trials)	Avoiding suddenly appearing obstacles while also performing a dual task. The dual task was an auditory Stroop task.	Normalized success rate	%	Obstacle avoidance success rate divided by success rate of the obstacle avoidance task times 100%, excluding subjects that had an obstacle-avoidance success rate of 0% at baseline.
					Success rate dual task	%	Number of correct responses divided by the number of stimuli given times 100% (excluding subjects that had an obstacle-avoidance success rate of 0% at baseline for ADT).
Total trials		**35**					

Abbreviations: SSS = symmetric stepping stones; ISS = irregular stepping stones; SU = speeding up; SD = slowing down; HT = half turns; FT = full turns; PDT = plain dual-task walking (8-meter walking test with dual task); ADT = augmented dual-task walking (obstacle avoidance with dual task); ART = available response time; SL = step length; WW = walkway width; SW = step width; FW = foot width; SSWS = self-selected walking speed of unconstrained walking.

Statistical analysis

The known-groups validity of clinical test scores, spatiotemporal gait parameters and IWW walking-adaptability outcome measures was evaluated by comparing them between stroke patients and healthy controls using independent-samples t-tests. We computed r ($r = \sqrt{t^2/(t^2+df)}$) to quantify the effect sizes, where values between 0.100-0.299 were regarded as small, between 0.300-0.499 as medium and above 0.500 as large effect sizes [26].

Pearson's correlation coefficients were determined only for stroke patients and calculated between and within the various types of walking-ability assessments (i.e., clinical tests, unconstrained walking and IWW walking adaptability). Absolute correlations between 0-0.499, 0.500-0.699, 0.700-0.899 and 0.900-1.000 were regarded as low, moderate, high and very high, respectively [27]. SPSS version 24 (IBM© SPSS©, Armonk, New York, United States) was used to perform the statistical analyses. Alpha was set at 0.05. No adjustment for multiple comparisons was made due to the exploratory nature of this study.

Results

Known-groups validity

Stroke patients performed significantly worse on all clinical tests compared to healthy controls ($p \leq 0.001$; Table 5.2). This was also seen for the spatiotemporal gait parameters: all outcome measures showed values associated with lower walking speeds, wider step widths and less symmetric steps for stroke patients ($p < 0.001$; Table 5.2). Furthermore, stroke patients performed significantly worse than healthy controls on all IWW walking-adaptability outcome measures, except stepping accuracy on irregular stepping stones, normalized walking speed of speeding up trials, turning time of half turns and normalized success rate during augmented dual-task walking (Table 5.2).

Relations between the three types of walking-ability assessments

First, correlation coefficients were determined between clinical tests scores and spatiotemporal gait parameters (second block in top row in Figure 5.3). Of the 54 possible correlations, 45 (83.3%) were significant, out of which 28 (51.9%) were high, 13 (24.1%) were moderate and 4 (7.4%) were low. Next, correlation coefficients were determined between clinical test scores and IWW walking-adaptability outcome measures (third block in top row in Figure 5.3). Of the 156 possible correlations, 56 (35.9%) were significant, out of which 2 (1.3%) were very high, 4 (2.6%) were high, 31 (19.9%) were moderate and 19 (12.2%) were low. Lastly, correlation coefficients were determined between spatiotemporal gait parameters and IWW walking-adaptability outcome measures (third block of center row in Figure 5.3). Of the 234 possible correlations, 70 (29.9%) were significant, out of which 15 (6.4%) were high, 32 (13.7%) were moderate and 23 (9.8%) were low.

Relations within each type of walking-ability assessments

Considerable redundancy was found for the clinical tests in stroke patients (top left block in Figure 5.3). All 15 possible correlations were significant (100.0%), out of which 3 (20.0%) were very high, 6 (40.0%) were high, 2 (13.3%) were moderate and 4 (26.7%) were low. The spatiotemporal gait parameters were also highly correlated (second block along the diagonal in Figure 5.3). Of the 36 possible correlations, 34 (94.4%) were significant, out of which 7 (19.4%) were very high, 8 (22.2%) were high, 10 (27.8%) were moderate and 9 (25.0%) were low. For IWW walking-adaptability outcome measures, a lower percentage of significant correlations was found (bottom right block in Figure 5.3). Of the 325 possible correlations, only 57 (17.5%) were significant, out of which 1 (0.3%) was very high, 6 (1.8%) were high, 19 (5.8%) were moderate and 31 (9.5%) were low.

Table 5.2 Means, standard deviations and between-groups statistics of outcome measures of clinical tests, unconstrained walking and walking adaptability tasks on the Interactive Walkway for stroke patients and healthy controls.

			Stroke mean ± SD	Control mean ± SD	*t*-value	*p*-value	*r*-value
Clinical test							
Timed-Up-and-Go test	**Time (s)***		17.3 ± 11.4	7.4 ± 2.2	$t_{31.1}$ = -4.62	<0.001	0.638
10-meter walking test	**Time (s)***	**CWS**	16.6 ± 13.2	7.3 ± 1.0	$t_{29.3}$ = -3.83	0.001	0.577
	Time (s)*	**MWS**	13.5 ± 11.3	5.3 ± 0.8	$t_{29.3}$ = -3.94	<0.001	0.588
Tinetti Balance Assessment	**Score***		21.1 ± 5.0	27.7 ± 0.5	$t_{29.6}$ = 7.19	<0.001	0.797
7-item Berg Balance Scale	**Score***		10.0 ± 2.5	13.3 ± 1.3	$t_{43.8}$ = 6.50	<0.001	0.701
Functional Reach Test	**Reaching distance (cm)***		22.3 ± 7.2	29.9 ± 5.6	t_{58} = 4.60	<0.001	0.517
Unconstrained walking							
8-meter walking test	**Walking speed (cm/s)***		83.0 ± 34.6	134.3 ± 1.0	$t_{45.0}$ = 7.11	<0.001	0.727
	Step length (cm)*		52.4 ± 14.2	74.5 ± 9.4	$t_{50.3}$ = 7.10	<0.001	0.707
	Stride length (cm)*		105.3 ± 28.7	149.9 ± 18.7	$t_{49.8}$ = 7.13	<0.001	0.711
	Step width (cm)*		17.3 ± 5.5	11.1 ± 2.8	$t_{43.3}$ = -5.55	<0.001	0.645
	Cadence (steps/min)*		94.0 ± 20.5	112.3 ± 7.5	$t_{36.7}$ = 4.57	<0.001	0.602
	Step time (s)*		0.669 ± 0.184	0.526 ± 0.038	$t_{31.4}$ = -4.15	<0.001	0.595
	Stride time (s)*		1.335 ± 0.378	1.047 ± 0.074	$t_{31.2}$ = -4.10	<0.001	0.591
	Symmetry step length (%)*		85.5 ± 15.0	96.6 ± 2.3	$t_{30.3}$ = 4.03	<0.001	0.591
	Symmetry step time (%)*		78.7 ± 13.8	96.1 ± 2.9	$t_{31.5}$ = 6.80	<0.001	0.771

Walking adaptability							
Obstacle avoidance	**Margins trailing limb (cm)***		9.0 ± 8.4	19.9 ± 7.3	t_{58} = 5.38	<0.001	0.577
	Margins leading limb (cm)*		2.3 ± 6.8	12.1 ± 6.1	t_{58} = 5.88	<0.001	0.611
	Success rate (%)*		45.1 ± 32.4	88.2 ± 11.3	$t_{35.9}$ = 6.88	<0.001	0.754
Sudden stops-and-starts	**Sudden-stop margins (cm)***		-1.8 ± 7.2	5.4 ± 9.2	t_{57} = 3.33	0.002	0.403
	Success rate (%)*		56.5 ± 25.9	76.8 ± 18.5	$t_{50.7}$ = 3.46	0.001	0.437
	Initiation time (s)*		1.653 ± 0.462	1.338 ± 0.235	$t_{41.3}$ = -3.28	0.002	0.455
Goal-directed stepping	**Stepping accuracy (cm)***	**SSS**	3.7 ± 1.7	2.5 ± 0.7	$t_{35.6}$ = -3.48	0.001	0.504
	Normalized walking speed (%)*	**SSS**	78.5 ± 18.9	96.0 ± 16.5	t_{56} = 3.77	<0.001	0.449
	Stepping accuracy (cm)	**ISS**	4.8 ± 2.1	3.9 ± 1.0	$t_{40.4}$ = -1.97	0.056	0.296
	Normalized walking speed (%)*	**ISS**	77.7 ± 18.4	96.0 ± 15.7	t_{57} = 4.11	<0.001	0.478
Narrow walkway	**Success rate (%)***		68.7 ± 27.4	84.3 ± 17.4	t_{57} = 2.62	0.011	0.328
	Normalized walking speed (%)*		80.4 ± 17.3	99.0 ± 11.9	t_{57} = 4.83	<0.001	0.539
	Normalized step width (%)*		66.8 ± 30.2	37.7 ± 16.1	t_{57} = -4.64	<0.001	0.523
Speed adjustments	**Success rate (%)***	**SU**	58.5 ± 13.9	69.7 ± 10.1	$t_{47.0}$ = 3.46	0.001	0.450
	Normalized walking speed (%)	**SU**	87.8 ± 9.9	90.2 ± 6.7	$t_{44.8}$ = 1.07	0.291	0.158
	Success rate (%)*	**SD**	72.3 ± 6.8	79.1 ± 5.2	t_{55} = 4.24	<0.001	0.496
	Normalized walking speed (%)*	**SD**	102.9 ± 4.1	99.4 ± 2.3	$t_{40.1}$ = -3.94	<0.001	0.528
Slalom	**Success rate (%)***		43.3 ± 21.1	55.3 ± 23.0	t_{54} = 2.03	0.048	0.266
	Normalized walking speed (%)*		79.8 ± 15.5	94.7 ± 9.6	$t_{40.5}$ = 4.23	<0.001	0.554
Turning	**Success rate (%)***	**HT**	11.1 ± 25.3	65.0 ± 35.1	$t_{52.6}$ = 6.69	<0.001	0.678
	Turning time (s)	**HT**	1.533 ± 0.285	1.435 ± 0.251	t_{55} = -1.38	0.174	0.182
	Turning time (s)*	**FT**	6.164 ± 4.508	2.149 ± 0.961	$t_{28.1}$ = -4.53	<0.001	0.650

Table 5.2 Continued.

			Stroke	Control			
			mean ± SD	**mean ± SD**	***t*-value**	***p*-value**	***r*-value**
Dual-task walking	**Normalized walking speed (%)***	**PDT**	79.7 ± 14.2	87.7 ± 9.5	t_{56} = 2.54	0.014	0.321
	Success rate dual task (%)*	**PDT**	77.4 ± 21.6	94.9 ± 12.2	$t_{43.9}$ = 3.80	<0.001	0.498
	Normalized success rate (%)	**ADT**	80.8 ± 69.3	97.2 ± 23.9	$t_{27.4}$ = 1.11	0.277	0.208
	Success rate dual task (%)*	**ADT**	68.3 ± 24.8	91.6 ± 9.2	$t_{28.1}$ = 4.38	<0.001	0.637

Abbreviations: CWS = comfortable walking speed; MWS = maximum walking speed; SSS = symmetric stepping stones; ISS = irregular stepping stones; SU = speeding up; SD = slowing down; HT = half turns; FT = full turns; PDT = plain dual-task walking (8-meter walking test with dual task); ADT = augmented dual-task walking (obstacle avoidance with dual task).

*Significant between-groups difference ($p < 0.05$).

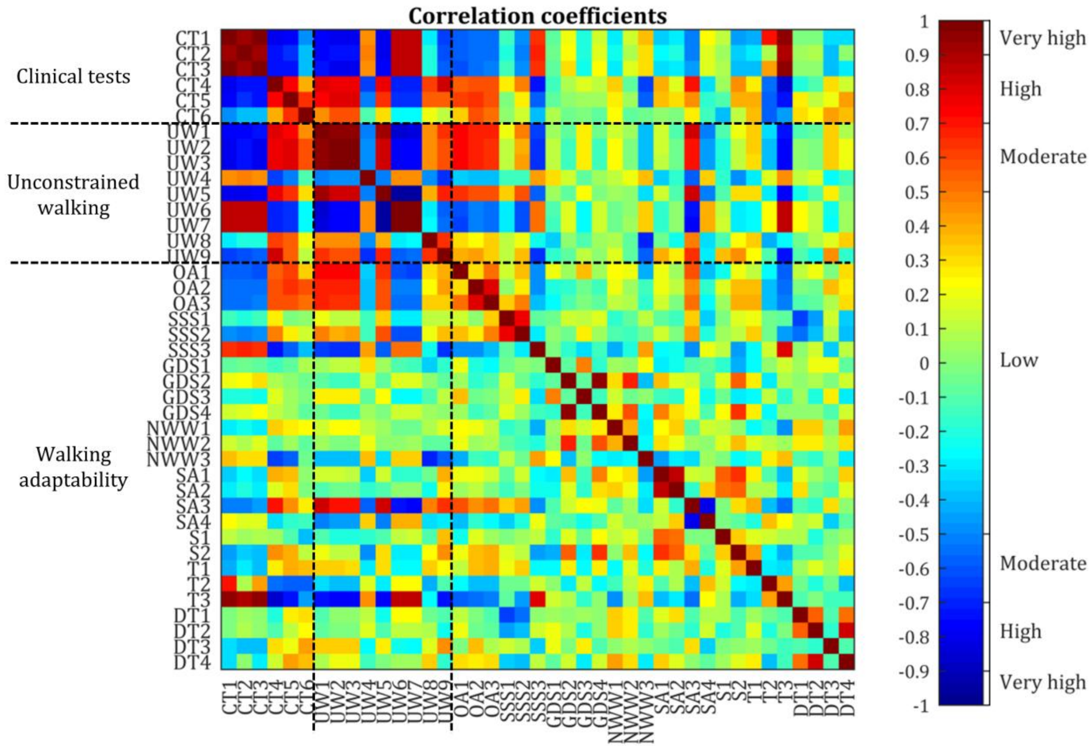

Figure 5.3 Overview of the correlation coefficients between (i.e., outer boxes) and within (i.e., boxes around the diagonal) the various types of walking-ability assessments (i.e., clinical tests [CT1-6], unconstrained walking [UW1-9] and walking adaptability [OA1-4, SSS1-4, GDS1-4, NWW1-3, SA1-4, S1-2, T1-4, DT1-15]) in stroke patients. The order of the outcome measures on the axes is in agreement with Table 5.2. The dotted black lines separate the three types of walking-ability assessments.

Discussion

A stroke may result in impaired walking adaptability and affect the ability to negotiate environmental challenges, thus potentially contributing to the high fall risk seen in this population [9]. Assessments of walking adaptability may guide gait rehabilitation programs or contribute to the design of future targeted and individualized interventions directed at improving safe community ambulation after stroke. However, currently available assessments of walking ability after stroke hardly take walking adaptability into account [2]. We therefore evaluated the potential of the IWW as a new technology for a quick, unobtrusive and comprehensive quantitative assessment of walking adaptability in stroke patients.

As a first step, we evaluated its known-group validity. As expected, for almost all outcome measures stroke patients performed significantly worse than healthy controls (Table 5.2). Group differences for spatiotemporal gait parameters measured with the IWW were as expected [28-30] and in line with the results of an earlier study showing that the Kinect v2 sensor can measure spatiotemporal gait parameters with considerable accuracy in stroke patients [31]. Also in accordance with the findings of previous studies, IWW outcome measures of the various walking-adaptability tasks revealed that stroke patients have problems avoiding obstacles [3,5,6], making sudden step adjustments [32,33], making full turns [34] and combining walking with secondary tasks [10,30]. Besides, normalized walking speeds were significantly lower for stroke patients, indicating that they adjusted their walking speed more than controls when walking in complex environments. These results emphasize the importance of assessing walking adaptability in an overground setting, which allows stroke patients to lower their walking speed depending on their ability to meet environmental demands [11]. In the current study, only stepping accuracy of the irregular stepping stones, normalized walking speed of speeding up trials, turning time of half turns and normalized success rate of augmented dual-task walking did not exhibit significant group differences.

Nonetheless, medium and large effect sizes were found for all other IWW outcome measures with differences occurring in the expected direction. Therefore, the results of this study suggest good known-groups validity for IWW walking-adaptability tasks, similar to that of clinical tests and spatiotemporal gait parameters.

Previous studies have indicated that there is a need for a more comprehensive clinical evaluation of walking ability, addressing all of its three key aspects (i.e., abilities to generate repetitive stepping, maintain balance while walking and adapt walking to environmental demands; [1,2]). Interesting in that regard is our observation of high to very high correlations between clinical tests and spatiotemporal gait parameters, which both mainly seem to address stepping and balance aspects of walking ability. IWW walking-adaptability tasks appeared to complement these tests, as evidenced by the relatively few significant correlations between walking-adaptability outcome measures and those pertaining to clinical tests and unconstrained walking (Figure 5.3). Moreover, the significant correlations were mostly low or moderate in magnitude, suggesting that the walking-adaptability tasks had added value by focusing especially on the third walking-ability aspect, that is, the ability to adjust walking to environmental circumstances [2].

We assessed walking adaptability quite broadly with, as it turned out, some redundancy in the outcome measures. Hence, not all of the assessed tasks need to be included for a comprehensive assessment of walking adaptability. That is, IWW tasks whose outcome measures do not exhibit group differences or are highly correlated with currently used tests can be excluded because they add little information. In this study this concerned sudden starts, speed adjustments, full turns and augmented dual-task walking tasks.

For a comprehensive assessment of walking ability, we recommend to include unconstrained walking (to identify gait impairments during steady-state walking) and some complementary IWW walking-adaptability tasks. With regard to unconstrained walking, assessing it with the IWW provides more detailed information than clinical test scores. In addition, the outcome measures may be more sensitive to changes over time as was suggested by Vernon et al. [35] for outcome measures of the Kinect-instrumented Timed Up-and-Go test. With regard to complementary IWW walking-adaptability tasks, various candidate tasks seem capable to address different aspects of walking adaptability. This was evidenced by the few significant correlations among outcomes of the various walking-adaptability tasks (bottom right block in Figure 5.3), in contrast to outcomes pertaining to clinical tests and unconstrained walking, which were highly interrelated and hence somewhat redundant with one another. Performing multiple clinical tests is therefore not only time-consuming, but also does not provide more insight into a patient's walking ability, in contrast to the addition of some complementary and discriminative IWW walking-adaptability tasks, such as obstacle avoidance, goal-directed stepping, narrow walkway and plain dual-task walking.

One of the limitations of this study was that clinical tests, unconstrained walking and walking adaptability were only assessed in a single session. Future studies should examine their test-retest reliability to estimate minimal detectable change scores that are essential for monitoring progress in gait rehabilitation. We further noticed that the available response times were significantly lower for stroke patients on some walking-adaptability tasks, which were caused by a higher self-selected walking speed in those tasks than in the preceding unconstrained walking task. This could have negatively influenced the outcome measures on these tasks and as such have amplified group differences. In future studies the available response times should therefore be based on a real-time indication of walking speed, which is quite feasible with the IWW. Another limitation could be that the IWW currently only uses 2D projections to evoke step responses, which do not actually pose a physical risk for the patient. This was clearly demonstrated in the study of Timmermans et al. [36]. Cognitive-motor interference did not differ between walking over physical or projected obstacles in stroke patients, although motor performance was prioritized more when walking over physical obstacles. Nevertheless, walking-adaptability tasks with 2D projections appeared effective, since outcome measures did demonstrate differences between groups with overall medium to large effect sizes.

Conclusions

The benefit of a broad assessment of walking adaptability is that it may reveal the specific aspects of walking adaptability that are most severely impaired, which could then be targeted in individualized training programs [37]. Van Swigchem et al. [5] found that even in mildly affected stroke patients walking adaptability may be reduced, possibly increasing their risk of falling. Training of walking adaptability, overground or on a treadmill, has shown to be effective in improving walking ability in stroke patients [4,9,38,39] and in reducing risk of falling [9]. The IWW assessment may thus contribute to a more optimized and individualized gait training program to improve safe community ambulation and reduce the risk of walking-related falls by adjusting the training content and difficulty level to the specific needs and competences of the patient.

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Supplement 5.1

Video of Interactive Walkway tasks of unconstrained walking and walking adaptability in a patient with stroke. This video is available at https://youtu.be/nV9tGvlPogs.

Supplement 5.2

Data pre-processing

The Kinect for Windows Software Development Kit (SDK 2.0, www.microsoft.com) provides 3D time series of 25 body points using inbuilt and externally validated human-pose estimation algorithms [1-5]. These body points are: head, neck, spine shoulder, spine mid, spine base and left and right shoulder, elbow, wrist, hand, thumb, hand tip, hip, knee, ankle and foot. For offline data analysis, the 3D positional data for these body points were first pre-processed per Kinect sensor separately. Body points labelled as inferred (i.e., Kinect's human-pose estimation software infers positions when segments are partially occluded for example) were treated as missing values. The body point's time series were linearly interpolated using Kinect's time stamps to ensure a constant sampling frequency of 30 Hz, without filling in the parts with missing values. We removed data points from the time series when they did not meet our stringent requirements for valid human-pose estimation (e.g., a minimum of 15 out of the 25 possible body points should be labeled as tracked, including the head and at least one foot and ankle, without outliers in segment lengths). In addition, a manual check of the data was added to remove errors of the algorithm due to depth occlusion of the right leg by the left leg. Subsequently, data of the four Kinect sensors were combined by taking for each sample the 3D positions of the body points of a validly estimated human pose. If, for a given sample, more than one sensor contained valid human pose data, the associated body point's 3D positions were averaged for that specific sample.

Body point's time series with more than 50% of missing values were excluded from further analyses. However, percentages of missing data for both groups did not exceed 23.1% with an average of 4.7 ± 2.2% for the body points' time series of interest (i.e., ankles, spine base and spine shoulder). The missing values were interpolated with a spline algorithm. The so-obtained time series were used for the calculation of the Interactive Walkway outcome measures of unconstrained walking and walking adaptability.

The outcome measures of the Interactive Walkway assessment were calculated from specific body points' time series, estimates of foot contact and foot off and step locations, as detailed in Table 5.1. Estimates of foot contact and foot off were defined as the maxima and minima of the anterior–posterior time series of the ankles relative to that of the spine base [3,6,7]. Step locations were determined as the median anterior–posterior and mediolateral position of the ankle joint during the single-support phase (i.e., between foot off and foot contact of the contralateral foot; [3,6]). Shoe edges and center of the foot were also needed to calculate several outcome measures. Ankle-to-shoe calibration trials, in which the subject was standing in two shoe-size-matched targets at a position on the walkway in front of the last Kinect, were included to determine the average distance between shoe edges and the ankle.

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