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

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Chapter 3

Walking-adaptability assessments with the Interactive Walkway: between-systems agreement and sensitivity to task and subject variations

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The ability to adapt walking to environmental circumstances is an important aspect of walking, yet difficult to assess. The Interactive Walkway was developed to assess walking adaptability by augmenting a multi-Kinect-v2 10-meter walkway with gait-dependent visual context (stepping targets, obstacles) using real-time processed markerless full-body kinematics. In this study we determined Interactive Walkway's usability for walking-adaptability assessments in terms of between-systems agreement and sensitivity to task and subject variations. Under varying task constraints, 21 healthy subjects performed obstacle-avoidance, sudden-stops-and-starts and goal-directed-stepping tasks. Various continuous walking-adaptability outcome measures were concurrently determined with the Interactive Walkway and a gold-standard motion-registration system: available response time, obstacle-avoidance and sudden-stop margins, step length, stepping accuracy and walking speed. The same holds for dichotomous classifications of success and failure for obstacle-avoidance and sudden-stops tasks and performed short-stride versus long-stride obstacle-avoidance strategies. Continuous walking-adaptability outcome measures generally agreed well between systems (high intraclass correlation coefficients for absolute agreement, low biases and narrow limits of agreement) and were highly sensitive to task and subject variations. Success and failure ratings varied with available response times and obstacle types and agreed between systems for 85-96% of the trials while obstacle-avoidance strategies were always classified correctly. We conclude that Interactive Walkway walking-adaptability outcome measures are reliable and sensitive to task and subject variations, even in high-functioning subjects. We therefore deem Interactive Walkway walking-adaptability assessments usable for obtaining an objective and more task-specific examination of one's ability to walk, which may be feasible for both high-functioning and fragile populations since walking adaptability can be assessed at various levels of difficulty.

Introduction

An important aspect of walking is one's ability to adapt walking to environmental circumstances [1-3]. Walking adaptability includes the ability to avoid obstacles, make sudden stops and starts and accurately place the feet to environmental context [1]. Most walking-related falls result from inadequate interactions with environmental context, leading to balance loss due to a trip, slip or misplaced step [4-6]. Walking adaptability thus seems to be an important determinant of fall risk, yet a comprehensive well-tested objective assessment of walking adaptability is lacking [1].

We try to fill this lacuna with the Interactive Walkway (IWW), a 10-meter walkway augmented with projected gait-dependent visual context, such as obstacles suddenly appearing at the position one would step next, demanding a step adjustment under time pressure. The basis of the IWW is an integrated multi-Kinect v2 set-up for markerless registration of 3D full-body kinematics during walking [7], which was recently validated over the entire 10-meter walkway against a gold standard in 3D measurement accuracy for both kinematics and derived gait parameters [7,8]. We have now equipped this set-up with a projector to augment the entire walkway with visual context, such as obstacles, sudden-stop-and-start cues and stepping targets, based on real-time processed integrated Kinect data. The so-elicited gait-environment interactions potentially allow for assessing various walking-adaptability aspects (e.g., the ability to avoid obstacles, suddenly stop or start, perform accurate goal-directed steps) as well as subject-specific variations and adaptations affecting walking-adaptability performance (e.g., adopting a slower walking speed to enhance goal-directed stepping accuracy).

The objective of this study is to determine the usability of the IWW for walking-adaptability assessments in a group of healthy adults in terms of between-systems agreement and sensitivity to task and subject variations. Walking-adaptability tasks and associated outcome measures are selected for their proven ability to distinguish between persons who vary in adaptive-walking limitations [2,3,9-12]. To determine the between-systems agreement, IWW-based walking-adaptability outcome measures are compared to those concurrently derived with a gold standard. The sensitivity to task variation is assessed by comparing walking-adaptability performance as a function of context variations, including different obstacle sizes and sequences of stepping targets. Sensitivity to subject variation is explored by quantifying speed-performance trade-offs between self-selected walking speed and adaptive stepping performance (success rates, safety margins). We expect that walking-adaptability outcomes agree well between systems and are sensitive to task and subject variations.

Methods

Subjects

A heterogeneous group of 21 healthy subjects (mean [range]: age 30 [19-63] years, height 176 [158-190] cm, weight 70 [53-83] kg, 11 males) without severe visual deficits or any medical condition that would affect walking participated. The local ethics committee approved the study. All subjects gave written informed consent prior to participation.

Experimental set-up and procedure

Full-body kinematics for walking over the entire 10-meter walkway was obtained with the IWW using four spatially and temporally integrated Kinect v2 sensors (Figure 3.1A) and the Optotrak system (Northern Digital Inc., Waterloo, Canada) for 19 matched body points as in [7; see also Supplement 3.1]. IWW and Optotrak data were sampled at 30 Hz (using custom-written software utilizing the Kinect-for-Windows Software Development Kit [SDK 2.0]) and 60 Hz (using First Principles data acquisition software), respectively. The IWW was equipped with a projector (Vivitek D7180HD, ultra-short-throw Full HD projector) to augment the entire 10-meter walkway with visual context for three sorts of walking-adaptability tasks: obstacle avoidance, sudden stops-and-starts and goal-directed stepping (Figure 3.1).

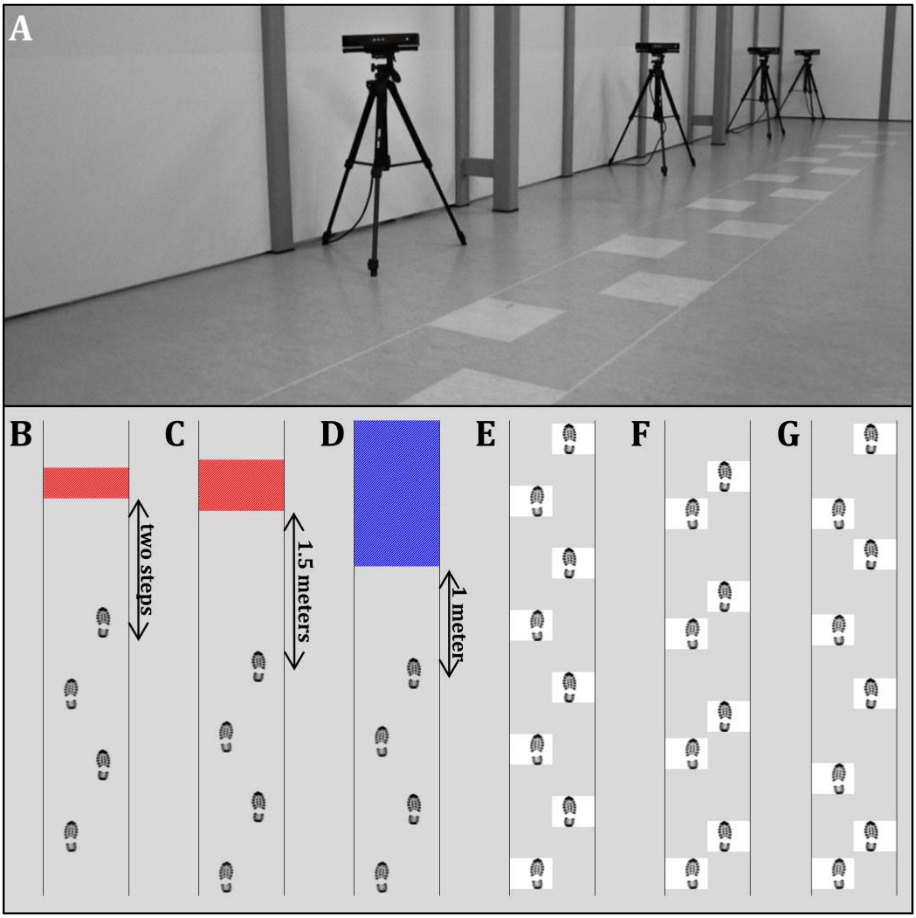

Figure 3.1 The set-up of the Interactive Walkway with visual context projected on the walkway (A). The four Kinect v2 sensors were positioned on tripods at a height of 0.75 meters alongside a walkway of 10 by 0.5 meters. The sensors were placed frontoparallel (i.e., with an angle of 70 degrees relative to the walkway direction) with a distance of 0.5 meters from the left border of the walkway. The first sensor was positioned at 4 meters from the start of the walkway and the other sensors were placed at inter-sensor distances of 2.5 meters. Schematics of the walking-adaptability tasks: obstacle avoidance with gait-dependent (B) and position-dependent obstacles (C), sudden stops-and-starts (D) and goal-directed stepping with symmetric stepping stones (E), asymmetric stepping stones (F) and variable stepping stones (G).

The obstacle-avoidance task consisted of 25 trials with one or two obstacles (a projected red rectangle) per trial. In total, 40 obstacles were presented, including 20 gait-dependent obstacles (obstacle at predicted foot-placement position appearing two steps ahead; Figure 3.1B) and 20 position-dependent obstacles (obstacle at an unpredictable predefined position appearing when a subject's ankle was within 1.5 meters from that obstacle; Figure 3.1C). Gait-dependent obstacles were 0.5 (width of the walkway) by 0.3 meters. Position-dependent obstacles were larger (0.5×0.5 meters) to increase the need for making step adjustments. Subjects were instructed to avoid suddenly appearing obstacles while walking at self-selected comfortable speeds.

The sudden-stops-and-starts task (Figure 3.1D) consisted of 25 trials with in total 40 cues (i.e., one or two sudden-stop-and-start cues per trial) to assess one's ability to suddenly stop and start walking. The cue was a big blue rectangle with a width of 0.5 meters that filled the walkway from an unpredictable predefined position till its end and appeared as soon as a subject's ankle was within 1 meter from this position, triggering the subject to stop walking. After a random period between 5 and 10 seconds, the rectangle disappeared, triggering the subject to start walking again. Subjects were instructed to walk at self-selected comfortable speeds and to stop behind the cue and to start walking as soon as the cue disappeared.

The goal-directed-stepping task consisted of symmetric-stepping-stones (SSS; Figure 3.1E), asymmetric-stepping-stones (ASS; Figure 3.1F) and variable-stepping-stones (VSS; Figure 3.1G) conditions. Subjects were instructed to step as accurately as possible onto the white shoe-size-matched stepping targets at a self-selected comfortable walking speed. For SSS, seven different imposed step-length trials ranging from 30 to 90 cm in steps of 10 cm were performed, all with three repetitions, yielding a total of 21 trials. For ASS, stride length remained 90 centimeters while left (L) and right (R) imposed step lengths were varied in separate trials from 15 to 75 centimeters in steps of 15 centimeters yielding five different imposed stepping asymmetries (L/R: *15/75*, *30/60*, *45/45*, *60/30*, *75/15*), all with three repetitions, yielding 15 trials. For VSS, imposed step lengths varied within each trial on a step-to-step basis randomly between 30 and 90 centimeters. Ten different VSS trials were performed, consisting of 21 stepping stones each.

The walking-adaptability tasks were block-randomized and preceded by a familiarization trial. Four ankle-to-shoe calibration trials, in which the subject was standing in two shoe-size-matched targets at different positions on the walkway, were also included to determine the average distance between shoe edges and the ankle for both systems. This calibration was needed to determine several walking-adaptability outcome measures (see below).

Data pre-processing and analysis

Data pre-processing followed established procedures [7]; details about the procedure and pre-processed data are presented as supplementary material (see Supplements 3.1 and 3.2). Due to excessive missing data, 62 out of 2,016 trials were excluded from further analysis, mainly for the gold-standard motion-registration system (i.e., marker occlusion and/or orientation issues) and concerning one subject.

The continuous walking-adaptability outcome measures were available response time (ART) and margins of the trailing and leading limb during obstacle crossing for the obstacle-avoidance task, ART and margin to the stop cue for the sudden-stops-and-starts task, step length, stepping accuracy and walking speed for SSS and VSS, and left and right step lengths, stepping accuracy and walking speed for ASS. These continuous outcome measures were calculated from specific body points' time series, estimates of foot contact and foot off and step locations, as detailed in Table 3.1, for both measurement systems alike in an aligned coordinate system, including the coordinates of obstacles, sudden-stop cues and targets. For all continuous outcome measures, statistical analyses were performed over averages over trials. For dichotomous outcome measures, step locations were extrapolated to the actual shoe dimensions based on the ankle-to-shoe calibration to determine whether or not obstacle-avoidance and sudden-stop trials were successfully performed, from which success rates were deduced. Successful gait-dependent obstacle-avoidance maneuvers were classified as short-stride or long-stride strategies [13].

Statistical analysis

Between-systems agreement was determined for continuous outcome measures using intraclass correlation coefficients for absolute agreement ($ICC_{(A,1)}$; [14]), with values above 0.60 and 0.75 representing good and excellent agreement, respectively; [15]. This analysis of between-systems agreement was complemented by mean differences and precision values obtained with a Bland-Altman analysis (i.e., the bias and the limits of agreement, respectively; [16]). For dichotomous outcome measures we report the percentage of non-matched ratings.

Sensitivity to task variation was examined using repeated-measures ANOVAs on continuous outcome measures of obstacle-avoidance and goal-directed-stepping tasks. For ART and obstacle-avoidance margins, a System (IWW, Optotrak) by Obstacle (gait-dependent, position-dependent) by Limb (trailing, leading) repeated-measures ANOVA was conducted. For step length, stepping accuracy and walking speed of SSS, a System by Imposed step length (*30*, *40*, *…, 90*) repeated-measures ANOVA was conducted. For left and right step lengths, stepping accuracy and walking speed of ASS, a System by Imposed step-length asymmetry (L/R: *15/75*, *30/60*, *45/45*, *60/30, 75/15*) repeated-measures ANOVA was conducted. For step length, stepping accuracy and walking speed of VSS, a System by Trial repeated-measures ANOVA was conducted. For the average stepping accuracy of the three goal-directed-stepping conditions, a System by Condition (SSS, ASS, VSS) repeated-measures ANOVA was conducted. One subject was excluded from the analyses of the goal-directed-stepping tasks due to multiple trials with excessive missing values.

Table 3.1 Calculation methods of continuous walking-adaptability outcome measures.

	Outcome measure	Unit	Calculation
Obstacle-avoidance	**Available response time**	s	The distance of the nearest anterior shoe edge to the border of the obstacle at the moment of its appearance divided by the average walking speed over the second before its appearance.
	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. Step locations were determined as the median anterior-posterior position of the ankle joint during the single-support phase (i.e., between foot off and foot contact of the contralateral foot) [7]. 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 [7,17].
Sudden-stops-and-starts	**Available response time**	s	The distance of the nearest anterior shoe edge to the border of the sudden-stop cue at the moment of its appearance divided by the average walking speed over the second before its appearance.
	Sudden-stop margin	cm	The minimum distance of the anterior shoe edge to the corresponding sudden-stop cue border during the period in which the cue was visible.
Goal-directed-stepping	**Step length**	cm	The median of the differences in the anterior-posterior direction of consecutive step locations.
	Stepping accuracy	cm	The standard deviation over the signed deviations between the center of the foot and the center of the target at step locations, as defined in step length. Stepping accuracy was determined over step locations that were identified for both systems to ensure a fair comparison. The center of the foot was determined using the average distance between the ankle and the middle of the shoe-size-matched targets of the calibration trials.
	Walking speed	cm/s	The distance travelled between the start and the 10-meter line of the walkway divided by the time, using the data of the spine shoulder.

The assumption of sphericity was checked according to Girden [18]. If Greenhouse-Geisser's epsilon exceeded 0.75, the Huynh-Feldt correction was applied; otherwise the Greenhouse-Geisser correction was used. Main effects were examined with a Least Significant Difference post-hoc test for factors with three levels and contrast analyses for factors with more than three levels. Paired-samples *t*-tests were used for significant interactions. Effect sizes were quantified with η_p^2.

Sensitivity to subject variation was examined by exploring speed-performance trade-offs. We determined Pearson's correlations between self-selected walking speed and stepping accuracy for all goal-directed-stepping tasks and between the speed-dependent ART and margins for obstacle-avoidance and sudden-stop tasks (i.e., significant positive correlations signal speed-performance trade-offs). We also assessed the influence of obstacle-avoidance and sudden-stop ratings on ART using a System by Rating (success, failure) repeated-measures ANOVA. In addition, obstacle-avoidance success rates were compared with a System by Obstacle repeated-measures ANOVA.

Results

Between-systems agreement

Excellent between-systems agreement was observed for ART and margins for obstacle-avoidance and sudden-stops-and-starts tasks, walking speed for all goal-directed-stepping conditions (SSS, ASS and VSS) and step length and stepping accuracy of VSS, supported by very high $ICC_{(A,1)}$ values, small biases and narrow limits of agreement (Table 3.2). The between-systems agreement for stepping accuracy of SSS and step lengths and stepping accuracy for ASS was overall good to excellent (Table 3.2). Between-systems statistics were ambiguous for step length of SSS (low $ICC_{(A,1)}$ values, negligible biases and very narrow limits of agreement; Table 3.2). Significant between-system biases, indicated in Table 3.2, all corresponded to significant System effects of associated outcome measures in the ANOVAs for the analysis of sensitivity to task and subject variations.

Success rates of gait-dependent and position-dependent obstacles were (mean ± SD) 94.7 ± 12.8% and 92.1 ± 15.6% for the IWW and 96.8 ± 6.5% and 93.2±12.1% for the gold standard, respectively. The percentage of non-matched ratings was 3.7% for gait-dependent obstacles (3.0% false negatives) and 5.1% for position-dependent obstacles (3.1% false negatives). Given the uneven distribution of ratings over categories (~95% success vs. ~5% failure), we also determined the percentages of specific agreement [19] for obstacle-avoidance successes (97.7%) and failures (61.5%), suggesting that the agreement for failures was considerably lower. The systems matched perfectly for classified avoidance strategies (0% non-matched ratings), with an overall preference for the long-stride strategy in avoiding gait-dependent obstacles (80.5 ± 15.3%). Success rates for sudden stops were 58.1 ± 23.5% for the IWW and 49.5 ± 22.0% for the gold standard, with 14.8% between-systems dis-matches (11.7% false positives).

Sensitivity to task variation

A significant Obstacle ($F(1,20) = 7.98$, $p = 0.010$, $\eta_p^2 = 0.285$) effect was found for ART, with longer ARTs for position-dependent obstacles (0.834 ± 0.016 s) than for gait-dependent obstacles (0.784 ± 0.011 s). Significant Obstacle ($F(1,20) = 508.73$, $p < 0.001$, $\eta_p^2 = 0.962$) and Limb ($F(1,20) = 29.40$, $p < 0.001$, $\eta_p^2 = 0.595$) effects were found for obstacle-avoidance margins, as well as a significant Obstacle×Limb interaction ($F(1,20) = 99.95$, $p < 0.001$, $\eta_p^2 = 0.833$). While margins were overall greater for gait-dependent obstacles and for the trailing limb, the interaction revealed that the difference between trailing and leading limbs was only evident for gait-dependent obstacles (27.7 ± 5.3 cm vs. 12.2 ± 5.3 cm) and not for position-dependent obstacles (11.4 ± 2.9 cm vs. 9.4 ± 4.9 cm).

Table 3.2 Mean values, between-subjects standard deviations (SD) and agreement statistics (bias, limits of agreement [95% LoA] and intraclass correlation coefficient for absolute agreement [$ICC_{(A,1)}$]) for the continuous outcome measures of the obstacle-avoidance, sudden-stops-and-starts and goal-directed-stepping tasks (symmetric-stepping-stones, asymmetric-stepping-stones and variable-stepping-stones conditions).

			Interactive Walkway mean ± SD	**Optotrak system mean ± SD**	**Bias (95% LoA)**	**$ICC_{(A,1)}$**
Obstacle-avoidance task						
Available response time (s)	**Gait-dependent**		0.792 ± 0.050	0.777 ± 0.049	-0.015* [-0.032 0.002]	0.945
	Position-dependent		0.834 ± 0.075	0.834 ± 0.076	0.000 [-0.023 0.024]	0.988
Margins (cm)	**Gait-dependent**	**Trailing limb**	27.68 ± 5.53	27.65 ± 5.06	-0.03 [-2.17 2.12]	0.980
		Leading limb	11.68 ± 5.45	12.78 ± 5.26	1.11* [-1.35 3.56]	0.954
	Position-dependent	**Trailing limb**	11.27 ± 3.08	11.54 ± 2.90	0.26 [-2.18 2.71]	0.913
		Leading limb	8.97 ± 4.91	9.82 ± 4.87	0.85* [-1.39 3.09]	0.960
Sudden-stops-and-starts task						
Available response time (s)			0.497 ± 0.067	0.490 ± 0.070	-0.007* [-0.035 0.021]	0.997
Margins (cm)			8.32 ± 7.29	8.35 ± 6.70	0.30 [-6.96 7.02]	0.876
Symmetric-stepping-stones						
Step length (cm)	**30**		29.95 ± 0.14	29.97 ± 0.32	0.02 [-0.55 0.58]	0.339
	40		39.96 ± 0.18	40.00 ± 0.28	0.04 [-0.61 0.68]	0.034
	50		50.06 ± 0.29	50.02 ± 0.35	-0.04 [-1.04 0.96]	-0.276
	60		60.02 ± 0.38	59.89 ± 0.48	-0.13 [-1.21 0.95]	0.189
	70		69.99 ± 0.25	69.91 ± 0.57	-0.07 [-1.05 0.90]	0.376
	80		79.89 ± 0.28	79.76 ± 0.48	-0.13 [-1.10 0.84]	0.210
	90		89.84 ± 0.37	89.81 ± 0.33	-0.03 [-0.82 0.76]	0.367

Table 3.2 Continued.

		Interactive Walkway mean ± SD	Optotrak system mean ± SD	Bias (95% LoA)	$ICC_{(A,1)}$
Stepping accuracy (cm)	**30**	1.77 ± 0.41	1.87 ± 0.38	0.10 [-0.55 0.75]	0.635
	40	1.80 ± 0.37	1.93 ± 0.45	0.13 [-0.66 0.92]	0.503
	50	1.81 ± 0.37	2.00 ± 0.47	0.20* [-0.49 0.88]	0.609
	60	1.91 ± 0.46	1.91 ± 0.52	0.00 [-0.77 0.78]	0.686
	70	1.91 ± 0.41	1.99 ± 0.49	0.08 [-0.64 0.80]	0.675
	80	1.88 ± 0.54	2.02 ± 0.53	0.15 [-0.89 1.19]	0.498
	90	2.02 ± 0.55	2.12 ± 0.56	0.10 [-0.59 0.78]	0.798
Walking speed (cm/s)	**30**	73.23 ± 12.95	72.89 ± 12.66	-0.34* [-1.03 0.35]	0.999
	40	86.93 ± 13.42	86.37 ± 13.04	-0.57* [-1.48 0.35]	0.999
	50	101.14 ± 14.11	100.42 ± 13.73	-0.72* [-1.67 0.23]	0.998
	60	112.28 ± 13.83	111.19 ± 13.28	-1.09* [-2.57 0.39]	0.995
	70	124.40 ± 13.38	123.24 ± 12.89	-1.16* [-2.59 0.26]	0.995
	80	136.70 ± 12.49	134.97 ± 12.07	-1.73* [-3.00 -0.46]	0.989
	90	145.07 ± 12.07	143.43 ± 11.67	-1.64* [-3.10 -0.19]	0.989
Asymmetric-stepping-stones					
Step length left (cm)	**15/75**	21.38 ± 3.66	19.75 ± 3.92	-1.63* [-4.30 1.03]	0.859
	30/60	34.23 ± 2.39	33.55 ± 2.71	-0.68 [-3.65 2.29]	0.803
	45/45	44.72 ± 1.17	44.50 ± 1.76	-0.22 [-3.03 2.59]	0.546
	60/30	55.44 ± 2.35	56.34 ± 2.82	0.90* [-2.03 3.83]	0.793
	75/15	67.44 ± 2.96	69.88 ± 3.58	2.45* [-0.96 5.86]	0.677

Step length right (cm)	**15/75**	68.57 ± 3.84	70.16 ± 3.96	1.60* [-1.41 4.61]	0.854
	30/60	55.76 ± 2.58	56.45 ± 2.84	0.69 [-2.48 3.86]	0.803
	45/45	45.37 ± 1.24	45.39 ± 1.87	0.01 [-2.85 2.88]	0.588
	60/30	34.62 ± 2.20	33.63 ± 2.66	-0.99* [-3.74 1.76]	0.777
	75/15	22.80 ± 2.89	19.96 ± 3.56	-2.83* [-6.37 0.71]	0.615
Stepping accuracy (cm)	**15/75**	3.87 ± 1.77	3.37 ± 1.58	-0.50* [-1.75 0.75]	0.891
	30/60	2.87 ± 1.13	2.65 ± 1.08	-0.21 [-1.54 1.11]	0.806
	45/45	1.73 ± 0.38	1.88 ± 0.46	0.14 [-0.59 0.88]	0.584
	60/30	3.02 ± 1.03	2.79 ± 1.03	-0.23 [-1.20 0.74]	0.869
	75/15	4.36 ± 1.36	3.34 ± 1.49	-1.02* [-2.35 0.31]	0.709
Walking speed (cm/s)	**15/75**	90.87 ± 12.05	90.33 ± 11.81	-0.54* [-1.34 0.25]	0.998
	30/60	92.01 ± 13.61	91.46 ± 13.35	-0.55* [-1.43 0.34]	0.999
	45/45	91.73 ± 14.14	91.20 ± 13.96	-0.53* [-1.34 0.28]	0.999
	60/30	89.23 ± 14.18	88.75 ± 13.92	-0.47* [-1.24 0.29]	0.999
	75/15	87.84 ± 13.51	87.31 ± 13.25	-0.53* [-1.33 0.26]	0.999
Variable-stepping-stones					
Step length (cm)		45.54 ± 0.82	45.49 ± 0.85	-0.05 [-0.96 0.86]	0.852
Stepping accuracy (cm)		2.60 ± 0.68	2.53 ± 0.65	-0.08 [-0.59 0.44]	0.920
Walking speed (cm/s)		97.89 ± 13.88	97.25 ± 13.56	-0.64* [-1.51 0.23]	0.998

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

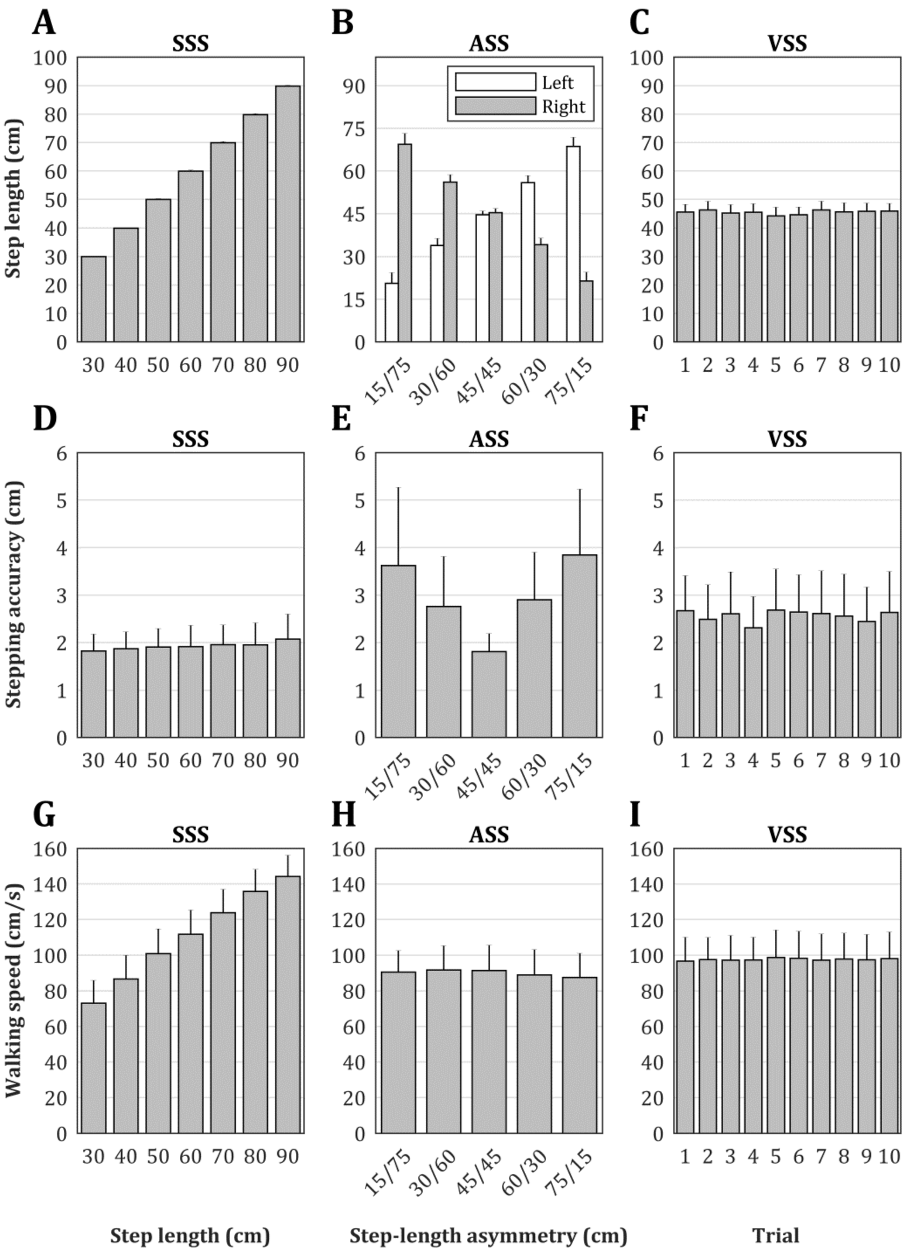

Figure 3.2 Step length (A, B and C), stepping accuracy (D, E and F) and walking speed (G, H and I) for the symmetric-stepping-stones (SSS; A, D and G), the asymmetric-stepping-stones (ASS; B, E and H) and the variable-stepping-stones (VSS; C, F and I) of the goal-directed-stepping task.

Subjects were well able to adjust their foot placement to the presented goal-directed-stepping targets (Table 3.2 and Figure 3.2). This was confirmed by very strong effects of Imposed step lengths on performed step lengths for SSS ($F(4.2,79.0) = 162327.08$, $p < 0.001$, $\eta_p^2 = 1.000$; Figure 3.2A) and ASS (left: $F(1.2,22.6) = 936.64$, $p < 0.001$, $\eta_p^2 = 0.980$; right: $F(1.2,22.7) = 913.62$, $p < 0.001$, $\eta_p^2 = 0.980$; Figure 3.2B). Stepping accuracy varied significantly with Imposed step-length asymmetry ($F(2.4,45.7) = 20.63$, $p < 0.001$, $\eta_p^2 = 0.521$), with significant quadratic ($F(1,19) = 53.99$, $p < 0.001$, $\eta_p^2 = 0.740$) and fourth-order ($F(1,19) = 18.83$, $p < 0.001$, $\eta_p^2 = 0.498$) contrasts (Figure 3.2E); no significant main or interaction effects were found on stepping accuracy for SSS (Figure 3.2D) or VSS (Figure 3.2F). Walking speed varied with step-length manipulations for SSS ($F(2.7,50.6) = 607.50$, $p < 0.001$, $\eta_p^2 = 0.970$; with significant linear [$F(1,19) = 1189.66$, $p < 0.001$, $\eta_p^2 = 0.984$] and quadratic [$F(1,19) = 9.29$, $p = 0.007$, $\eta_p^2 = 0.328$] contrasts; Figure 3.2G) and ASS ($F(2.7,50.6) = 4.72$, $p = 0.007$, $\eta_p^2 = 0.199$; with a significant linear contrast [$F(1,19) = 13.67$, $p = 0.002$, $\eta_p^2 = 0.418$]; Figure 3.2H). Average stepping accuracy varied significantly over goal-directed-stepping conditions ($F(1.5,28.3) = 36.80$, $p < 0.001$, $\eta_p^2 = 0.659$); stepping accuracy improved from ASS (2.99 ± 0.21 cm) to VSS (2.57 ± 0.15 cm) to SSS (1.93 ± 0.08 cm), with significant differences between all conditions.

Sensitivity to subject variation

Self-selected walking speed affects the available response time for obstacle-avoidance and sudden-stop tasks on the IWW, and thereby the difficulty of these walking-adaptability tasks. For sudden stops the overall success rate was 53.8 ± 22.4%, with a clear influence of rating on ART ($F(1,20) = 172.88$, $p < 0.001$, $\eta_p^2 = 0.896$); ARTs were longer for successful stops (0.536±0.012 s) than for failed stops (0.416 ± 0.012 s). In Figure 3.3 sudden-stop success and failure rates are depicted as a function of ART, showing a steady increase in stopping successes (and hence a decrease in stopping failures) with longer ARTs. A speed-performance trade-off was also found on margins to the stopping cue, with longer ARTs being associated with larger margins, for both systems alike (IWW: $r(20) = 0.597$, $p = 0.004$; gold standard: $r(20) = 0.698$, $p < 0.001$).

The influence of obstacle-avoidance ratings on ART could not be determined because of a ceiling effect; overall success rate was 94.2 ± 11.3%, with slightly higher success rates for gait-dependent obstacles (95.8 ± 2.1%) than for position-dependent obstacles (92.6 ± 2.9%; main Obstacle effect, $F(1,20) = 7.05$, $p = 0.015$, $\eta_p^2 = 0.261$). Obstacle-avoidance margins were not associated with ART (i.e., no speed-performance trade-off; $r(20) = [-0.115\ 0.211]$, $p > 0.359$).

Clear speed-performance trade-offs were observed for goal-directed stepping, with faster walking speeds being associated with poorer stepping accuracy, as evidenced by significant positive correlations between self-selected walking speed and stepping accuracy for SSS, ASS and VSS, for both systems alike (IWW: $r(20) = 0.722$, $p < 0.001$, $r(20) = 0.715$, $p < 0.001$ and $r(20) = 0.637$, $p < 0.001$, respectively; gold standard: $r(20) = 0.523$, $p = 0.018$, $r(20) = 0.668$, $p = 0.001$ and $r(20) = 0.569$, $p < 0.001$, respectively).

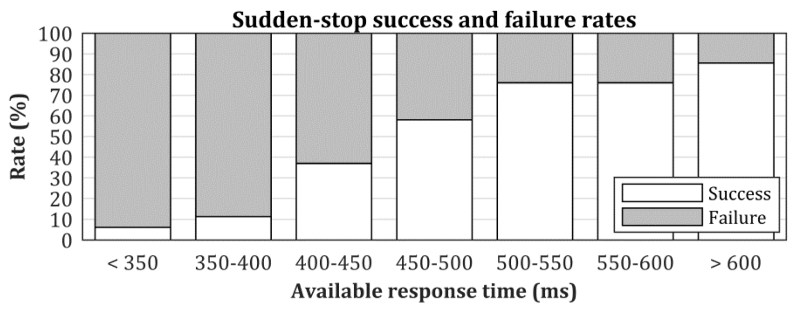

Figure 3.3 Sudden-stop success and failure rates for different available response times.

Discussion

We determined the usability of IWW walking-adaptability assessments in a group of healthy adults in terms of between-systems agreement and sensitivity to task and subject variations. We expected that walking-adaptability outcome measures agreed well between systems and were sensitive to task and subject variations. The results were in line with our expectations, which led us to conclude that the IWW is usable for walking-adaptability assessments.

First, the between-systems agreement for continuous walking-adaptability outcomes proved to be good to excellent, with high ICC values, small biases and narrow limits of agreement (Table 3.2). For the SSS conditions of goal-directed stepping, however, ICC values for step length were considerably lower, suggesting a poor between-systems agreement, which stood in stark contrast with excellent Bland-Altman agreement statistics (negligible biases and narrow limits of agreement; Table 3.2). This discrepancy was likely due to a lack of subject heterogeneity in step lengths since these were experimentally imposed with stepping targets, yielding minimal between-subject variance (see also Figure 3.2A) and hence arbitrarily low ICC values [20]. This discrepancy illustrates the importance of a complementary set of agreement statistics instead of relying solely on ICC as the measure for between-systems agreement [20]. The between-systems agreement for dichotomous walking-adaptability outcomes varied, ranging from 100% overall agreement for obstacle-avoidance strategies to 85.2% for successes and failures in sudden stops. The specific agreement for obstacle-avoidance failures was lower (~60%), yet based on a limited number of observations. Future research may exploit IWW's possibility to vary task difficulty to achieve a similar distribution of obstacle-avoidance successes and failures to properly quantify their between-systems agreement.

Second, continuous walking-adaptability outcomes were sensitive to task and subject variations. With goal-directed stepping, task variations led to different step lengths, stepping accuracies and walking speeds (Figure 3.2) while ARTs and margins of the trailing limb varied with obstacle type. This testifies to the power of projected visual context in modifying gait and in eliciting (sudden) step adjustments, in line with previous studies exploring the same concept during treadmill walking [3,21-23], as well as to the sensitivity of continuous walking-adaptability outcomes. Success rates differed between obstacle types, although differences were very small in the vicinity of a ceiling effect. Future studies may increase obstacle-avoidance difficulty with the IWW by reducing ART, projecting larger obstacles, and/or adding attention-demanding secondary tasks [24]. Varying task difficulty with ART manipulations seems particularly effective, since in the present study ART had a prominent effect on sudden-stop success rates (Figure 3.3) and in other studies on obstacle-avoidance success rates [12,25]. Sensitivity to subject variation was further demonstrated by speed-performance trade-offs in goal-directed stepping (subjects who walked faster stepped less accurately onto targets) and sudden stops (subjects with shorter ARTs had smaller margins to the stop cue). Revealing such context-dependent interactions by objectively quantifying a complementary set of outcome measures can be considered one of the strengths of the IWW, which may prove useful in identifying fallers [26] and designing tailored interventions to reduce fall risk [1].

Taken together, our results confirmed that IWW walking-adaptability outcome measures are reliable (albeit that obstacle-avoidance failure rates have to be considered with caution) and sensitive to task and subject variations, even in high-functioning subjects. Sensitivity to task and subject variations is important for walking-adaptability assessments in relatively high-functioning groups (such as community-dwelling older adults), where ceiling effects are a common concern in fall-risk assessments [27]. The same holds for floor effects in relatively fragile groups (such as fall-prone populations). The IWW potentially allows for walking-adaptability assessments that are feasible for both high-functioning and fragile populations since task difficulty can be varied. IWW assessments are also relatively safe (e.g., visual instead of physical obstacles), unobtrusive (markerless data) and hence time-efficient and patient-friendly. The premise is that persons at risk of falling during walking may be better identified with task-specific assessments attuned to common causes and circumstances of falls [4-6], such as IWW walking-adaptability tasks. Future studies are warranted to determine which walking-adaptability tasks and associated outcomes are good indicators of safe walking and accurate predictors of falls during walking.

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Supplement 3.1

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 (Figure S3.1B). 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). 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. Note that the online integration process of multiple Kinect v2 data was similar to this offline integration process, except for the linear interpolation based on time stamps.

For motion registration with the Optotrak system (Northern Digital Inc., Waterloo, Canada), Smart Marker Rigid Bodies (Northern Digital Inc., Waterloo, Canada) were attached to the head, upper arms, forearms, lower abdomen, upper legs, lower legs and feet, allowing for 6 degrees of freedom tracking of body segments (Figure S3.1A). In addition, 30 anatomical landmarks were digitized using a 3-marker digitizing probe to define various body point positions (so-called virtual markers) on abovementioned body segments. Smart markers were also placed on the sternum, hands and feet. Body point's time series of the Optotrak system were computed from the virtual markers and/or smart markers to resemble corresponding Interactive Walkway (IWW) body points (see Table S3.1). In case of a single virtual marker or smart marker, the time series of that specific marker was taken as the time series of the associated body point (e.g., sternum data representing the spine shoulder body point of the IWW). In case of multiple virtual markers and/or smart markers, the associated marker positions were averaged in all three directions for each time sample. Positions of the neck, spine mid, thumbs and hand tips body points were not tracked with the Optotrak system due to the limited number of available smart markers, rendering a total of 19 out of aforementioned 25 matched body points.

The coordinate systems of the IWW (3D body points and projector pixels) and the Optotrak system were spatially aligned to a common coordinate system using a spatial calibration grid. Optotrak data were down-sampled to 30 Hz. Subsequently, the cross-covariance and time lag were determined for paired time series in the mediolateral and vertical direction of the elbows, wrists and hands during the synchronization movement (i.e., ab- and adduction of both arms). These time series were first interpolated with a spline algorithm in case of missing data. The median of the time lags was used to temporally align the time series of the two motion-registration systems. Body point's time series with more than 50% of missing values were excluded from further analyses. The missing values of the remaining data were interpolated with a spline algorithm. The so-obtained time series were used for the calculation of the walking-adaptability outcome measures. In the current study, only the time series of the spine shoulder, spine base and left and right ankle in the anterior-posterior direction were needed for the calculation of the walking-adaptability outcome measures (Figure S3.2).

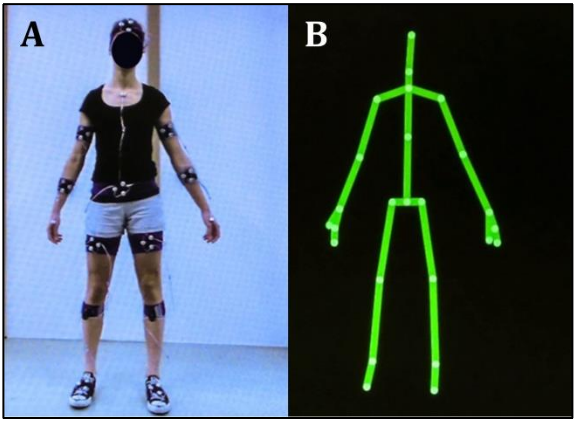

Figure S3.1 Body point determination with the Optotrak system and the Interactive Walkway. (A) Subject with all markers of the Optotrak system; (B) Snapshot of available Interactive Walkway body points of the same subject (derived with established human-pose estimation algorithms of Kinect v2).

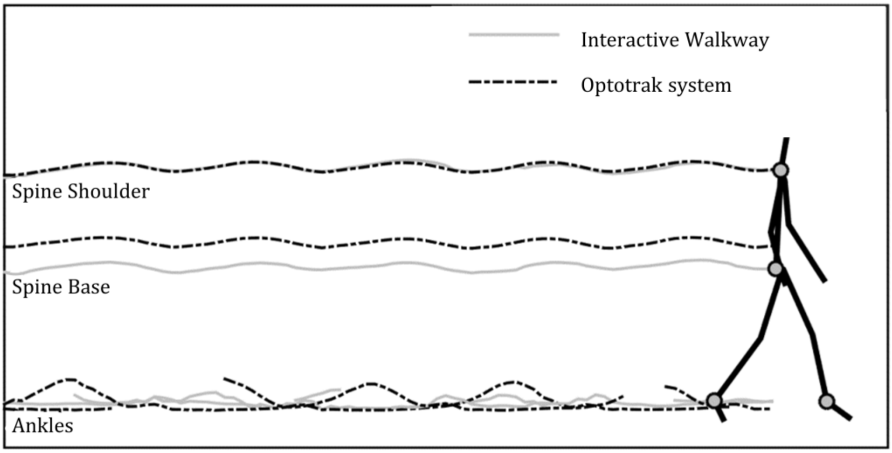

Figure S3.2 Raw time series of the two systems for the body points of interest to the current study. Note the missing values in the ankle data for the Optotrak time series.

Table S3.1 Overview of Optotrak marker data for deriving body points resembling Interactive Walkway body points.

Interactive Walkway body points	Smart Marker Rigid Body position	Virtual marker position	Smart marker position
Head	Head	Nasion, inion and left and right ear	-
Neck	-	-	-
Spine shoulder	-	-	Sternum
Spine mid	-	-	-
Spine base	Lower abdomen	Left and right anterior superior and posterior superior iliac spine	-
Shoulders	Upper arms	Head of the humurus	-
Elbows	Upper arms	Medial and lateral epicondyles	-
Wrists	Forearms	Distal head of the radius and ulna	-
Hands	-	-	Back of the hand
Hand tips	-	-	-
Thumbs	-	-	-
Hips	Upper legs	Trochantor major	-
Knees	Upper legs	Medial and lateral condyles	-
Ankles	Lower legs	Medial and lateral malleoli	-
Feet	Feet	Calcaneus	Head of the distal phalanx of the hallux

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Supplement 3.2

Data of body point's time series in the anterior-posterior, mediolateral and vertical direction for the Interactive Walkway and the Optotrak system. This data is available at: https://ars.els-cdn.com/content/image/

- 1-s2.0-S0966636217300553-mmc2.zip
- 1-s2.0-S0966636217300553-mmc3.zip
- 1-s2.0-S0966636217300553-mmc4.zip
- 1-s2.0-S0966636217300553-mmc5.txt