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Can falls be predicted with gait analytical and posturographic measurement systems? A prospective follow-up study in a nursing home population

René Schwesig[1], David Fischer[1], Andreas Lauenroth[2], Stephan Becker[3] and Siegfried Leuchte[1]

Abstract

Objective: To validate previously proposed findings and to develop an objective, feasible and efficient bifactorial (risk factors: gait impairment and balance disorders) fall risk assessment.
Design: Prospective follow-up study
Setting: Nursing homes (Halle/Saale, Germany).
Subjects: One hundred and forty-six nursing home residents (aged 62–101 years) were recruited.
Methods: Gait data were collected using a mobile inertial sensor-based system (RehaWatch). Postural regulation data were measured with the Interactive Balance System. Falls were recorded in standardized protocols over a follow-up period of 12 months.
Main measures: Gait parameters (e.g. spatial-temporal parameters), posturographic parameters (e.g. postural subsystems), number of falls.
Results: Seventeen (12%) of the participants had more than two falls per year. The predictive validity of the previously selected posturographic parameters was inadequate (sensitivity: 47%). The new measurement tool defined 67 participants showing an increased risk of falls. In reality, only 8 participants actually fell more than twice during the follow-up period (positive predictive value (PPV): 12%). The negative predictive value (NPV) was 88%. The posturographic frequency range F2–4 (peripheral–vestibular system), stride time and standard deviation of landing phase were the most powerful parameters for fall prediction. Gait and postural variability were larger in the high-risk group (e.g. gait speed; confidence interval $(CI)_{high}$: 0.57–0.79 vs. CI_{low}: 0.72–0.81 m/s).
Conclusion: RehaWatch and the Interactive Balance System are able to measure two of the most important fall risk factors, but their current predictive ability is not satisfactory yet. The correlation with physiological mechanisms is only shown by the Interactive Balance System.

Keywords

Fall risk, gait impairments, balance disorders, fall prevention, nursing home, elderly

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[1]Department of Sport-Science, Martin-Luther-Universität Halle-Wittenberg, Halle (Saale), Germany
[2]Network Aging Research, Universität Heidelberg, Heidelberg, Germany
[3]Institute for Musculoskeletal Analysis, Research and Therapy IMSART, Vienna, Austria

Corresponding author:
René Schwesig, Department of Sport-Science, Martin-Luther-Universität Halle-Wittenberg, von-Seckendorff-Platz 2, 06120 Halle (Saale), Germany.
Email: rene.schwesig@sport.uni-halle.de

Introduction

From the age of 65 onwards, an increased risk of falls can be observed.[1,2] In general, two of the six most important clinically identifiable risk factors for falls are gait impairments and balance disorders.[3] There are a variety of tests that may relate to the risk of falls,[4–7] but these have not been validated in a prospective study yet.[8,9] Most of them (e.g. the Berg Balance Scale, Performance Oriented Mobility Assessment) depend on supervised settings and expert ratings.[10] They are mostly skill orientated without any connection to physiological mechanisms. Furthermore, some of them are too challenging for the target group.[8,9,11]

The evidence for the external validity of these tools is weak.[10] All measures (Berg Balance Scale, Performance Oriented Mobility Assessment, Dynamic Gait Index) had a low sensitivity towards the original sample.[12]

Maki[13] showed that a small increase in stride-to-stride variability in stride length doubled the likelihood of future falls. Therefore, Lindemann et al.[10] developed the maximum step length test as a powerful and feasible tool predicting future falls in community-dwelling older persons. A low and variable gait speed,[13,14] a variable stride time[15,16] and prolonged double support[13] were also found to be consistent fall risk factors.

Our purpose was to validate the outcome of an earlier study.[17] In that study, the posturographic parameters F1 (frequency band 1: 0.03–0.1 Hz; Table 1) and weight distribution index (Table 1) showed the best results with regard to predictive power (sensitivity: 88%). The second aim of the study was to complement the posturography by mobile gait analysis in order to develop an objective, feasible and efficient bifactorial fall risk evaluation tool to be used for tailoring preventive interventions for falls.

Table 1. Stance positions, frequency bands and parameters of motor output used in the posturographic assessment

Stance position[18]	Description	
	Eye position	Standing and head position
NO	Eyes open	Head straight
NC	Eyes closed	Head straight
PO	Eyes open	On elastic pad, head straight
PC	Eyes closed	On elastic pad, head straight
HR	Eyes closed	Head turned 45° to the right
HL	Eyes closed	Head turned 45° to the left
HB	Eyes closed	Head reclined
HF	Eyes closed	Head anteverted
Frequency bands[19–21]	Frequency (Hz)	Postural subsystem
F1	0.03–0.1	Visual and nigrostriatal system
F2–4	0.1–0.5	Peripheral–vestibular system
F5–6	0.5–1.0	Somatosensory system
F7–8	<1.0	Cerebellar system
Parameters of motor output		
Stability indicator (ST)	Root mean square of successive differences of pressure signals; describes the postural stability state; the greater ST, the greater instability	
Weight distribution index (WDI)	Standard deviation of the weight distribution score assuming equal weight distribution on each plate (25% per plate)	
Synchronization	Six values describing the relationship of vibration patterns between plates calculated as scalar product; 1000 − complete coactivity; –1000 − complete compensation, 0 − no coactivity or compensation	

Methods

Local nursing homes were contacted by phone and mail to recruit an adequate cohort of nursing home residents. Inclusion criteria were: age above 60 years and the absence of neurological impairment affecting gait and posture (e.g. Parkinson's disease, cerebellar diseases). A written consent form was obtained in all cases. Exclusion criteria were the inability to stand or walk independently. Prior to data collection, all participants were informed by their caregivers and an investigator regarding study aim, testing procedure and testing methods. First, subjects completed a questionnaire on relevant data, including level of care, time of falls and medication intake. The study was approved by the local ethics committee.

Participants were equipped with a mobile inertial sensor-based system RehaWatch (HASOMED GmbH, Magdeburg, Germany, Figure 1 online). They wore their personal flat shoes without high heels during the walking trials and were asked to walk straight at a self-selected speed towards a target at 20 m distance to ensure that a sufficient number of stable walking cycles were recorded. The first two walking trials were used to adjust to the test conditions. Data from the third trial were used for further analysis. Mean and standard deviations of each gait parameter of all recorded steps were computed for each subject and used for further analysis. For bilateral parameters, values for the left leg were included.

Afterwards, postural regulation was measured using the Interactive Balance System (Neurodata GmbH, Vienna, Austria). This consists of four independent forceplates supporting heels and forefeet in order to measure postural stability and regulation. Postural regulation was measured as stability indicator, weight distribution index, synchronization and sway intensities at different frequency ranges determined by Fast Fourier Transformation (FFT) of the postural sway waves (Table 1). Subjects were tested during one trial (32 seconds) for each of eight standardized barefoot test conditions.[18] All parameters used in the Interactive Balance System are dimensionless values. A comprehensive description of both systems, including the information regarding reliability, validity, reference data and their value to measure falls risk, is available elsewhere.[17,18,21–25]

Data collection for each subject took approximately 20 minutes. During a follow-up period of 12 months, all falls were recorded by the caregivers at the nursing home in a standardized falls protocol. The caregivers were instructed at the beginning of the study to meticulously document falls and their consequences on internal falls protocols over the follow-up period. Falls were defined as 'an unexpected event in which the subject comes to rest on the ground, floor, or lower level'.[26]

Statistical analysis

All statistical analyses were performed using SPSS version 18.0 for Windows (SPSS Inc., Chicago, IL, USA). Participants were assigned into two groups based on their number of falls during the follow-up (high risk: three or more falls; low risk: fewer than three falls).[23] Binary logistic regression was performed initially (method: backwards) to select relevant parameters. The dichotomous parameter fall risk (high versus low) represented the dependent variable and the metrical scaled gait and posturographic parameters represented the independent variables. In an area under the curve analysis (AUC), the coordinates of the receiver operating characteristic (ROC) curves were used to determine assessment-appropriate cut-off values. The cut-off values were determined by accumulating sensitivity and specificity (boundary condition: sensitivity > specificity) from the ROC curves.

Sensitivity was defined as the total number of fallers correctly identified as high risk. Specificity was defined as total number of non-fallers (low fall risk). The positive predictive value (PPV) was defined as the number of high-risk subjects who actually did fall. The negative predictive value (NPV) was the number of low-risk subjects who did not fall.[27] Finally the comparison of subjects with high risk for falls and subjects with low risk for falls was calculated with a multivariate model (MANOVA).

Differences of means were considered statistically significant at *P*-values less than 0.05 and partial eta-squared (η^2)-values greater than 0.05. Due to the large number of cases, decisions on significance were made primarily based on η^2-values.

Results

One hundred and forty-six subjects (113 women; mean age: 82.7 years, range: 62–101 years) were recruited. One hundred and thirty-five participants (93%) were able to perform both tests. One patient (0.7%) showed no medical condition or disease at the time of the study. 89% (n = 130) of nursing home residents presented with a cardiovascular, 54% (n = 79) a neurological and 34% (n = 49) with an orthopaedic condition or disease, respectively. Ninety-five participants (65%) had at least two conditions or diseases. Medication records were available for 133 participants (91%), and only 5 participants (4%) did not take any medications at the time of the study.

Data for rate of falls were collected for 141 subjects (97%). Overall, 171 falls were recorded during the 12-month follow-up period. Eighty-three subjects (59%) did not experience any falls, 13 subjects (22%) fell once, 10 subjects (7%) fell twice and 17 subjects (12%) fell at least three times during the follow-up period. Hence, 17 subjects were classified as being at high risk for falls.[23]

Table 2 shows the predictive validation for frequency band 1 (visual and nigrostriatal system) and weight distribution index.[17] The number of subjects predicted to fall or not to fall, and the number of participants who did fall or did not fall during the follow-up period are also given in Table 2. The test quality criteria, especially the sensitivity, were very low (Table 3) and much lower than those found in our first study.[17] These findings are supported by the results of the comparison of Schwesig et al.[17] and the current study: AUC = 0.791, P < 0.001, confidence interval (CI): 0.696–0.885 vs. AUC = 0.587, P = 0.244, CI: 0.421–0.753.

Frequency band 1 and weight distribution index determined by Schwesig et al.[17] using binary logistic regression analysis were not selected for this study sample under inclusion of gait and posturographic[17] parameters (Table 4). The binary logistic regression showed that the gait parameters stride time and the standard deviation of the landing phase (defined according to Beckers and Deckers[28]) are generally predicting risk for falls. Frequency band 2, 3 and 4 (Table 1) was the only posturographic parameters that predicted risk for falls (Table 4).

AUC analysis revealed only small differences between the parameters stride time, standard deviation (SD) landing phase and F2–4 (Figure 2). The predictive ability of stride time, SD landing phase and F2–4 for fall risk was 0.66, 0.70 and 0.66, respectively. The cut-off values, including sensitivity and specificity, are shown in Table 5.

The variability of gait and posture was calculated by means of MANOVA (Table 6). Persons at high risk for falls demonstrated a significant larger variability in both gait and posture (exception: SD stride length) than persons with low risk for falls. Only the parameter F2–4 (P = 0.003 and η^2 = 0.061) showed a significant difference. The multivariate main effect is more pronounced in posturographic parameters than gait parameters (P = 0.011, η^2 = 0.115 vs. P = 0.138, η^2 = 0.074).

Table 2. Prediction of falls (high fall risk: F1 and weight distribution index ≥26.7) related to the number of subjects who did fall and did not fall during the follow-up period of 12 months

		Prediction of falls		Overall
		Low fall risk	High fall risk	
Falls during the follow-up period	Low fall rate (fewer than 3 falls)	65	59	124
	High fall rate (3 or more falls)	9	8	17
Overall		74	67	141

Table 3. Predictive values for F1 and weight distribution index (cut-off ≥ 26.7), determined using the samples from Schwesig et al.[17] and validated in this study

Total *n* (*n* high risk for falls)	141 (17)
Sensitivity (%), 95% CI	47 (8/17), 23.0–72.2
Specificity (%), 95% CI	52 (65/124), 43.3–61.5
PPV (%), 95% CI	12 (8/67), 5.30–22.2
NPV (%), 95% CI	88 (65/74), 78.2–94.3

(…/…), absolute values in relation.
CI, confidence interval; PPV, positive predictive value; NPV, negative predictive value.

Table 4. Binary linear regression analysis (method forward likelihood ratio) for gait and posturographic parameters. For bilateral gait parameters, values for the left leg were included

Parameter	Reg.-Co. B	SE	Significance	Exp(*B*)	95% CI for Exp(*B*)	
					Lower limit	Upper limit
Gait analysis						
SD landing phase	0.062	0.020	0.001	1.064	1.023	1.106
Constant	–3.805	0.686	<0.001	0.022		
Stride time	3.648	1.839	0.047	38.382	1.045	1.410
SD landing phase	0.060	0.020	0.003	1.062	1.021	1.106
Constant	–8.289	2.445	0.001	0.000		
Posturography						
F2–4	0.140	0.051	0.006	1.151	1.041	1.273
Constant	–3.964	0.819	<0.001	0.019		

Dependent variable: fall risk high/low (high fall risk: 3 or more falls per year; *n* = 17).
Reg.-Co. B, regressions-coefficient B; SE, standard error; CI, confidence interval.

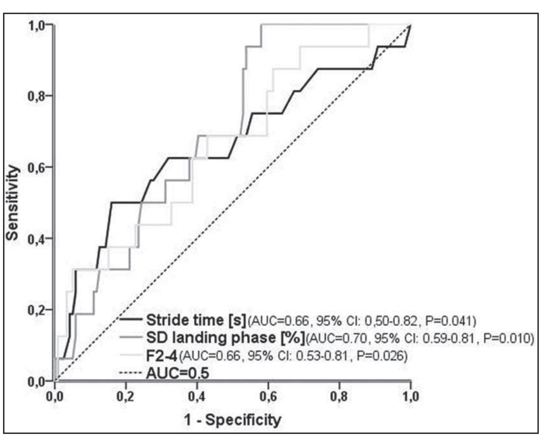

Figure 2. Receiver operating characteristic curve (ROC) showing the performance of the parameters stride time, standard deviation (SD) landing phase and F2–4. AUC, area under the curve; CI, confidence interval.

The diagnostic groups cardiovascular ($P = 0.552$, $\chi^2 = 0.354$), neurological ($P = 0.710$, $\chi^2 = 1.38$) and orthopaedic ($P = 0.802$, $\chi^2 = 0.063$) displayed no significant differences regarding their respective impact upon the risk for falls. Consistently 13% (12.6–13.0%) of the test persons within the three diagnostic groups showed a risk for falls.

Discussion

The novelty of this study consists in the following: the two main risk factors for falls – gait impairments and balance disorders – can actually be measured and predicted using adequate practical reliable and valid assessments. Furthermore, we could demonstrate that not only gait instability is an indicator for the risk for falls,[10,15,29] but also

Table 5. Cut-off values, sensitivity and specificity based on the receiver operating characteristic curves and calculated by adding sensitivity and specificity (boundary condition: sensitivity > specificity)

Parameter	Cut-off	Sensitivity	Specificity
Stride time (s)	1.19	63	61
SD landing phase (%)	15.3	100	42
F2–4	10.7	88	39

Table 6. Multivariate model (MANOVA) for gait and posturographic parameters (dependent parameters) for both samples (high fall risk vs. low fall risk)

Parameter	High-risk group			Low-risk group			MANOVA	
	Mean	CI		Mean	CI		*P*-value	η^2
		LL	UL		LL	UL		
Gait analysis	(*n* = 16)			(*n* = 115)				
Stride time (s)	1.24	1.17	1.31	1.16	1.13	1.18	0.024	0.039
SD Stride time (s)	0.07	0.06	0.08	0.05	0.05	0.06	0.026	0.038
Stride length (m)	0.86	0.74	0.98	0.91	0.87	0.96	0.427	0.005
SD Stride length (m)	0.11	0.08	0.14	0.13	0.12	0.14	0.299	0.008
Walking speed (m/s)	0.68	0.57	0.79	0.77	0.72	0.81	0.156	0.016
Double support (%)	34.6	30.5	38.6	30.5	29.0	32.0	0.067	0.026
Posturography	(*n* = 17)			(*n* = 124)				
F1	23.9	20.6	27.3	19.7	18.5	21.0	0.022	0.037
F2–4	16.0	13.9	18.0	12.6	11.8	13.4	0.003	0.061
F5–6	7.04	5.87	8.20	6.20	5.77	6.63	0.185	0.013
F7–8	1.49	1.22	1.77	1.25	1.15	1.35	0.108	0.018
ST	40.5	33.4	47.6	35.2	32.6	37.9	0.169	0.014
WDI	5.88	4.75	7.01	6.89	6.47	7.31	0.102	0.019

Only hypotheses-relevant parameters were selected. Main effects: gait analysis: $P = 0.138$, $\eta^2 = 0.074$; posturography: $P = 0.011$, $\eta^2 = 0.115$.
SD, standard deviation; CI, confidence interval; LL, lower limit; UL, upper limit; F, frequency; ST, stability indicator; WDI, weight distribution index.

posture regulation variability. While our proposed methods are easy to use, their current predictive ability needs to be increased. Hence, the results of these methods should be confirmed in a second (gait analysis) and third (posturographic) sample, respectively.

In detail, it turned out that the posturographic parameters F1 and weight distribution index are not suitable predictors for falls in a nursing home population. Their performance was clearly lower than that reported in the literature.[11,17,23] The predictive efficiency (sensitivity: 47%; PPV: 12%) and the lack of selection (binary logistic regression) confirm this observation. In this current study, only F2–4 (peripheral–vestibular subsystem) was selected. Their predictive validity was slightly higher (0.66) than those reported in the literature (0.51–0.61).[30] Consequently, this postural subsystem is the most relevant parameter for the design of fall prevention interventions.

While the results of an earlier study[17] suggest optometric visual training, the current results support the use of training programmes aimed at improving the peripheral–vestibular accentuation (e.g. Spacecurl, mini trampoline). In addition, with this examinations we were able to show that the variability difference between the posturographic parameters is even larger (e.g. stability indicator: $CI_{high\ risk}$: 33.4–47.6 vs. $CI_{low\ risk}$: 32.6–37.9) than the range of variability in the gait parameters (Table 6).

With regard to gait parameters, only stride time and standard deviation of the landing phase were identified as fall predictors. According to the literature,[7,13,15,16] the confidence intervals for all gait parameters (Table 6) were larger in the high-risk group (e.g. walking speed: $CI_{high\ risk}$: 0.57–0.79 m/s vs. $CI_{low\ risk}$: 0.72–0.81 m/s). Therefore, the gait variability distinguishes fallers from non-fallers.[7] The predictive ability of gait analysis parameters indicate that nursing home residents at a high risk for falls take longer for each step and have a highly variable landing phase. Lindemann et al.[10] identified mean step length (sensitivity: 77%; specificity: 62%) and maximum step length (sensitivity: 70%; specificity: 69%) as relevant parameters for the prediction of risk for falls. Hence, gait patterns of persons who are at higher risk for falls are also characterized by continual readjustments (landing phase, step length). Therefore, gait training using optical (markings on walking track) and/or acoustic (predetermined cadence using a metronome, music) rhythmization may be an effective intervention.[29,31]

The main difference between RehaWatch/Interactive Balance System and established methods for fall risk assessment is the introduction of measurements of the inherent motor dimension (gait, upright stance). Measurement data were captured using FFT and forceplates in the Interactive Balance System, such as accelerometers and gyroscopes in the RehaWatch system. Although the Interactive Balance System and RehaWatch are technologically based, they are as easy and quick to use as established methods.

In contrast to the findings of Pardasaney et al.,[12] we found that it is not advisable to develop more challenging measures for better discrimination of balance ability. A higher complexity implicates increased learning effects and reduces the study sample size. The 'ideal test' is maximally facilitated to avoid learning effects (ceiling effects) and still contains enough sensitivity to represent the whole spectrum of subjects (cerebellar patients up to target shooter).[21]

The following limitations should be borne in mind. The examination is based on a non-representative study population. Merely 12% of all residents of 15 nursing homes were able to participate in this study. Furthermore, the inclusion of additional functional parameters in the fall risk model may be necessary for application to future study populations because of different pathophysiologies in these patients (e.g. patients suffering from dizziness, osteoporosis or Parkinson's disease). Moreover, a complete clinical history (medication, previous diseases, time of falls, muscular potential, fear of falls, etc.) should be mandatory in all cases with technical gait and balance diagnostic systems.

Clinical messages

- The use of motoric tests and questionnaires is not recommended because of their orientation to skills and ordinal estimation. Objective measurement is better than subjective estimation.
- We recommend measurements that are able to provide valuable information for therapy. In this case, sports and physiotherapeutic concepts should include gait rhythmization and targeted sensorimotor training.

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Conflict of interest

The authors do not have any conflicts of interest.

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