ACRM
AMERICAN CONGRESS OF REHABILITATION MEDICINE

Archives of Physical Medicine and Rehabilitation

journal homepage: www.archives-pmr.org

Archives of Physical Medicine and Rehabilitation 2021;102:582-90

ORIGINAL RESEARCH

The Gait Disorientation Test: A New Method for Screening Adults With Dizziness and Imbalance

Colin R. Grove, PT, DPT, PhD,[a,b] Bryan C. Heiderscheit, PT, PhD, FAPTA,[b,c] G Mark Pyle, MD,[a] Brian J. Loyd, PT, DPT, PhD,[d,e] Susan L. Whitney, DPT, PhD, FAPTA[f]

From the [a]School of Medicine and Public Health, Department of Surgery, University of Wisconsin-Madison, Madison, WI; [b]Institute for Clinical and Translational Research, School of Medicine and Public Health, University of Wisconsin-Madison, Madison, WI; [c]Department of Orthopedics and Rehabilitation, School of Medicine and Public Health, University of Wisconsin-Madison, Madison, WI; [d]Department of Physical Therapy and Rehabilitation Science, University of Montana, Missoula, MT; [e]Department of Physical Therapy and Athletic Training, University of Utah, Salt Lake City, UT; and [f]Department of Physical Therapy, University of Pittsburgh, Pittsburgh, PA.

Abstract

Objective: To develop and evaluate a new method for identifying gait disorientation due to vestibular dysfunction.

Design: The gait disorientation test (GDT) involves a timed comparison of the ability to walk 6.096 m with eyes open versus eyes closed. In this prospective study, participants were grouped based on vestibular function. All participants completed a clinical examination, self-report- and performance-based measures relevant to vestibular rehabilitation, and the tasks for the GDT. Vestibular-impaired participants underwent the criterion standard, videonystagmography and/or rotational chair testing.

Setting: Ambulatory clinic, tertiary referral center.

Participants: Participants (N=40) (20 vestibular-impaired, 30 women, 49.9±16.1years old) were enrolled from a convenience/referral sample of 52 adults.

Main Outcome and Measure(s): We determined test-retest reliability using the intraclass correlation coefficient model 3,1; calculated the minimal detectable change (MDC); examined concurrent validity through Spearman correlation coefficients; assessed criterion validity with the area under the curve (AUC) from receiver operator characteristic analysis; and computed the sensitivity, specificity, diagnostic odds ratio (DOR), likelihood ratios for positive (LR+) and negative (LR−) tests, and posttest probabilities of a diagnosis of vestibulopathy. The 95% confidence interval demonstrates measurement uncertainty.

Results: Test-retest reliability was 0.887 (0.815, 0.932). The MDC was 3.7 seconds. Correlations with other measures ranged from 0.59 (0.34, 0.76) to −0.85 (−0.92, −0.74). The AUC was 0.910 (0.822, 0.998), using a threshold of 4.5 seconds. The sensitivity and specificity were 0.75 (0.51, 0.91) and 0.95 (0.75, 1), respectively. The DOR=57 (6, 541.47), LR+ =15 (2.18, 103.0), and LR− =0.26 (0.12, 0.9). Positive posttest probabilities were 89%-94%.

Conclusions and Relevance: The GDT has good reliability, excellent discriminative ability, strong convergent validity, and promising clinical utility.

Archives of Physical Medicine and Rehabilitation 2021;102:582-90

An estimated 33 million American adults annually experience imbalance or dizziness.[1,2] Vestibular dysfunction is a common cause of impaired balance.[3-5] Presently, improving the diagnosis, treatment, and prevention of imbalance and dizziness is a top priority in the United States.[6] Screening persons for vestibular dysfunction is an important step in determining whether further

Supported by the Clinical and Translational Science Award program, through the NIH National Center for Advancing Translational Sciences (grant nos. UL1TR000427 and TL1TR002375). The content is solely the responsibility of the authors and does not necessarily represent the official views of the NIH. Additional funding for Colin R. Grove was provided by the University of Wisconsin through a research assistantship in the Department of Surgery and a research grant from the Department of Orthopedics and Rehabilitation. Brian J. Loyd received funding from the Foundation for Physical Therapy Research: New Investigator Fellowship Training Initiative and US Army Advanced Medical Technology Initiative. These funding sources were not involved in the study design, data collection, data analysis and interpretation, the writing of this article, or the decision to submit this article for publication.

Disclosures: Colin R. Grove is a consultant for Wicab, Inc. Susan L. Whitney is a paid speaker for Interacoustics and Medbridge and a consultant for IAI, Inc. Bryan C. Heiderscheit has an ownership interest in NxtMile, LLC, as well as Science of Running Medicine, LLC, and is a consultant for Altec, Inc and Mountain Land Rehabilitation. The other authors have nothing to disclose.

0003-9993/21/$36 - see front matter © 2020 by the American Congress of Rehabilitation Medicine
https://doi.org/10.1016/j.apmr.2020.11.010

diagnostic workup, referral to specialty providers, and/or therapies for vestibular dysfunction may be indicated.[7]

Vestibular disorders result in impairments in gaze stability,[8] spatial orientation,[9] postural control,[10] and gait.[11] Tests of vestibular-ocular reflex function,[8,12,13] spatial orientation,[4,5] standing balance,[14-17] and walking[18-20] have been used to screen for the presence of vestibular dysfunction.[21-26] Despite the fact that many vestibular-impaired persons perform poorly on these tests, their screening utility is limited by suboptimal discriminative validity.[21-26]

Persons with peripheral,[27-35] central,[36-38] and age-related[39] vestibular dysfunction also have impaired spatial navigation, visual dependence,[40] and gait disorientation, that is, difficulty walking under challenging sensory conditions. Path integration tasks, during which a person walks while blindfolded along a memorized path or toward a previously viewed target, are used to assess accuracy in spatial navigation.[41] Prior studies of vestibular-impaired adults used linear[27,28,33,34] or geometrically shaped[42-44] paths. Impairment in spatial navigation is responsive to vestibular rehabilitation[27,28,31,45]; however, deficits may persist.[46,47]

To our knowledge, spatial navigation assessments have not been used to screen for vestibular dysfunction. The objectives of this study were to develop and validate a screening method for gait disorientation. We hypothesized that greater difficulty navigating with eyes closed compared to with eyes open would discriminate vestibular impaired from healthy adults.

Methods

The main dataset was collected prospectively at the University of Wisconsin (UW)-Madison (site 1) from adults who were either healthy or had documented vestibular loss (fig 1). The Gait Disorientation Test (GDT), which was developed from specific items from the Functional Gait Assessment (FGA),[48] was the index test. Vestibular-impaired adults underwent the criterion tests (videonystagmography [VNG] and/or rotational chair [RC] testing)[49] prior to enrollment (supplemental appendix S1, available online only at http://www.archives-pmr.org/). All participants were 20-79 years old; spoke English fluently; were independently functioning; did not have a history of neurologic, musculoskeletal, vision, or pain conditions; had normal, bilateral lower-extremity strength[50] and sensation[51]; could stand for 20 minutes without sitting and walk 6.096 m unaided; could abstain from alcohol and withhold any antivertigo, sedative, and narcotic or barbiturate medications for 48 hours prior to study visits; and were not pregnant during the study.

The GDT was externally validated using a second dataset from a study conducted at the University of Utah (site 2) in which the effects of vestibular loss on gait were investigated.[52] Adults who were 4 to 8 weeks post−unilateral, vestibular schwannoma resection, and healthy adults with no history of vestibulopathy were recruited. Participants in this study were 18-70 years old, able to walk unaided, and had no history of lower extremity injuries within the previous 12 months. Persons with unstable medical conditions, for example, angina, seizures, were excluded.

Each study was approved by an institutional review board from the site at which the data were collected and was conducted in accordance with the Declaration of Helsinki.[53] Informed consent was obtained from all participants.

The assessor at site 1 (C.R.G.) was a physical therapist with 26 years of experience in vestibular rehabilitation and was aware of group assignment and VNG/RC results. The Activities-specific Balance Confidence Scale (ABCS),[54] Dizziness Handicap Inventory (DHI),[55] FGA,[48] GDT, and Sensory Organization Test (SOT)[56,57] were collected at 2 time points (A and B) that were 8 weeks (±3days) apart. The Five-times Sit-to-stand Test (FTSTST), horizontal head impulse test (hHIT), head-shaking nystagmus (HSN), and noninstrumented, dynamic visual acuity test (DVAT) were administered at time point A only (see supplemental appendix S1).

ABCS[54]: This 16-question survey measures how confident the responder feels about their balance in specific situations. The average score ranges between 0% and 100% with higher scores indicating greater balance-related confidence.

DHI[55]: This 25-question survey is used to assess how often dizziness has affected the person's function. The DHI total score, which ranges from 0 to 100, records perceived handicap with higher scores indicating greater perceived handicap.

FGA[48]: This standardized test includes 10 gait-related balance tasks. The total score for the FGA ranges from 0 to 30 and higher scores indicate better balance. The GDT was created using FGA items 1 (FGA1: walking, eyes open) and 8 (FGA8: walking, eyes closed). The GDT result was calculated by subtracting the time to complete FGA1 in seconds from the time to complete FGA8.

Participants at site 1 performed the FGA in their preferred, flat-soled shoes along a dedicated path. Markings designating the beginning, ending, and lateral boundaries of a 6.096-m-long by 1.067-m-wide scoring section are integrated into the design pattern of the flooring. We used visual observation and a stopwatch to record performance on timed tasks. Participants began walking at their preferred speed prior to entering the scoring section and continued walking until they were told to stop at a point beyond the end of the scoring section. Timing began when the leading foot crossed the marking indicating the beginning of the scoring section and stopped when the leading foot crossed the marking indicating the end of the scoring section.

List of abbreviations:

95% CI	**95% confidence interval**
ABCS	**Activities-specific Balance Confidence Scale**
AUC	**area under the curve**
COMP	**composite score**
DHI	**Dizziness Handicap Inventory**
DOR	**diagnostic odds ratio**
DVAT	**dynamic visual acuity test**
FGA	**Functional Gait Assessment**
FGA1	**Functional Gait Assessment, item 1**
FGA8	**Functional Gait Assessment, item 8**
FTSTST	**Five-times Sit-to-stand Test**
GDT	**Gait Disorientation Test**
hDVAT	**horizontal dynamic visual acuity test**
hHIT	**horizontal head impulse test**
HSN	**head shaking nystagmus**
LR	**likelihood ratio**
LR+	**likelihood ratio for a positive test**
LR−	**likelihood ratio for a negative test**
MDC	**minimal detectable change**
RC	**rotational chair**
ROC	**receiver operator characteristic**
SOM	**somatosensory score**
SOT	**Sensory Organization Test**
vDVAT	**vertical dynamic visual acuity test**
VNG	**videonystagmography**

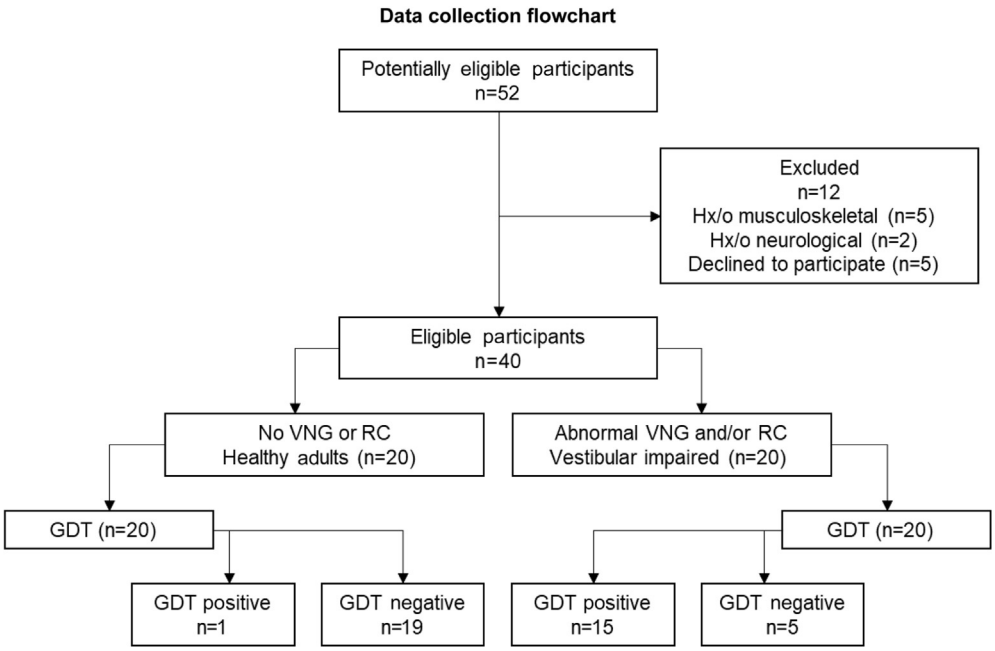

Fig 1 Data collection flowchart. These data are reported for time point A in the main study. The criteria for abnormal or positive results on VNG, RC, and the GDT are provided in supplemental appendix S1. All healthy and vestibular-impaired participants underwent a thorough clinical examination to screen for previously undetected vestibular dysfunction in healthy participants or to confirm vestibular loss in impaired participants, as well as to rule out somatosensory, visual, musculoskeletal, and neuromuscular conditions that might interfere with testing (see supplemental appendix S1). Abbreviation: Hx/o, history of musculoskeletal or neurological exclusion criteria.

Participants at site 2 performed the FGA while wearing their preferred, flat-soled shoes and a suite of triplanar, inertial measurement units.[a] The times to complete FGA1 and FGA8 were calculated by graphing acceleration data from the sternal inertial measurement unit that was processed through a second-order, low-pass, Butterworth filter with a cutoff of 6.0 Hz and zero phase shift and then capturing the time between the manually selected beginning and end of each walking period.

GDT: A detailed description of the GDT is provided in supplemental appendix S2 (available online only at http://www.archives-pmr.org/). The GDT should be performed in a quiet area along a 10-m pathway that includes a 6.096-m by 1.067-m scoring section and using a stopwatch for timing each task.

SOT[56,57]: The SOT[b] is used to evaluate sensory contributions to standing balance. Overall performance on the SOT is represented by the composite score (COMP). The manufacturer-calculated somatosensory score (SOM) provides an objective expression of Romberg's sign.[14]

Statistical considerations

The reliability of the GDT, FGA1, and FGA8 was assessed with the intraclass correlation coefficient model 3,1[58] by comparing performances on these tasks at time points A and B. The minimal detectable change (MDC) values for the GDT, FGA1, and FGA8 were calculated using $1.96^{*}\sqrt{2}*\mathrm{SEM}$,[59] where the SEM was estimated by taking the square root of the within-subjects variance from a 2-way, random-effects, analysis of variance. Spearman correlation coefficient method was used to assess concurrent validity between the GDT and ABCS, DHI, DVAT (horizontal dynamic visual acuity test [hDVAT], vertical dynamic visual acuity test [vDVAT]), FGA, and COMP.

The discriminative ability of the GDT was assessed using receiver operator characteristic (ROC) analysis.[60] Similarly, ROC analyses were completed for FGA1, FGA8, FTSTST, hDVAT, vDVAT, COMP, and SOM. The threshold for the hDVAT and vDVAT was a degradation in visual acuity of 3 lines when comparing static to dynamic visual acuity.[8] Otherwise, Youden's method was employed to calculate the optimal threshold. Subsequently, the sensitivity and specificity for these tests were computed based on contingency tables constructed by using their thresholds. Separately, contingency tables for the hHIT and HSN tests were constructed based on dichotomizing the results.

The diagnostic odds ratio (DOR) and likelihood ratios for a positive (LR+) and a negative (LR−) test were calculated.[61] In addition, the positive and negative posttest probability was determined for the GDT using the LRs we calculated and published data regarding the prevalence of vestibular dysfunction in specific clinical settings[62] and the general population.[3]

An ROC analysis was used to compute the area under the curve (AUC) (95% confidence interval [95% CI]) for the GDT from the external dataset. The optimal threshold for the GDT that was obtained from site 1 was used to create a contingency table of the external dataset for subsequent calculation of diagnostic performance measures.

All analyses were conducted post hoc using R version 3.5.[c] The GDT data were not normally distributed.

Results

Twenty healthy adults and 20 adults with chronic (3mo to 20y) vestibular hypofunction (left: n = 2, right: n = 12, bilateral: n = 6) participated at site 1. Vestibular-impaired participants were

Table 1 Study population characteristics

Variable	All	Site 1: Main Study		
		Healthy (n=20)	Impaired (n=20)	*P* Value
Age (y)	49.9 (16.1)	38.7 (11.7)	61.1 (11.2)	<.001*
Sex (women)	30 (75.0%)	16 (80.0%)	14 (70.0%)	.7†
BMI	26.1 (4.4)	26.4 (4.7)	25.8 (4.3)	.71*
GDT	3.7 (1.4-7.7)	1.6 (1.1-2.7)	7.7 (4.5-12.6)	<.001‡
	All	Site 2: External Validation Study		
		Healthy (n=16)	Impaired (n=13)	*P* Value
Age (y)	39.4 (14.8)	32.8 (12.3)	47.6 (13.7)	.006*
Sex (women)	18 (62.1%)	9 (56.2%)	9 (69.2%)	.7†
BMI	25.7 (5.0)	22.5 (2.3)	29.7 (4.5)	<.001*
GDT	2.3 (1.0-6.4)	1.1 (0.7-2.1)	7.3 (3.1-11.1)	<.001‡

NOTE. These data are presented as mean ± SD for age, percentages for sex, and mean ± SD for BMI (BMI: 703*weight/height^2). The median (interquartile range) is presented for the GDT because these data were not normally distributed.
Abbreviation: BMI, body mass index.
* The *P* values are from 2-tailed *t* tests.
† The *P* values are from a chi-squared test.
‡ The *P* values are from Wilcoxon rank-sum tests.

significantly older and had worse performance on the GDT than healthy participants (table 1). Based on post hoc modeling, age was not a significant factor in GDT times ($P=.954$) (supplemental appendix S3, available online only at http://www.archives-pmr.org/). One adverse event, a soleus tear that occurred while the participant was bicycling home from work, led a healthy adult to withdraw.

Sixteen healthy adults and 13 adults with surgically induced vestibular loss (left: n=8; right: n=5) contributed to the external dataset at site 2. These vestibular-impaired adults were significantly older and had worse performance on the GDT than healthy participants. Healthy participants at both sites performed comparably on the DHI, FGA, and gait speed.

Across all participants at site 1, the test-retest reliability for the GDT, FGA1, and FGA8 ranged from good to excellent (table 2). Reliability for these measures was moderate to good within healthy participants and good for vestibular-impaired participants (table 2). The MDC values were 3.7, 0.74, and 3.6 seconds for the GDT, FGA1, and FGA8, respectively. The GDT was moderately and negatively associated with the ABCS; strongly and positively related to the DHI; moderately and positively associated with performance on the hDVAT, vDVAT, and FTSTST; and strongly and negatively associated with the FGA and COMP (table 3).

The optimal threshold for discriminating between healthy and vestibular-impaired adults using the GDT was 4.5 seconds at site 1 (AUC [95% CI]=0.910 [0.822-0.998]) (table 4). The only other measures with an AUC >0.900 were FGA8 and the COMP. The sensitivities of each test ranged from poor to excellent, while the specificities ranged from moderate to excellent (table 5). When the times for FGA8 and the GDT were analyzed in parallel and with either result exceeding the optimal threshold, the sensitivity and specificity were 0.98 and 0.81, respectively. The DORs for all measures except the FTSTST and SOM were significant given that their 95% CIs excluded 1.0 (table 5). The GDT had a high DOR

Table 2 Test-retest reliability of the GDT, FGA1, and FGA8 in seconds

Measure	Time Point A	Time Point B	$ICC_{3,1}$ (95% CI)
	All Participants		
GDT	5.7±6.2	4.7±5.0	0.887 (0.815-0.932)
FGA1	4.7±0.8	4.7±0.9	0.818 (0.708-0.889)
FGA8	10.4±6.6	9.5±5.6	0.909 (0.850-0.946)
	Healthy Participants		
GDT	2.0±1.4	1.8±1.3	0.449 (0.097-0.702)
FGA1	4.4±0.7	4.3±0.7	0.847 (0.696-0.927)
FGA8	6.4±1.6	6.1±1.6	0.591 (0.285-0.788)
	Vestibular-Impaired Participants		
GDT	9.4±6.9	7.7±5.6	0.856 (0.711-0.931)
FGA1	5.1±0.9	5.2±0.9	0.731 (0.495-0.866)
FGA8	14.4±7.2	12.8±6.1	0.878 (0.753-0.942)

NOTE. These data are reported as the mean ± SD and $ICC_{3,1}$ (95% CI) for data from the main study. The $ICC_{3,1}$ was used because it performs well with data that are not normally distributed. The inclusion of imputed data in the calculation of reliability did not affect the strength of the ICCs; thus, only ICCs based on a complete data set are reported.
Abbreviation: $ICC_{3,1}$, intraclass correlation coefficient model 3,1.

Table 3 Correlation of the GDT with the ABCS, DHI, hDVAT, vDVAT, FTSTST, FGA, and the COMP

	N	ρ (95% CI)	*P* Value
Patient-reported outcome measures			
ABCS (average score)	40	−0.69 (−0.83 to −0.48)	<.001
DHI (total score)	40	0.74 (0.56-0.85)	<.001
Performance-based outcome measures			
hDVAT (degradation in acuity)	40	0.61 (0.37-0.77)	<.001
vDVAT (degradation in acuity)	40	0.59 (0.34-0.76)	<.001
FTSTST (time)	40	0.65 (0.43-0.80)	<.001
FGA (total score)	40	−0.85 (−0.92 to −0.74)	<.001
COMP (from the SOT)	40	−0.74 (−0.86 to −0.56)	<.001

NOTE. These data are presented as Spearman ρ (95% CI) for data collected at time point A in the main study. The Spearman correlation coefficient method was used to analyze all of these data due to their nonnormal distribution. The *P* value indicates the probability of finding a value for ρ within the associated 95% CI.

and a strong LR+ value (table 5). In addition, the positive, posttest probability for the GDT was projected to be high across clinical practice settings and the general population (table 6).

The AUC (95% CI) for the GDT was 0.894 (0.783-1.0) at site 2. The sensitivity, specificity, DOR, LR+, and LR−, as calculated from the validation cohort, differed somewhat from those values obtained in the main analysis (table 5). Chi-squared tests were not statistically significant when comparing the sensitivity ($P>.99$) and specificity ($P=.441$) of the GDT across datasets.

Discussion

The GDT provides an objective comparison of a person's ability to walk within a standardized path with eyes open versus their ability to perform the same task with eyes closed. The result is a composite measure of several determinants of spatial navigation, for example, walking speed,[33] spatial memory,[27] and cognitive-perceptual processes.[34] In this study, GDT times >4.5 seconds identified persons with vestibular disorders.

When deciding whether to use a new test, one must first consider whether the test accurately and consistently measures what it proposes to measure.[63] Our finding of excellent, intrarater reliability for the GDT is consistent with prior studies that found good to excellent reliability for measuring self-selected walking speed with a stopwatch in persons with locomotor impairments[64] and for assessing spatial navigation in persons with depression[65] and healthy, older adults.[66] Low variability within the healthy group may explain the discrepancies in intraclass correlation coefficient values across groups.

Table 4 Summary of ROC analyses

Test	Threshold	AUC (95% CI)	*P* Value
GDT	4.5 s	0.910 (0.822-0.998)	NA
FGA1	4.4 s	0.740 (0.584-0.896)	.039
FGA8	7.9 s	0.925 (0.844-1)	.391
FTSTST	8.7 s	0.846 (0.720-0.973)	.353
hDVAT	3 lines lost	0.831 (0.693-0.97)	.302
vDVAT	3 lines lost	0.861 (0.729-0.993)	.560
COMP	75.7	0.932 (0.861-1)	.676
SOM	98.5	0.406 (0.22-0.593)	<.001

NOTE. These data are based on the statistical considerations for data gathered at time point A in the main study. The *P* values compare the AUC of the GDT to all the other tests using a ROC comparison test.
Abbreviation: NA, not applicable.

The criterion validity of the GDT is excellent. We attribute the discrepancies in the diagnostic performance of the GDT across studies to differences in the vestibular-impaired groups. Adults with chronic unilateral and bilateral vestibular dysfunction were enrolled in the main study, whereas adults with surgically induced, subacute, unilateral involvement comprised the validation cohort.

The GDT has strong convergent validity. Similarly, virtual navigation[67] and self-selected walking speed[68] have been found to be valid measures of spatial memory and gait performance, respectively, in adults with and without vestibular dysfunction. The construct validity of the GDT must be corroborated through correlations with established spatial navigation assessments.[30,32,37,42,69,70]

One must also consider feasibility when deciding whether to use a clinical test.[71] Fritz et al[71] suggest that clinicians need to know whether the test is safe, how easy it is to administer, how easy is it to interpret the results, and if the test is cost effective.

Most patients with vestibular dysfunction can walk short distances over level, indoor surfaces with eyes open unaided. Although walking in the dark (or with eyes closed) is more challenging, participants at site 1 completed FGA8 96% of the time. Thus, the GDT appears to be a safe method of evaluating gait disorientation when conducted by providers who are trained in appropriate guarding techniques.

The GDT could be performed by individuals with a variety of technical and professional backgrounds who have minimal to extensive experience with vestibular-impaired persons. Also, the distance required for the GDT is consistent with the recommended feasible distance for measuring walking speed.[72] Stopwatch and instrumented methods for measuring self-selected walking speed are shown to be highly correlated and not significantly different.[73] We found that diagnostic accuracy for the GDT was similar when stopwatch and instrumented methods were used to measure performance. Thus, using a stopwatch for timing provides a readily available and accurate alternative to instrumented gait testing. Finally, we constructed the GDT using subtraction because we surmised this method would be more easily integrated into clinical practice than calculating a quotient with times.

Because *scoring* of the GDT is accomplished with the start and stop of a stopwatch, interpretation is objective. Determining whether the result is abnormal in this population is uncomplicated

Table 5 Comparison of the diagnostic performance of all screening tests

Test	TP	FP	FN	TN	Sn (95% CI)	Sp 95% CI	DOR (95% CI)	LR+ (95% CI)	LR− (95% CI)
GDT	15	1	5	19	0.75 (0.51-0.91)	0.95 (0.75-1)	57 (6-541.47)	15 (2.18-103.0)	0.26 (0.12-0.9)
GDT (V)	9	3	4	13	0.69 (0.39-0.91)	0.81 (0.54-0.96)	9.75 (1.74-54.52)	3.69 (1.25-10.9)	0.38 (0.16-0.88)
FGA1	17	8	3	12	0.85 (0.62-0.97)	0.60 (0.36-0.81)	8.5 (1.86-38.82)	2.12 (1.2-3.75)	0.25 (0.08-0.8)
FGA8	18	3	2	17	0.90 (0.68-0.99)	0.85 (0.62-0.97)	51 (7.57-343.73)	6 (2.09-17.21)	0.12 (0.03-0.4)
FTSTST	5	0	15	20	0.26 (0.1-0.5)	0.98 (0.8-1)	14.6 (0.75-283.4)	11 (0.65-186.6)	0.76 (0.6-0.98)
hHIT	16	0	4	20	0.79 (0.55-0.93)	0.98 (0.8-1)	150.3 (7.5-2998)	33 (2.11-515.0)	0.2 (0.1-0.5)
HSN	9	0	11	20	0.45 (0.24-0.68)	0.98 (0.8-1)	33.87 (1.8-636.9)	19 (1.18-305.9)	0.56 (0.38-0.8)
hDVAT	14	2	6	18	0.70 (0.46-0.88)	0.90 (0.68-0.99)	21 (3.66-120.37)	7 (1.82-26.89)	0.33 (0.17-0.7)
vDVAT	13	0	7	20	0.64 (0.41-0.84)	0.98 (0.8-1)	73.8 (3.9-1401.6)	27 (1.71-425.4)	0.37 (0.21-0.7)
COMP	17	2	3	18	0.85 (0.62-0.97)	0.90 (0.68-0.99)	51 (7.57-343.73)	8.5 (2.25-32.06)	0.17 (0.06-0.5)
SOM	10	12	10	8	0.50 (0.27-0.73)	0.40 (0.19-0.64)	0.67 (0.19-2.33)	0.83 (0.47-1.47)	1.25 (0.63-2.5)

NOTE. These data are presented as the appropriate value (95% CI) for data collected at time point A in the main study unless otherwise noted. Calculations for the DOR and LR+ were adjusted by adding 0.5 to each cell in the contingency tables for the FTSTST, hHIT, HSN, and vDVAT, because these values would be undefined if they were calculated with *0* values for FP.[61]
Abbreviations: FN, false negative; FP, false positive; Sn, sensitivity; Sp, specificity; TN, true negative; TP, true positive; V, values are from the validation data set.

and is accomplished by comparing the GDT time to the 4.5-second threshold.

Because the GDT is inexpensive, fast, and poses minimal risk when patients are appropriately guarded, whether the GDT proves to be cost-effective will depend largely on how clinicians use it to help guide their decision making and whether patients benefit from interventions offered after testing positive. Recent evidence suggests that early vestibular rehabilitation results in reduced dizziness and more complete functional recovery than the standard of care alone.[74] If the GDT is used as an outcome measure, a change of >3.7 seconds would exceed the measurement error for the test.

Findlay et al[75] provide the only other publication in which similar methods were used to screen patients. Their *walking Romberg sign* was based on comparing the ability of 50 persons with a diagnosis of cervical myelopathy to walk 5 m with eyes open versus their ability to do this task with eyes closed. The criteria for a positive walking Romberg sign were observed swaying, subjective reports of feeling unstable, or the inability to complete the walk with eyes closed. Although just 34% of patients with radiographically confirmed cervical myelopathy had a positive, traditional Romberg sign, 75% of patients were found to have a positive, walking Romberg sign. Our results extend those of Findlay and colleagues by demonstrating that comparing gait with eyes open to eyes closed can discriminate healthy persons from those who have gait disorientation resulting from a loss of sensory input to the central nervous system.

The sensitivity of the GDT (75%) is like that of the walking Romberg sign.[75] Because the criteria for an abnormal GDT is objective, we anticipate that it would have superior reliability compared to the walking Romberg sign. The sensitivity and specificity of detecting vestibular dysfunction with the GDT are comparable to the ability of the Walking Trail-making Test to detect mild cognitive dysfunction,[76] but less robust than the ability to identify impaired spatial navigation in concussed collegiate athletes using a computerized neuropsychological evaluation.[37]

Though walking, eyes closed (FGA8) had 90% sensitivity, there is strong rationale for including walking, eyes open (FGA1). Vestibular loss effects spatial navigation with eyes open and eyes closed.[28,33,46] Conducting the eyes open task may help patients develop the spatial memory needed to complete the eyes closed task[34,43,77-81] and provides clinicians with an objective basis for comparing performance under normal and challenging sensory conditions. Analyzing both the eyes closed task and the difference between the eyes closed and eyes open tasks in parallel yields 98% sensitivity for detecting gait disorientation due to vestibular dysfunction.

Ultimately, the clinical utility of a test relates to its diagnostic accuracy and whether the results lead to large changes from the pretest probability of the outcome of interest to the posttest probability of that outcome.[82] The diagnostic performance of the GDT is comparable to tests that require specialized training and/or costly equipment (hHIT, HSN, DVAT, SOT). The DOR for the GDT suggests that those who had a GDT time >4.5 seconds were 57 times more likely to have peripheral, vestibular dysfunction.

Table 6 Projected posttest probabilities for the gait disorientation test

Setting (Population)	Pretest Probability (%)	Positive Posttest Probability (%)	Negative Posttest Probability (%)
Primary care*	43	92	17
Emergency department*	34	89	12
Dizziness clinic*	46	93	18
Neurology*	49	94	20
General population†	35	89	12

NOTE. Likelihood ratios from the main study were used in these analyses.
* Prevalence based on data from Kroenke et al.[62]
† Prevalence based on data from Agrawal et al.[3]

Although this suggests that the GDT may be clinically valuable,[82] diagnostic accuracy varies by setting and population. Our projections of positive posttest probability suggest that it may be reasonable to expect a ~90% probability of the diagnosis of vestibular dysfunction based on VNG and/or RC tests for a patient who presents to primary care, the emergency department, a dizziness specialty clinic, or neurology; is suspected to have vestibular dysfunction; and has a positive GDT.

Study limitations

Our findings are applicable to adults with and without peripheral vestibular dysfunction; however, there are numerous reasons why a person might have difficulty walking with their eyes closed. Prospective studies of the GDT in persons with visual, somatosensory, auditory, and cognitive-perceptual conditions are needed to assess whether it is broadly applicable. To address potential effects of age on GDT results, future studies should enroll age-matched participants. Finally, though the GDT is feasible, the space requirements for the test may hinder its adoption in some settings.

Conclusion

Our findings demonstrate that the GDT has promising clinical utility. The GDT is a simple metric that health care professionals could easily integrate into the examination of persons with dizziness and imbalance to screen for gait disorientation. Providers may use the threshold of 4.5 seconds for the GDT to help them determine if further workup, referral to specialty providers, and/or vestibular rehabilitation may be indicated.

Suppliers

a. Opal inertial measurement units; APDM, Inc.
b. SOT, Bertec Balance Advantage computerized dynamic posturography device; Bertec Corp.
c. R version 3.5; R Foundation for Statistical Computing.

Keywords

Bilateral vestibulopathy; Rehabilitation; Sensitivity and specificity; Spatial navigation; Vestibular diseases

Corresponding author

Colin R. Grove, PT, DPT, PhD, University of Wisconsin-Madison, School of Medicine and Public Health, Department of Surgery, 6630 University Avenue, Middleton, WI 53562. *E-mail address:* crgrove@wisc.edu.

Acknowledgments

We thank Dr Lee Dibble, PT, PhD, who assisted with the data acquisition and analysis used for the external validation of the GDT. We thank Mr Scott J. Hetzel, MS for his technical assistance with data analysis. We also thank Dr Laura H. Hogan, PhD and Dr Brooke N. Klatt, PT, DPT, PhD, who critically reviewed the manuscript prior to submission.

References

1. Ward BK, Agrawal Y, Hoffman HJ, Carey JP, Della Santina CC. Prevalence and impact of bilateral vestibular hypofunction: results from the 2008 US National Health Interview Survey. JAMA Otolaryngol Head Neck Surg 2013;139:803-10.
2. Blackwell DL, Lucas JW, Clarke TC. Summary health statistics for U.S. adults: national health interview survey, 2012. Vital Health Stat 10 2014:1-161.
3. Agrawal Y, Carey JP, Della Santina CC, Schubert MC, Minor LB. Disorders of balance and vestibular function in US adults: data from the National Health and Nutrition Examination Survey, 2001-2004. Arch Intern Med 2009;169:938-44.
4. Zwergal A, Rettinger N, Frenzel C, Dieterich M, Brandt T, Strupp M. A bucket of static vestibular function. Neurology 2009;72:1689-92.
5. Fukuda T. The stepping test: two phases of the labyrinthine reflex. Acta Otolaryngol 1959;50:95-108.
6. National Institute of. Deafness and Other Communication Disorders. 2017-2021 strategic plan. National Institutes of Health. 2017. Available at: https://www.nidcd.nih.gov/about/strategic-plan/2017-2021-nidcd-strategic-plan. Accessed June 30, 2020.
7. Cohen HS. A review on screening tests for vestibular disorders. J Neurophysiol 2019;122:81-92.
8. Longridge NS, Mallinson AI. The dynamic illegible E-test: a technique for assessing the vestibulo-ocular reflex. Acta Otolaryngol 1987;103:273-9.
9. Brandt T, Schautzer F, Hamilton DA, et al. Vestibular loss causes hippocampal atrophy and impaired spatial memory in humans. Brain 2005;128:2732-41.
10. Black FO, Wall C 3rd, Nashner LM. Effects of visual and support surface orientation references upon postural control in vestibular deficient subjects. Acta Otolaryngol 1983;95:199-201.
11. Tucker CA, Ramirez J, Krebs DE, Riley PO. Center of gravity dynamic stability in normal and vestibulopathic gait. Gait Posture 1998;8:117-23.
12. Halmagyi GM, Curthoys IS, Cremer PD, et al. The human horizontal vestibulo-ocular reflex in response to high-acceleration stimulation before and after unilateral vestibular neurectomy. Exp Brain Res 1990;81:479-90.
13. Hain TC, Fetter M, Zee DS. Head-shaking nystagmus in patients with unilateral peripheral vestibular lesions. Am J Otolaryngol 1987;8:36-47.
14. Romberg MH. A manual for the nervous diseases of man. London: Syndenham Society; 1853.
15. Graybiel A, Fregly AR. A new quantitative ataxia test battery. Acta Otolaryngol 1966;61:292-312.
16. Berg KO, Wood-Dauphinee SL, Williams JI, Maki B. Measuring balance in the elderly: validation of an instrument. Can J Public Health 1992;83(Suppl 2):S7-11.
17. Nashner LM, Peters JF. Dynamic posturography in the diagnosis and management of dizziness and balance disorders. Neurol Clin 1990;8:331-49.
18. Podsiadlo D, Richardson S. The timed "Up & Go": a test of basic functional mobility for frail elderly persons. J Am Geriatr Soc 1991;39:142-8.
19. Shumway-Cook A, Baldwin M, Polissar NL, Gruber W. Predicting the probability for falls in community-dwelling older adults. Phys Ther 1997;77:812-9.
20. Mulavara AP, Cohen HS, Bloomberg JJ. Critical features of training that facilitate adaptive generalization of over ground locomotion. Gait Posture 2009;29:242-8.
21. Harvey SA, Wood DJ, Feroah TR. Relationship of the head impulse test and head-shake nystagmus in reference to caloric testing. Am J Otol 1997;18:207-13.

22. Peters BT, Mulavara AP, Cohen HS, Sangi-Haghpeykar H, Bloomberg JJ. Dynamic visual acuity testing for screening patients with vestibular impairments. J Vestib Res 2012;22:145-51.
23. Cohen HS, Sangi-Haghpeykar H. Subjective visual vertical in vestibular disorders measured with the bucket test. Acta Otolaryngol 2012;132:850-4.
24. Cohen HS, Kimball KT. Usefulness of some current balance tests for identifying individuals with disequilibrium due to vestibular impairments. J Vestib Res 2008;18:295-303.
25. Fregly AR, Graybiel A. Labyrinthine defects as shown by ataxia and caloric tests. Acta Otolaryngol 1970;69:216-22.
26. Longridge NS, Mallinson AI. Clinical Romberg testing does not detect vestibular disease. Otol Neurotol 2010;31:803-6.
27. Peruch P, Borel L, Gaunet F, Thinus-Blanc G, Magnan J, Lacour M. Spatial performance of unilateral vestibular defective patients in nonvisual versus visual navigation. J Vestib Res 1999;9:37-47.
28. Cohen HS. Vestibular disorders and impaired path integration along a linear trajectory. J Vestib Res 2000;10:7-15.
29. Paquet N, Kulkarni K, Fung J, Watt D. Spatial navigation after surgical resection of an acoustic neuroma: pilot study. J Otolaryngol 2003;32:180-4.
30. Schautzer F, Hamilton D, Kalla R, Strupp M, Brandt T. Spatial memory deficits in patients with chronic bilateral vestibular failure. Ann N Y Acad Sci 2003;1004:316-24.
31. Borel L, Harlay F, Lopez C, Magnan J, Chays A, Lacour M. Walking performance of vestibular-defective patients before and after unilateral vestibular neurotomy. Behav Brain Res 2004;150:191-200.
32. Guidetti G, Monzani D, Trebbi M, Rovatti V. Impaired navigation skills in patients with psychological distress and chronic peripheral vestibular hypofunction without vertigo. Acta Otorhinolaryngol Ital 2008;28:21-5.
33. Cohen HS, Sangi-Haghpeykar H. Walking speed and vestibular disorders in a path integration task. Gait Posture 2011;33:211-3.
34. Arthur JC, Kortte KB, Shelhamer M, Schubert MC. Linear path integration deficits in patients with abnormal vestibular afference. Seeing Perceiving 2012;25:155-78.
35. Kremmyda O, Hufner K, Flanagin VL, et al. Beyond dizziness: virtual navigation, spatial anxiety and hippocampal volume in bilateral vestibulopathy. Front Hum Neurosci 2016;10:139.
36. Franke LM, Walker WC, Cifu DX, Ochs AL, Lew HL. Sensorintegrative dysfunction underlying vestibular disorders after traumatic brain injury: a review. J Rehabil Res Dev 2012;49:985-94.
37. Teel E, Gay M, Johnson B, Slobounov S. Determining sensitivity/-specificity of virtual reality-based neuropsychological tool for detecting residual abnormalities following sport-related concussion. Neuropsychology 2016;30:474-83.
38. Beylergil SB, Ozinga S, Walker MF, McIntyre CC, Shaikh AG. Vestibular heading perception in Parkinson's disease. Prog Brain Res 2019;249:307-19.
39. Xie Y, Bigelow RT, Frankenthaler SF, Studenski SA, Moffat SD, Agrawal Y. Vestibular loss in older adults is associated with impaired spatial navigation: data from the triangle completion task. Front Neurol 2017;8:173.
40. Bronstein AM. The visual vertigo syndrome. Acta Otolaryngol Suppl 1995;520:45-8.
41. Bigelow RT, Agrawal Y. Vestibular involvement in cognition: visuospatial ability, attention, executive function, and memory. J Vestib Res 2015;25:73-89.
42. Loomis JM, Klatzky RL, Golledge RG, Cicinelli JG, Pellegrino JW, Fry PA. Nonvisual navigation by blind and sighted: assessment of path integration ability. J Exp Psychol Gen 1993;122:73-91.
43. Philbeck JW, Klatzky RL, Behrmann M, Loomis JM, Goodridge J. Active control of locomotion facilitates nonvisual navigation. J Exp Psychol Hum Percept Perform 2001;27:141-53.
44. Peruch P, Borel L, Magnan J, Lacour M. Direction and distance deficits in path integration after unilateral vestibular loss depend on task complexity. Brain Res Cogn Brain Res 2005;25:862-72.
45. Cohen HS, Kimball KT. Improvements in path integration after vestibular rehabilitation. J Vestib Res 2002;12:47-51.
46. Glasauer S, Amorim MA, Vitte E, Berthoz A. Goal-directed linear locomotion in normal and labyrinthine-defective subjects. Exp Brain Res 1994;98:323-35.
47. Glasauer S, Amorim MA, Viaud-Delmon I, Berthoz A. Differential effects of labyrinthine dysfunction on distance and direction during blindfolded walking of a triangular path. Exp Brain Res 2002;145:489-97.
48. Wrisley DM, Marchetti GF, Kuharsky DK, Whitney SL. Reliability, internal consistency, and validity of data obtained with the functional gait assessment. Phys Ther 2004;84:906-18.
49. Barber HO, Stockwell CW. Manual of electronystagmography. St. Louis: CW Mosby; 1980.
50. Bohannon RW, Bubela DJ, Magasi SR, Wang YC, Gershon RC. Sit-to-stand test: performance and determinants across the age-span. Isokinet Exerc Sci 2010;18:235-40.
51. Feng Y, Schlosser FJ, Sumpio BE. The Semmes Weinstein monofilament examination as a screening tool for diabetic peripheral neuropathy. J Vasc Surg 2009;50:675-682, 682.e1.
52. Paul SS, Dibble LE, Walther RG, Shelton C, Gurgel RK, Lester ME. Reduced purposeful head movements during community ambulation following unilateral vestibular loss. Neurorehabil Neural Repair 2018;32:309-16.
53. World Medical Association. World Medical Association Declaration of Helsinki ethical principles for medical research involving human subjects. J Am Med Assoc 2013;310:2191-4.
54. Powell LE, Myers AM. The Activities-specific Balance Confidence (ABC) scale. J Gerontol A Biol Sci Med Sci 1995;50:M28-34.
55. Jacobson GP, Newman CW. The development of the Dizziness Handicap Inventory. Arch Otolaryngol Head Neck Surg 1990;116:424-7.
56. Mirka A, Black FO. Clinical application of dynamic posturography for evaluating sensory integration and vestibular dysfunction. Neurol Clin 1990;8:351-9.
57. Monsell EM, Furman JM, Herdman SJ, Konrad HR, Shepard NT. Computerized dynamic platform posturography. Otolaryngol Head Neck Surg 1997;117:394-8.
58. Shrout P, Fleiss J. Intraclass correlation: uses in assessing rater reliability. Psychol Bull 1979;86:420-8.
59. Weir JP. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. J Strength Cond Res 2005;19:231-40.
60. DeLong ER, DeLong DM, Clarke-Pearson DL. Comparing the areas under two or more correlated receiver operating characteristic curves: a nonparametric approach. Biometrics 1988;44:837-45.
61. Glas AS, Lijmer JG, Prins MH, Bonsel GJ, Bossuyt PM. The diagnostic odds ratio: a single indicator of test performance. J Clin Epidemiol 2003;56:1129-35.
62. Kroenke K, Hoffman RM, Einstadter D. How common are various causes of dizziness? A critical review. South Med J 2000;93:160-7. quiz 8.
63. Portney LG, Watkins MP. Foundations of clinical research. 2nd ed. New Jersey: Prentice-Hall; 2000.
64. Youdas JW, Atwood AL, Harris-Love MO, Stiller TL, Egan KS, Therneau TM. Measurements of temporal aspects of gait obtained with a multimemory stopwatch in persons with gait impairments. J Orthop Sports Phys Ther 2000;30:279-86.
65. Gould NF, Holmes MK, Fantie BD, et al. Performance on a virtual reality spatial memory navigation task in depressed patients. Am J Psychiatry 2007;164:516-9.
66. Sanders AE, Holtzer R, Lipton RB, Hall C, Verghese J. Egocentric and exocentric navigation skills in older adults. J Gerontol A Biol Sci Med Sci 2008;63:1356-63.

67. Tippett WJ, Lee JH, Mraz R, et al. Convergent validity and sex differences in healthy elderly adults for performance on 3D virtual reality navigation learning and 2D hidden maze tasks. Cyberpsychol Behav 2009;12:169-74.
68. Schmidheiny A, Swanenburg J, Straumann D, de Bruin ED, Knols RH. Discriminant validity and test re-test reproducibility of a gait assessment in patients with vestibular dysfunction. BMC Ear Nose Throat Disord 2015;15:6.
69. Hegarty M, Richardson AE, Montello DR, Lovelace K, Subbiah I. Development of a self-report measure of environmental spatial ability. Intelligence 2002;30:425-48.
70. Lawton CA. Gender differences in way-finding strategies: relationship to spatial ability and spatial anxiety. Sex Roles 1994;30:765-79.
71. Fritz S, Lusardi M. White paper: "walking speed: the sixth vital sign." J Geriatr Phys Ther 2009;32:46-9.
72. Middleton A, Fritz SL, Lusardi M. Walking speed: the functional vital sign. J Aging Phys Act 2015;23:314-22.
73. Martin E, Kim S, Unfried A, et al. 6th vital sign app: testing validity and reliability for measuring gait speed. Gait Posture 2019;68:264-8.
74. Tokle G, Morkved S, Brathen G, et al. Efficacy of vestibular rehabilitation following acute vestibular neuritis: a randomized controlled trial. Otol Neurotol 2020;41:78-85.
75. Findlay GF, Balain B, Trivedi JM, Jaffray DC. Does walking change the Romberg sign? Eur Spine J 2009;18:1528-31.
76. Perrochon A, Kemoun G. The Walking Trail-Making Test is an early detection tool for mild cognitive impairment. Clin Interv Aging 2014; 9:111-9.
77. Israël I, Bronstein AM, Kanayama R, Faldon M, Gresty MA. Visual and vestibular factors influencing vestibular "navigation." Exp Brain Res 1996;112:411-9.
78. Philbeck JW, O'Leary S. Remembered landmarks enhance the precision of path integration. Psicológica 2005;26:7-24.
79. Arthur JC, Philbeck JW, Chichka D. Spatial memory enhances the precision of angular self-motion updating. Exp Brain Res 2007;183: 557-68.
80. Arthur JC, Philbeck JW, Chichka D. Non-sensory inputs to angular path integration. J Vestib Res 2009;19:111-25.
81. Arthur JC, Philbeck JW, Kleene NJ, Chichka D. The role of spatial memory and frames of reference in the precision of angular path integration. Acta Psychol 2012;141:112-21.
82. Guyatt G, Rennie D, Meade MO, Cook DJ. Users' guide to the medical literature: essentials of evidence-based clinical practice. 3rd ed. Chicago: McGraw-Hill Education; 2015.