Published in final edited form as:

Otol Neurotol. 2019 June ; 40(5): 658–665. doi:10.1097/MAO.0000000000002173.

Screening for vestibular disorders using the modified Clinical Test of Sensory Interaction and Balance and Tandem Walking with eyes closed

Helen S. Cohen, EdD, OTR⁽¹⁾, Ajitkumar P. Mulavara, PhD⁽²⁾, Jasmine Stitz, MS⁽³⁾, Haleh Sangi-Haghighpeykar, PhD⁽⁴⁾, Susan P. Williams, MD⁽⁵⁾, Brian T. Peters, PhD⁽²⁾, and Jacob J. Bloomberg, PhD⁽⁶⁾

⁽¹⁾Bobby R Alford Department of Otolaryngology – Head and Neck Surgery, Baylor College of Medicine, Houston, TX

⁽²⁾KBRwyle, Houston, TX

⁽³⁾Department of Medical Engineering, University of Applied Sciences/ Upper Austria, Linz, Austria

⁽⁴⁾Department of Obstetrics and Gynecology, Baylor College of Medicine, Houston, TX,

⁽⁵⁾Department of Medicine, Baylor College of Medicine, Houston, TX

⁽⁶⁾Neuroscience Laboratories, NASA/ Johnson Space Center

Introduction

Dizziness is a common complaint, particularly in people aged 65 years and older ^{1–4}. Many such complaints are probably cardiovascular in nature but vestibular disorders are also common ⁵. Vestibular disorders are notoriously difficult to distinguish due to vague language, the multifactorial nature of much dizziness ⁶, and the paucity of well-validated screening tests. Thus, improving the available screening tests would help primary care physicians determine the need for specialty care referrals, and would help non-physician clinicians to screen patients and provide data to physicians who must make referral decisions. Better tests would also help to determine the effects of intervention.

Balance tests, such as the Romberg test, have been used for many years to screen people for vestibular disorders ^{7,8}. On a computerized Romberg test with dynamic support surface movement, the Sensory Organization Test (SOT), with large, expensive equipment, decreased responses on some conditions are consistent with vestibular disorders ^{9,10}. The Romberg test, simplified as the Clinical Test of Sensory Interaction on Balance (CTSIB) ^{11,12}, has become widely used among occupational and physical therapists. Although technologically simpler than SOT, CTSIB is challenging and may detect subtle balance problems. For example, patients with benign paroxysmal positional vertigo (BPPV) may appear to have normal balance but many of them have impaired SOT performance pre-

treatment¹³. In these patients CTSIB is more sensitive than the SOT¹⁴. Sharpening SOT and CTSIB by including conditions with head movements^{14–16}, makes each test battery more challenging for subjects who can pass the test with the head stationary¹⁷. CTSIB has been used in a study of the United States population as the main measure of vestibular function¹⁸. It has also been used as one of several dependent measures in studies of the general population and the HIV/AIDS populations^{19,20}. Those studies used norms that were developed with relatively small sample sizes^{12,16}.

Walking balance is often tested with tandem walking (TW)^{21,22}. Standing and walking balance differ^{23,24}, as the control of balance and mobility require different mechanisms for static and dynamic balance^{25–27}. Clinicians frequently test standing and walking. When astronauts were screened with both types of tests after exposure to microgravity sensitivity and specificity increased²⁸.

This study had several goals: 1) to sharpen CTSIB by developing norms on a larger sample than previous work^{12,16}, which was more likely to be representative of the general population, especially with test conditions involving head movements; 2) to determine which subtests best identified patients with vestibular disorders; 3) to clarify differences in sensitivity and specificity among age groups; 4) to determine if CTSIB trials, combined with TW performed with eyes closed, is more useful for screening than any one of the CTSIB trials or the TW test alone.

Materials and Methods

Subjects

Newly recruited subjects included 292 healthy controls (181 females, 111 males, mean age 55.1 yrs., SD 18.9 yrs., range 21–95 yrs.) and 90 patients (54 females, 36 males, mean age 59.7 yrs., SD 14.4 yrs., range 24–88 yrs.). They were free of known neurologic and significant musculoskeletal impairments and could walk unassisted without a cane. Control subjects had no significant otologic disease. They were recruited from among staff, students at this institution and visitors in our waiting room.

Patients had been diagnosed with vestibular impairments by board-certified physicians, mostly otolaryngologists and neurologists: unilateral vestibular weakness (UW) (n=33), unilateral BPPV of a posterior semicircular canal (n= 28), dual diagnoses, UW and BPPV (n=8), Meniere's disease (n=7), vestibular migraine (n=3), pre-operative acoustic neuroma (n=5), post-operative acoustic neuroma (n=2), bilateral vestibular weakness (n=2), dual diagnoses BPPV and migraine (n=2). BPPV patients had unilateral, classical responses to Dix-Hallpike maneuvers, and the physicians had ruled out other diagnoses. UW patients all had at least a 20% weakness on bi-thermal caloric testing with water, recorded with infra-red video-oculography. Some patients also had decreased vestibulo-ocular reflex responses to low frequency sinusoidal rotations in darkness and impaired cervical vestibular-evoked myogenic potentials. Bilateral vestibular weakness patients had total bi-thermal caloric responses less than 24°/sec and reduced gains on low frequency sinusoidal rotations in darkness.

All subjects gave written informed consent prior to participating. The study was approved by the Institutional Review Board for the senior author's institution.

Methodology

Tests were performed in a well-lighted room with a vinyl tile floor. Subjects wore socks but no shoes. Every subject wore two lightweight inertial motion units (IMU; Xsens North America, Inc.) 5.25 X 3.75 X 2 cm, weight 28.3 g, centered on the head with a headband and centered on the back at mid-torso with a lightweight vest. To cue head motions during head movement trials, subjects heard an auditory signal that oscillated at 0.33 Hz, with the sound varying between 170 and 450 Hz at a comfortable intensity level, via the amplifier on a tablet computer. The subject was trained to oscillate his head left-right (yaw) or up-down (pitch) at 0.33 Hz, so that as he heard the high sound (450 Hz) his head reached the maximum point upward or to one side and as he heard the low sound (170 Hz) his head reached the lowest point downward or to the other side.

For all CTSIB trials, subjects stood on SunMate medium density, compliant foam, PSI = 93, 71 X 62 X 10 cm, with a 2 mm polyurethane (Skinsoft) coating on one side (Dynamic Systems, Inc, Leicester, NC, sunmatecushions.com). They stood with feet adjacent and arms crossed, initially with eyes open for at least 10 seconds. They were guarded by a staff member, for safety. The trial began when they closed their eyes. Trial duration was a maximum of 30 seconds but was shorter if the subject opened his eyes, moved his arms, took a step, or leaned so far that he was unable to stay upright, slipped, and was caught by the staff member or leaned against the wall. Usually, some or all of those events happened simultaneously. Trial 1 was performed with the head stationary (still). Trials 2 and 3 were performed with the head moving in yaw (head yaw), i.e. leftward-rightward, and head moving in pitch (head pitch), i.e., upward-downward, respectively, in time to the tone. Prior to Trials 2 and 3 each subject practiced head movements in time with the tone, with eyes open while standing on the floor.

Dependent measures were trial duration (seconds), number of head movements during Trials 2 and 3, and kinematic measures derived from the torso-mounted IMU data including resultant acceleration, angular velocity about the roll axis, angular velocity about the pitch axis, and angular velocity about the yaw axis¹⁴. Kinematic measures were used for Trials 2 and 3 if the head-mounted IMU data indicated that the subject made at least 5 head movement cycles during the trial. For head stationary tests, parameters were calculated for each anticipated cycle of head motion and were computed based on an assumed periodicity of 3 seconds (frequency=0.33 Hz). Kinematic parameters were calculated to quantify sway in the mediolateral and anteroposterior directions for the trunk¹⁶.

Subjects all performed the TW test during the same session, too. They took 5 practice steps of heel-to-toe walking with their arms crossed and eyes open²⁹ and then took 3 to 4 practice steps with eyes closed. TW, itself, involved taking 10 tandem steps with eyes closed and arms crossed. The dependent measure considered in this paper was just the total number of correct tandem steps taken out of 10, as reported previously²⁴; that measure is used in this paper for the combined analysis with the CTSIB data set.

Statistical methods

Least squares regression analysis was used to examine the association between age and variables of interest: (trial duration, head still, yaw and pitch). Patients and controls were compared by logistic regression analysis for estimation of area under the curve (AUC), i.e. receiver operative characteristics (ROC), and corresponding sensitivity/specificity/likelihood ratios for various cut-points. Mixed methods analysis was used for comparing patients and controls on various conditions.

The same data could be considered as the likelihood of obtaining a true positive (a response that is correctly interpreted as consistent with an abnormality), a false positive (a response that is incorrectly interpreted as consistent with an abnormality), a false negative (a response that is incorrectly interpreted as consistent with a normal system) or a true negative (a response that is correctly interpreted as consistent with a normal system), based on the cut-points. True positives, i.e. sensitivity, correctly identify patients; true negatives, i.e. specificity, correctly identify controls. Thus 1.0 would mean perfect sensitivity or specificity. To present a measure of combined sensitivity and specificity, we also provide likelihood ratio+ (sensitivity/(1-specificity)) for the optimal test combinations. A positive likelihood ratio indicates how much the odds of the disease increases when a test is positive.

Analyses were performed in SAS statistical software (version 9.4, Cary, NC). To increase the sample size with available data, we added some data from a previous study¹⁶ to the dataset, including 54 UW patients, 18 post-operative acoustic neuroma patients, and 68 controls. These subjects had been tested on the same CTSIB battery. Including these subjects yielded a total sample size of 360 controls and 162 patients. Increasing the sample size improved precision of our estimated ROC values by up to 4%, by reducing the width of the corresponding 95% confidence intervals.

Results

CTSIB trial duration

Initially, control and patient subjects' data were examined separately to determine age-related inflection points. Age-related decrements in trial duration were found in all three conditions, $p < 0.001$. See Figure 1. Slopes were: for head stationary, $-.36$; for head moving in yaw, $-.30$; for head moving in pitch, $-.31$. See Table 1 for normative CTSIB data for all age decades.

With all ages combined in each group, i.e., healthy controls and patients, controls performed the tests for significantly longer than patients, $p < 0.0001$ for each test condition. See Table 2.

Patients and controls were then examined to determine ROC values, sensitivity and specificity. Based on the analyses of controls' data and a common-sense approach 20-year age groups were used for the three younger groups; subjects aged 80 years were considered separately. Some subjects volunteered the comment that the head stationary condition was easier to perform than the head yaw and pitch conditions. See Table 3. ROC values were moderate for young subjects and slightly higher for middle-aged and older

subjects. The ROC values for subjects in the oldest group should be interpreted with caution due to the smaller sample of patients.

The head movement trials seemed equally challenging. Some subjects performed abnormally on only the yaw or the pitch condition. To save time, clinicians might prefer to give only one head movement test. Therefore, using the established cut-points in Table 3 we recalculated ROC values, sensitivity and specificity to determine if they change when both tests are given and only one test has an abnormal result. ROC values were slightly higher when both subtests were taken into account. Sensitivity improved for the three younger groups, but specificity decreased. See Table 3.

To reduce confusion, Table 3 also shows the results as true and false positives. Sensitivity indicates the percent of true positives; specificity indicates the percent of true negatives. The percentages of false negatives and false positives, i.e. the chance of incorrect identification of patients and controls, respectively, are included for comparison.

CTSIB head movements

ROC values, sensitivity and specificity were also examined for the number of head movements during the yaw and pitch head movement trials. ROC values were only 0.75 (yaw) and 0.71 (pitch). Sensitivity/ specificity were similarly only moderate at best for yaw (0.87/ 0.40) and for pitch (0.70/ 0.34). When ROC values were calculated for the number of head movements combined with trial duration the improvement to ROC values was slight for some age groups and ROC decreased for some age groups.

CTSIB kinematics

Few subjects could generate at least 5 complete head rotations in the yaw (controls: 126/292, patients: 10/90) and pitch (controls: 126/292, patients: 15/90) trials. Therefore, the sample size for kinematic measures was reduced. In general, no significant differences were found between control and patient groups at any ages. Thus, in our opinion, the kinematic measures had limited use for screening patients in this paradigm.

CTSIB data combined with TW data

Results from TW tests, described previously ²⁴, showed ROC values and sensitivity and specificity similar to the CTSIB data. Based on that work and previous work with post-flight astronauts ²⁸, we tested the hypothesis that higher values would be obtained if the CTSIB trials and the TW data were used in combination. To obtain ROC values for a combination of both CTSIB and TW, we combined the current CTSIB data and TW (n=292 controls, 90 patients) by trying various combinations of trials from the CTSIB and the first trial of TW with eyes closed.

The CTSIB head stationary condition was easy to perform for most younger adults and some subjects with vestibular disorders. Therefore, to simplify the analyses, the data from the head still condition were not used in the combined analyses. The ROC values were higher when both head movement trials for CTSIB were combined with TW or if just yaw was combined with TW. ROC values were slightly lower when CTSIB head pitch was combined with TW.

When the ages were combined, ROC values decreased. Thus, the age groups should be separated. Because using just one CTSIB head movement trial was as good as using both head movement trials, Table 4 shows the data for only TW plus CTSIB head yaw, with sensitivity and specificity, and cut-points. With TW and CTSIB together, positive likelihood ratios ranged from 2.0 to 3.5 for various age groups (Table 4), indicating odds for disease increases 2 to 3.5 times with a positive test for different age groups.

Discussion

ROC values increased when CTSIB trials or CTSIB and TW tests were combined. Thus, then using more than one test increases the likelihood of determining the presence of a vestibular disorder. Because people are variable, even in patients with the same diagnoses, some people performed CTSIB with pitch well but not CTSIB with yaw, or vice versa. Similarly, some subjects could perform CTSIB well but not TW, or they could perform TW well but not CTSIB; some subjects performed all trials poorly. The differences were not related to any obvious differences in scores on objective diagnostic tests. Individual differences beyond the scope of this study may account for those differences, such as variations in vestibular perception^{30–32}. Because the test is affected by head rotation our findings support recent work indicating that performance indicates semicircular canal inputs to postural control³³.

The age-related changes in test performance support previous studies showing age-related changes in balance skills, including an epidemiologic study using CTSIB performed with the head still/ eyes closed¹⁸. That study used older cut-points to define normals without regard to age¹². We know now that age affects performance on this test so control and patient groups in that study may not have been well defined. The present study extends those findings with more detailed data about cut-points for controls vs. patients and about head movement trials. Having an objective basis for assessing people in every decade is important for providing good clinical care. Thus, Table 1 should be particularly useful for clinicians.

CTSIB conditions using yaw pitch and head movements had greater ROC values and higher sensitivity than the head stationary condition, especially in the groups aged 40 to 79. The tests were not very good for screening younger adults, probably because they have more physical resources to draw upon, such as greater strength and flexibility. In other words, the tests were too easy for them.

These tests take less than 5 minutes. They involve minimal technology, only a stopwatch or stopwatch app on a smart phone and an inexpensive (less than \$50) slab of foam. Ancillary staff, e.g. nurses or medical assistants, can be trained easily to give these tests. The data are easily interpreted and should be useful for clinical decision-making in conjunction with a brief history and the physician's clinical exam. If a patient has a history of vertigo, has responses within normal ranges on the rest of the clinical exam, and has scores that are more than one standard deviation below the mean for the relevant age group, referral for objective diagnostic tests, e.g. bi-thermal caloric tests, should be considered.

These tests are easily administered with a simple clinical protocol. Have the patient sit down and remove her shoes. Then, stand up and with eyes open and arms crossed, practice 5 to 10 steps of tandem walking. Then, having passed through the first stage of motor learning, i.e. “getting the idea of the movement”³⁴ the patient can be asked to perform tandem walking with eyes closed. Both trials of TW, together, should take no more than 30 seconds. Then the patient can be asked to step up on to a piece of medium density foam -- placed in a corner of the room for safety, with eyes open, and she can be given a few second to learn how to stand on the foam for stage 1 of motor learning ³⁴. Then, the patient can be asked to perform CTSIB with head still. If she fails the test with head still, no further testing is needed. If she performs the test within the normal range for her age, she should be asked to step off, and practice the head movements in yaw and pitch, and the step back onto the foam, relax with eyes open, and then close her eyes and perform the yaw trial with eyes closed. If she fails the test, no more testing is needed. If she passes the test at the age-appropriate duration, she should be asked to perform the pitch trial. The CTSIB trials should take no more than 2.5 minutes, total. These tests can be administered by a trained medical assistant and then interpreted by the professional.

We grouped together patients with subacute and chronic conditions, with different diagnoses, to simulate a realistic clinical caseload. Patients in the community often visit a primary care physician, non-physician provider such as a physician assistant or nurse practitioner, or a general otolaryngologist or neurologist after their acute symptoms have subsided. In residential facilities or home health care patients are seen first by a nurse and sometimes by an occupational or physical therapist prior to referral to the primary care physician or general otolaryngologist, who might then refer to neurotology. Some of those care providers may be unable to make a diagnosis. Nevertheless, they need tools with which to obtain valid, objective data for clinical decision-making. Similarly, in an initial visit the neurotologist needs valid, objective data for screening. In these commonplace scenarios the diagnosis will be unknown; the duration of symptoms may also be unknown.

This study had several limitations. We had more female than male subjects. Vestibular disorders are more common in women than men ^{35–38}. Women are more likely than men to escort patients to visits to our clinics, as either paid caregivers or family members, and we recruited many control subjects from among clinic visitors. Recruiting more males was impossible in the time available. The oldest group had fewer subjects because many potential subjects had comorbidities that precluded participation. Finding more elderly subjects, especially patients, would have taken several years. These tests are not designed to screen for other health conditions that cause “dizziness,” i.e., we have no data on the effect of cardiovascular or respiratory problems on test performance. TW, however, is useful for screening patients who have peripheral neuropathy ²⁹.

We used only one trial of each condition. Therefore we have no data about test-retest variability. Some patients may improve from Trial 1 to Trial 2. For that reason, some clinics use two trials. Our data do not provide guidance about differences in cut-points when more than one trial is used. We suggest using the cut-point for the appropriate age group with one trial.

Thus, this quick, low-tech test battery yields good data for screening adults for vestibular disorders. Sensitivity improves when both CTSIB and TW are used. The tests are easily administered by ancillary staff and quickly interpreted in conjunction with a history and physical exam.

Acknowledgements:

The authors thank Chris Miller, KBRwyle; and the staffs of the Center for Balance Disorders and the Geriatric Medicine Clinic, Baylor College of Medicine, for their assistance.

Funding/Support: NIH grant 2R01DC009031 (HSC), National Space Biomedical Research Institute through NASA NCC 9–58 (APM, JJB), and a fellowship from the Austria Marshall Plan Foundation (JS).

References

1. Aggarwal NT, Bennett DA, Bienas JL, Mendes de Leon CF, Morris MC, Evans DA. The prevalence of dizziness and its association with functional disability in a biracial community population. *Journal of Gerontology: A Biological Sciences and Medical Sciences* 2000;55:M288–M292.
2. Sheldon JH. *The social medicine of old age: report of an inquiry in Wolverhampton* London: Oxford University Press; 1948.
3. Sloane PD. Dizziness in primary care. Results from the National Ambulatory Medical Care Survey. *Journal of Family Practice* 1989;29:323–338.
4. Stevens K, Lang IA, Guralnik JM, Melzer D. Epidemiology of balance and dizziness in a national population: findings from the English Longitudinal Study of Ageing. *Age and Ageing* 2008;37:300–305. [PubMed: 18270246]
5. Maarsingh OR, Dros J, Schellevis FG, van Weert DA, ter Riet G, van der Horst HE. Causes of persistent dizziness in elderly patients in primary care. *Annals of Family Medicine* 2017;8:196–205.
6. Kao AC, Nancarrow A, Williams CS, M.E. T. Validation of dizziness as a possible geriatric syndrome. *J Am Geriatr Soc* 2001;49:72–75. [PubMed: 11207845]
7. Zamysłowska-Smytko E, Szustek-Rogula S, Sliwinska-Kowalska M. Bedside examination for vestibular screening in occupational medicine. *International Journal of Occupational Medicine and Environmental Health* 2015;28:379–387. [PubMed: 26182932]
8. Lanska DJ. The Romberg sign and early instruments for measuring postural sway. *Seminars in Neurology* 2002;22:409–418. [PubMed: 12539062]
9. Nashner LM, Black FO, Wall C III. Adaptation to altered support and visual conditions during stance: patients with vestibular deficits. *J Neurosci* 1982;2:536–544. [PubMed: 6978930]
10. Nashner LM. Computerized dynamic posturography: clinical applications. In: Jacobson GP, Newman CW, Kartush JM, eds. *Handbook of Balance Function Testing* St. Louis, MO: Mosby-Year Book; 1993:308–334.
11. Shumway-Cook A, Horak FB. Assessing the influence of sensory interaction on balance. *Phys Ther* 1986;66(10):1548–1550. [PubMed: 3763708]
12. Cohen H, Blatchly CA, Gombash LL. A study of the Clinical Test of Sensory Interaction and Balance. *Phys Ther* 1993;73:346–351. [PubMed: 8497509]
13. Cohen HS, Kimball KT. Effectiveness of treatments for benign paroxysmal positional vertigo of the posterior canal. *Otol Neurotol* 2005;26:1034–1040. [PubMed: 16151355]
14. Mulavara AP, Cohen HS, Peters BT, Sangi-Haghpeykar H, Bloomberg JJ. New analyses of the Sensory Organization Test compared to the Clinical Test of Sensory Integration and Balance in patients with benign paroxysmal positional vertigo. *Laryngoscope* 2013;123:2276–2280. [PubMed: 23553110]
15. Wood SJ, Paloski WH, Clark JB. Assessing sensorimotor function after long-duration spaceflight with computerized dynamic posturography. *Aviat Space Environ Med* 2015;86:A45–A53.

16. Cohen HS, Mulavara AP, Peters BT, Sangi-Haghpeykar H, Bloomberg JJ. Standing balance tests for screening people with vestibular impairments. *Laryngoscope* 2014;124:545–550. [PubMed: 23877965]
17. Paloski WH, Wood SJ, Feivson AH, Black FO, Hwang EY, Reschke MF. Destabilization of human balance control by static and dynamic head tilts. *Gait Posture* 2006;23:315–323. [PubMed: 15961313]
18. Agrawal Y, Carey JP, Hoffman HJ, Sklare DA, Schubert MC. The modified Romberg Balance Test: normative data in U.S. adults. *Otol Neurotol* 2011;32:1309–1311. [PubMed: 21892121]
19. Cohen HS, Cox C, Springer G, et al. Prevalence of abnormalities in vestibular function and balance among HIV-seropositive and HIV-seronegative women and men. *PLoS One* 2012;7:e3841.
20. Cohen HS, Mulavara AP, Sangi-Haghpeykar H, Peters BT, Bloomberg JJ, Pavlik V. Screening people in the waiting room for vestibular impairments. *Southern Med J* 2014;107:549–553. [PubMed: 25188617]
21. Fregly AR, Graybiel A. Labyrinthine defects as shown by ataxia and caloric tests. *Acta Otolaryngologica* 1970;69:216–222.
22. Graybiel A, Fregly AR. A new quantitative ataxia test battery. *Acta Otolaryngologica* 1966;61:292–312.
23. Cohen HS, Mulavara AP, Peters BT, Sangi-Haghpeykar H, Bloomberg JJ. Tests of walking balance for screening vestibular disorders. *J Vestib Res* 2012;22:95–104. [PubMed: 23000609]
24. Cohen HS, Stitz J, Sangi-Haghpeykar H, et al. Tandem walking as a quick screening test for vestibular disorders. *The Laryngoscope* 2017;in press.
25. Mulavara AP, Cohen HS, Bloomberg JJ. Critical features of training that facilitate adaptive generalization of over ground locomotion. *Gait Posture* 2009;29:242–248. [PubMed: 18838271]
26. Schubert TE, Schrodt LA, Mercer VS, Busby-Whitehead J, Giuliani CA. Are scores on balance screening tests associated with mobility in older adults? *Geriatric Physical Therapy* 2006;29:33–39.
27. Kang HG, Dingwell JB. A direct comparison of local dynamic stability during unperturbed standing and walking. *Exp Brain Res* 2006;172:35–48. [PubMed: 16432700]
28. Cohen HS, Kimball KT, Mulavara AP, Bloomberg JJ, Paloski WH. Posturography and locomotor tests of dynamic balance after long-duration spaceflight. *J Vestib Res* 2012;22:191–196. [PubMed: 23142833]
29. Cohen HS, Mulavara AP, Peters BT, et al. Sharpening the tandem walking test for screening peripheral neuropathy. *Southern Med J* 2013;106:565–569. [PubMed: 24096950]
30. Miller MA, Crane B. Static and dynamic visual vertical perception in subjects with migraine and vestibular migraine. *World Journal of Otorhinolaryngology - Head and Neck Surgery* 2016;2:175–180. [PubMed: 28782063]
31. Karmali F, Bermudez Rey MC, Clark TK, Wang W, Merfeld DM. Multivariate analyses of balance test performance, vestibular thresholds, and age. *Front Neurol* 2017;8:578. [PubMed: 29167656]
32. Bermudez Rey MC, Clark TK, Wang W, Leeder T, Bian Y, Merfeld DM. Vestibular perceptual thresholds increase above the age of 40. *Front Neurol* 2016;7:162. [PubMed: 27752252]
33. Anson E, Bigelow RT, Studenski S, Deshpande N, Agrawal Y. Failure on the Foam Eyes Closed test of standing balance associated with reduced semicircular canal function in healthy older adults. *Ear Hearing* 2018;20:in press.
34. Gentile AM. A working model of skill acquisition with application to teaching. *Quest* 1972;17:3–23.
35. Wojtczak R, Narozny W, Kuczkowski J, Siebert J. Epidemiology of dizziness in northern Poland - the first Polish neurotologic survey of the general population. *Annals of Agricultural and Environmental Medicine* 2017;24:502–506. [PubMed: 28954498]
36. Neuhauser HK, von Brevern M, Radtke A, et al. Epidemiology of vestibular vertigo: a neurotologic survey of the general population. *Neurology* 2005;65:898–904. [PubMed: 16186531]
37. Lai YT, Wang TC, Chuang LJ, Chen MH, Wang PC. Epidemiology of vertigo: a National Survey. *Otolaryngology - Head and Neck Surgery* 2011;145:110–116. [PubMed: 21493319]

38. Bisdorff A, Bosser G, Gueguen R, Perrin P. The epidemiology of vertigo, dizziness, and unsteadiness and its links to co-morbidities. *Front Neurol* 2013;4(#29).

Author Manuscript

Author Manuscript

Author Manuscript

Author Manuscript

Figure 1.

Age-related changes in trial duration by controls. Head still, head moving in yaw, head moving in pitch. Maximum trial duration was 30 seconds.

Table 1.

Normative data for subjects by age decade and head movement condition on foam with eyes closed and arms crossed, N=292 healthy controls: mean (time in seconds); mean $\pm$ standard deviation, range minimum to maximum

Age decade	Head movement trial condition		
	Stationary	Yaw	Pitch
21–29 (N=40)	29.3 $\pm$ 2.80, 17.14 to 30	23.4 $\pm$ 0.05, 4.0 to 30	23.2 $\pm$ 9.3, 4.1 to 30
30–39 (N=37)	26.7 $\pm$ 8.3, 0 to 30	24.23 $\pm$ 9.03, 3.1 to 30	24.7 $\pm$ 9.2, 3.7 to 30
40–49 (N=40)	26.5 $\pm$ 7.5, 4.2 to 30	21.40 $\pm$ 9.87, 3.4 to 30	21.9 $\pm$ 9.4, 4.7 to 30
50–59 (N=41)	24.3 $\pm$ 9.7, 2.9 to 30	19.55 $\pm$ 3.89, 4.3 to 30	19.3 $\pm$ 10.2, 2.6 to 30
60–69 (N=52)	17.5 $\pm$ 12.0, 0 to 30	11.62 $\pm$ 9.0, 2.0 to 30	14.3 $\pm$ 9.4, 3.5 to 30
70–79 (N=50)	15.9 $\pm$ 11.6, 0 to 30	13.2 $\pm$ 10.52, 0 to 30	12.1 $\pm$ 9.5, 0 to 30
80–89 (N=32)	6.7 $\pm$ 7.1, 1.5 to 30	6.4 $\pm$ 4.7, 1.4 to 22.5	5.2 $\pm$ 3.2, 0.5 to 15

Table 2.

CTSIB conditions, data for head stationary, moving in yaw and in pitch; mean times (sec), (Standard errors) for patient and control subjects by subtests.

Head movement	Healthy Controls	Patients
Stationary	20.98 (0.48)	11.85 (0.87)
Yaw	16.85 (0.48)	8.42 (0.87)
Pitch	16.92 (0.48)	8.95 (0.87)

Table 3.

CTSIB conditions, data for head stationary, moving in yaw and moving in pitch, including historical data ¹⁶, divided into age groups. N, sample size.

Age (yrs.)	Test conditions	ROC	Identify patients		Identify controls		Recommended cut-point (sec)
			Sensitivity (% true +)	% false –	% false +	Specificity (% true –)	
21 to 39 (N=114)	Stationary	0.67	0.47	0.53	0.13	0.87	30
40 to 59 (N=164)	Stationary	0.74	0.67	0.33	0.30	0.70	30
60 to 79 (N=208)	Stationary	0.72	0.62	0.38	0.38	0.62	7.5
80 (N=36)	Stationary	0.68	0.67	0.33	0.29	0.71	3.2
21 to 39	Yaw	0.61	0.71	0.29	0.39	0.61	29.5
40 to 59	Yaw	0.84	0.81	0.19	0.22	0.78	10.5
60 to 79	Yaw	0.81	0.75	0.25	0.30	0.70	5.2
80	Yaw	0.92	1.0	0	0.18	0.88	2.4
21 to 39	Pitch	0.61	0.59	0.41	0.31	0.69	24.8
40 to 59	Pitch	0.78	0.75	0.25	0.21	0.79	10.7
60 to 79	Pitch	0.73	0.67	0.33	0.36	0.64	7.0
80	Pitch	0.88	1.00	0	0.21	0.79	3.0
21 to 39	Abnormal pitch or yaw	0.65	0.81	0.19	0.54	0.47	
40 to 59	Abnormal pitch or yaw	0.88	0.93	0.71	0.38	0.62	
60 to 79	Abnormal pitch or yaw	0.85	0.95	0.48	0.48	0.53	
80	Abnormal pitch or yaw	0.93	1.00	0	0.30	0.70	

Table 4.

ROC, sensitivity, specificity and Positive Likelihood Ratio (LR+) with combinations of age, TW and CTSIB head yaw (Y) and pitch (P). Cut-points shown for CTSIB duration, and the number of correct tandem steps (#TW steps) ⁴⁰.

Analyses	Age groups (yrs.)	ROC	Sensitivity	Specificity	LR+	Cut-point, CTSIB trial dur (sec)	Cut-point, # TW steps
TW + CTSIB, P, Y or P+Y	21 to 39	0.80	1.00	0.51	2.0	<22.0	<7
	40 to 59	0.86	0.89	0.69	3.0	<7.0	<2
	60 to 79	0.84	0.85	0.76	3.5	<3.0	<2
	80	0.97	1.00	0.70	3.3	<2.5	<1
Y+TW	21 to 39	0.80				<22.0	<7
	40 to 59	0.86				<7.0	<2
	60 to 79	0.84				<3.0	<2
	80	0.98				<2.5	<1
P+TW	21 to 39	0.77				<22.0	<7
	40 to 59	0.87				<7.0	<2
	60 to 79	0.82				<3.0	<2
	80	0.90				<2.5	<1
Y+ P + TW	21 to 39	0.80				<22.0	<7
	40 to 59	0.88				<7.0	<2
	60 to 79	0.85				<3.0	<2
	80	0.79				<2.5	<1
Y+ P + TW	Ages combined	0.79					
Y+TW	Ages combined	0.78					
P+TW	Ages combined	0.77					