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Standing Balance Tests for Screening People With Vestibular Impairments

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Objectives/Hypothesis: To improve the test standards for a version of the Romberg test and to determine whether measuring kinematic variables improved its utility for screening.

Study Design: Healthy controls and patients with benign paroxysmal positional vertigo, postoperative acoustic neuroma resection, and chronic peripheral unilateral weakness were compared.

Methods: Subjects wore Bluetooth-enabled inertial motion units while standing on the floor or medium-density, compliant foam, with eyes open or closed, with head still or moving in pitch or yaw. Dependent measures were time to perform each test condition, number of head movements made, and kinematic variables.

Results: Patients and controls did not differ significantly with eyes open or with eyes closed while on the floor. With eyes closed, on foam, some significant differences were found between patients and controls, especially for subjects older than 59 years. Head movement conditions were more challenging than with the head still. Significantly fewer patients than controls could make enough head movements to obtain kinematic measures. Kinematics indicated that lateral balance control is significantly reduced in these patients compared to controls. Receiver operator characteristics and sensitivity/specificity analyses showed moderately good differences with older subjects.

Conclusions: Tests on foam with eyes closed, with head still or moving, may be useful as part of a screening battery for vestibular impairments, especially for older people.

Key Words: Balance testing, screening, Romberg, vestibular testing.

Level of Evidence: 3b

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INTRODUCTION

For many years variations of the Romberg test have been used for screening balance problems,[1] including vestibular disorders. Computerized versions show significant differences between normals and patients with vestibular disorders,[2] especially the Sensory Organization Test (SOT) of computerized dynamic posturography. That equipment, however, is not suitable for clinics with small equipment budgets or for situations requiring rapid screening.[3,4] The less precise Clinical Test of Sensory Interaction and Balance (CTSIB), described for use by therapists,[5] is portable and inexpensive. Preliminary norms based on a small sample showed age-related changes.[6] Subsequent work verified that for older subjects, standing on compliant foam with eyes closed is more challenging than with eyes open on foam or the floor, and subjects display greater postural sway.[7,8] Recent work suggests that although CTSIB resembles SOT in some ways, it is more challenging.[9]

For some years the National Health and Nutrition Examination Survey collected data on CTSIB.[10] Normative values were reported for subjects aged 40 to $\geq$80 years and showed some age-related changes, but the sample size per age decade and the upper end of the age range were not reported.[11] We collected a smaller sample of controls but with a broader age range, plus kinematic data on postural sway. Also we compared controls to patients with vestibular disorders to obtain cut-points that, for the first time, were determined statistically rather than arbitrarily.

MATERIALS AND METHODS

Subjects

Subjects included asymptomatic healthy controls, and three groups of patients with known vestibular impairments:

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Preliminary analyses were presented as posters at the Association for Research in Otolaryngology MidWinter Meeting, Baltimore, Maryland, U.S.A., February 20, 2011, and the Society for Neuroscience Annual Meeting, Washington, District of Columbia, U.S.A., November 15, 2011.

Data were collected at the Bobby R. Alford Department of Otolaryngology–Head and Neck Surgery, Baylor College of Medicine.

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unilateral benign paroxysmal positional vertigo of the posterior semicircular canal (BPPV) prior to treatment with repositioning maneuvers, unilateral peripheral vestibular weakness (UW) excluding Ménière disease and migraine; and postoperative acoustic neuroma (AN) patients at least 3 months postsurgery. Controls were recruited from staff and visitors to the laboratory and were screened with a health history, head impulse tests, observation of gait, and Dix–Hallpike maneuvers. All subjects were independently ambulatory, had no joint replacements or history of neurologic disease, and had functional vision with their corrective lenses.

All patients were diagnosed by board-certified physicians, mostly otolaryngologists and neurologists on the faculty of Baylor College of Medicine. BPPV patients were diagnosed based on a positive response to the Dix–Hallpike maneuver and any other clinical and laboratory tests used by the physician. UW patients all had at least a 20% weakness on bithermal caloric testing. Some patients also had decreased vestibulo-ocular reflex responses to low-frequency sinusoidal rotations in darkness and/or impaired vestibular-evoked myogenic potentials.

This study was approved by the institutional review board for human subjects research for Baylor College of Medicine and affiliated hospitals. Subjects gave informed consent prior to participation.

Materials and Equipment

To obtain kinematic data during testing, each subject wore a lightweight vest with an inertial motion sensor (IMU; Xsens North America, Los Angeles, CA) measuring 5.25 × 3.75 × 2 cm and weighing 28.3 g, centered on the back at the midthoracic level, and a plastic headband with another IMU. To cue head motions during head movement trials, subjects heard a 0.33-Hz frequency-modulated auditory signal that oscillated between 170 and 450 Hz at a comfortable intensity level, via an iPod (Apple, Cupertino, CA) attached to external amplifiers placed on a desktop or clipped to the safety vest and heard via an earbud.[9] They were instructed to move their heads in time with the tone, and the staff member demonstrated making upward pitch when the tone was highest and downward pitch when the tone was lowest, simultaneously saying, "Move your head in time with the tone like this: up, down, up, down." For tests on foam, subjects stood on Sunmate medium-density foam measuring 96 × 62 × 10 cm (Dynamic Systems, Leicester, NC).

Procedure

Subjects arrived wearing a variety of shoes, from stiletto heels to flip-flops. To standardize footwear and maintain good hygiene subjects wore socks without shoes.[9] We loaned athletic socks to subjects who arrived without socks. They were tested in a quiet room with industrial carpeting. Subjects were guarded during all trials. For every trial they were instructed to stand quietly with feet together and arms crossed, for up to 30 seconds.[6,9] A trial ended if the subject took a step, moved one or both arms, or, for tests with eyes closed, if the subject opened his eyes. To avoid a possible learning effect, each subject had only one trial per condition. The time to complete the trial was recorded in seconds.

The 12 subtests were given to all subjects in the same order, in increasing order of difficulty: on the floor before on the foam; with eyes open before with eyes closed. Tests were given without augmented head motions (head still) before being given with yaw head rotations (yaw) and then with pitch head rotations (pitch). Initially, the patient groups and 10 control subjects per decade from ages 21 to 79 years were tested on all conditions. Later, to increase the sample size and improve statistical power on the more challenging conditions, which showed greater variability, 24 more normal subjects aged 24.9 to 78.8 years and 24 UW patients aged 27.1 to 75.5 years were added to the eyes closed/foam (ECF)/head still (ECF still) and eyes closed/foam/head pitch (ECF pitch) conditions. To avoid fatiguing our subjects who were older than 80 years, after ascertaining that they could perform the condition on the floor with eyes open, they were tested only on the ECF still and ECF pitch conditions.

Kinematic data from the torso-mounted IMU were analyzed if data from the head-mounted IMU indicated that subjects made five or more head movement cycles. For head still conditions, the vector indices for each anticipated cycle of head motion were computed based on an assumed periodicity of 3 seconds (frequency = 0.33 Hz). Parameters were calculated to quantify sway in the mediolateral and anteroposterior directions for the trunk. The root mean squares of five balance parameters were calculated: anteroposterior acceleration (AX), mediolateral acceleration (AY), roll angular velocity (R), pitch angular velocity (P), and yaw angular velocity (Y).

Statistical Analyses

Patients and controls were compared on changes in the dependent measures of interest as a function of various conditions by multilevel statistical techniques.[12] PROC GLIMMIX in SAS (SAS Institute, Cary, NC) was used to fit generalized linear mixed models and to estimate the parameters by maximum likelihood. A separate model was fitted to each dependent variable (time to perform the task, number of head movements, and kinematic variables). For each model, within-subject (condition) and between-subjects (groups) effects were tested. Interaction effects were included in each model and tested. Akaike information criterion, Bayesian information criterion, and −2 log likelihoods were used to assess model fit. Adjustments were made for multiple comparisons. To determine whether any test is useful in identifying people with vestibular disorders and to determine the optimal cut-point on each test, we performed logistic regression and receiver operating characteristic (ROC) analyses by age groups (21–59 and 60–79 years) and provided corresponding sensitivity and specificity values for various cutoffs. $P < .05$ was considered statistically significant. All kinematics analyses were adjusted for age. All analyses were performed using SAS statistical software, version 9.3.

RESULTS

The final sample included 156 controls, 18 AN subjects, 21 BPPV subjects, and 51 UW subjects; 27 UW subjects performed all conditions, 24 UW additional subjects performed tests on the three most challenging conditions. Controls included 24 subjects each in groups aged 21 to 29 and 30 to 39 years, 23 aged 40 to 49 years, 22 aged 50 to 59 years, 25 aged 60 to 69 years, 27 aged 70 to 79 years, and 11 aged 80 to 89 years (elderly). Male and female controls did not differ on any head movement conditions (Table I).

Time, Less Challenging Conditions

For tests performed on the floor with eyes open, no significant differences were found between controls and patient groups, among patient groups, or among age groups. For tests on foam with eyes open/head still, no significant differences were found between controls and

TABLE I. Demographic Details of the Study Sample.			
Group	Age, yr	Sex	Length of Illness, yr
Controls, n = 156	52.8 (18.0, 23.3–89.5)	80 M, 76 F	
AN, n = 18	55.2 (10.8, 35.2–72.9)	6 M, 12 F	5.5 (5.8, 0.27–27)
BPPV, n = 21	58.8 (11.7, 34.7–78.8)	10 M, 11 F	0.28 (0.45, 0.03–1.63)
UW, n = 51	55.1 (15.6, 21.4–75.5)	19 M, 32 F	4.0 (9.0, 0.07–40)

Mean age (standard deviation, range); number of males (M) and females (F); and mean time that UW and BPPV patients reported having illness or length of time postoperatively for AN patients (standard deviation, range).

AN = acoustic neuroma; BPPV = benign paroxysmal positional vertigo; n = number of subjects; UW = unilateral weakness.

the combined patient group; for head pitch, controls and patients differed significantly ($P = .015$). Patients stood for significantly longer with head still than head pitch ($P = .01$) or head yaw ($P = .01$; Table II).

For tests on the floor with eyes closed, significant differences ($P = .01$) were found between UW patients and controls with head still, pitch, and yaw. AN and BPPV subjects did not differ from controls (Table II). The differences between groups for conditions on the floor were not strong enough to consider for use as a screening test. Therefore the rest of the data analysis is presented only for the ECF conditions.

Time, More Challenging Conditions With Eyes Closed on Foam

For head still and head pitch, a significant effect of age was found for controls ($P < .001$), such that time was relatively stable until approximately age 59 years, decreased significantly to age 79 years, and then decreased significantly again for subjects in their 80s. Consistent with this pattern, significant differences were found among the three age groups at $P < .0001$ for head still and at least $P < .01$ for head pitch (Fig. 1). All elderly controls could stand on the floor with feet together for practice trials. Because clinicians see patients in this age range, the reference values may be useful. Those data are shown in Table III. Paired comparisons showed that the time scores for head still and head pitch did not differ significantly.

Time, with eyes closed on foam and head still. For ECF still, controls performed all trials for significantly longer than the patient groups combined ($P < .0001$). AN patients approached performing the task for significantly less time than the UW ($P = .056$) or BPPV ($P = .09$) groups. The BPPV and UW groups did not differ significantly. For the combined patient groups compared to normal subjects, the significant odds ratio (OR) = 0.93, 95% confidence interval (CI) = 0.90–0.95, $P < .0001$ (Fig. 2).

The ROC value was weak: ROC = 0.73. Adjusting for age improved the odds ratio and ROC values very slightly: OR = 0.92, 95% CI = 0.88–0.95, $P < .0001$, ROC = 0.75. Without the BPPV subgroup, the OR and ROC values for the combined AN and UW group were slightly stronger: OR = 0.90, 95% CI = 0.865–0.937, $P < .0001$, ROC = 0.78. ROCs for the age groups of 21 to 59 years and 60 to 79 years were 0.72 and 0.79, respectively. Table IV shows the best pairs of sensitivity and specificity values.

Time, with eyes closed on foam and head yaw. For ECF/head yaw controls performed the test for significantly longer than the combined patient group ($P < .0001$). Time was significantly reduced compared to

TABLE II.
Time to Perform the Test, Eyes Open and Eyes Closed, on the Floor and on Foam.

	On the Floor			On Foam		
Group	Still	Pitch	Yaw	Still	Pitch	Yaw
Eyes open						
Controls	30 (0, 30)	30 (0, 29.9–30)	30 (0, 30)	30 (0, 29.9–30)	30 (0, 30)	29.6 (2.9, 7.5–30)
AN	30 (0, 30)	30 (0, 30)	30 (0, 30)	30 (0, 30)	28.1 (6.2, 4.5–30)	26.4 (8.4, 4.1–30)
BPPV	30 (0, 30)	30 (0, 30)	30 (0, 30)	30 (0, 30)	30 (0.1, 29–6–30)	28.1 (5.8, 9.1–30)
UW	30 (0, 30)	30 (0, 30)	30 (0, 30)	30 (0, 30)	27.0 (7.4, 7.7–30)	29.0 (3.7, 13.0–30)
Eyes closed						
Controls	30 (0.1, 29.5–30)	30 (0, 30)	30 (0, 30)	24.4 (10, 2.4–30)	20.5 (10.4, 2.3–30)	19.8 (10.4, 2.6–30)
AN	30 (0, 30)	29.2 (3.5, 15.3–30)	29.1 (4.0, 13.2–30)	8.4 (8.3, 2.5–30)	5.9 (6.3, 2.5–30)	6.7 (6.7, 2.7–30)
BPPV	30 (0, 30)	30 (0, 30)	30 (0, 30)	14.4 (11.3, 2.1–30)	11.3 (9.9, 3.1–30)	12.3 (9.5, 2.6–30)
UW	28.4 (5.6, 7.2–30)	28.4 (5.9, 7.6–30)	27.4 (7.6, 2.7–30)	14.9 (11.7, 1.6–30 7.7–30)	9.7 (9.1, 1.8–30)	10.3 (10.0, 2.1–30)

Head movement conditions are head still, head pitch, and head yaw. Means (standard deviation, ranges). Controls are aged 21 to 79 years. Data for elderly controls, aged ≥80 years, are shown separately for conditions on foam with eyes closed.

AN = acoustic neuroma; BPPV = benign paroxysmal positional vertigo; UW = unilateral weakness.

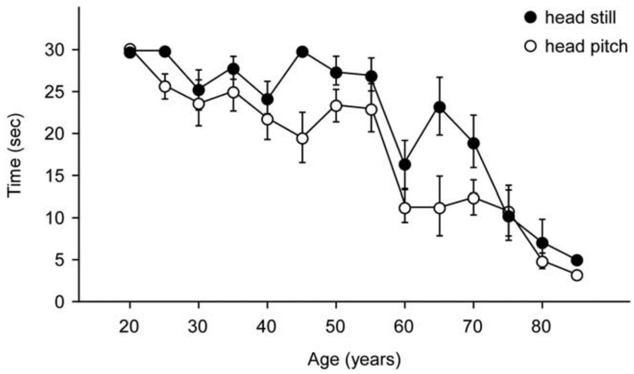

Fig. 1. Mean time scores of normal controls on head still and head pitch trials on foam with eyes closed across the age range in 5-year increments. Error bars represent standard errors.

ECF still ($P < .0001$), but was not significantly different from ECF pitch. Within the patient subgroups, the BPPV and AN groups approached significant differences ($P < .06$), but no other paired comparisons showed any differences (Table II).

Time, with eyes closed on foam and head pitch. For ECF pitch using the combined patient groups compared to controls, the significant OR = 0.91 (95% CI = 0.88–0.94) and ROC = 0.77 ($P < .0001$). Adjusting for age improved the OR and ROC values slightly: OR = 0.895, 95% CI = 0.857–0.93, $P < .001$, ROC = 0.78. Without the BPPV subgroup, the OR for the combined AN and UW group was stronger: OR = 0.87, 95% CI = 0.82–0.91, $P < .001$, ROC = 0.82. Table III shows the best sensitivity/specificity pairs by age. ROCs for age groups of 21 to 59 years and 60 to 79 years were 0.80 and 0.84, respectively (i.e., better for older subjects). Table IV shows that the best cut-point for the older group is lower than for the younger group; the exact cut-point depends on the evaluator's concern for sensitivity or specificity. Table III summarizes the recommended cutoff scores for normal subjects aged 21 to 79 years and lists the descriptive statistics of elderly subjects aged ≥80 years. The clinician may use these values during clinical testing.

Analysis of Head Movement, With Eyes Closed on Foam

Due to a technical issue, no kinematic data were recorded from one UW subject. Table V indicates the percentage of subjects per group who could perform enough head movements. Controls were significantly more likely than the total patient group to be able to perform at least five cycles of head motions ($P \leq .0003$).

TABLE III.
Summary Table of Time Cutoff Scores Recommended for Clinical Testing.

Group	Head Still, s	Head Pitch, s
Younger	29.8	29.9
Older	8.1	5.9
Elderly	7/4.1 (8.9, 2.0–30)	4.7/3.4 (2.6, 2.1–9.8)

Recommended cut-points from ROC analyses are shown for younger subjects (aged 21–59 years) and older subjects (aged 60–79 years). Scores for elderly control subjects aged ≥80 years are shown as mean/median (standard deviation, range).

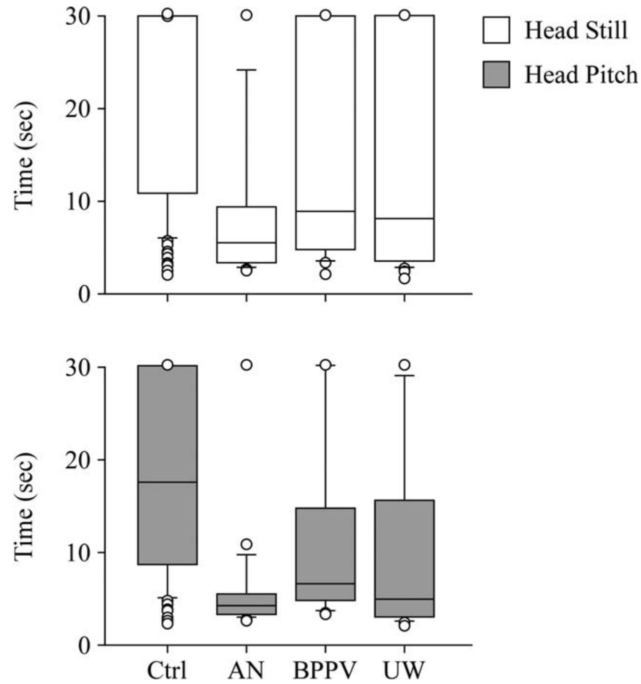

Fig. 2. Time scores of controls and patient groups on foam with eyes closed. (Top) Head still condition. (Bottom) Head pitch condition. Center horizontal bars represent medians; rectangle ends are interquartile ranges, error bars are 10th and 90th, and circles are outliers. AN = acoustic neuroma; BPPV = benign paroxysmal positional vertigo; Ctrl = control; UW = unilateral weakness.

Kinematic Analyses of Trunk Movement, With Eyes Closed on Foam

For AX, controls and patients did not differ significantly with the head still or moving. Within the controls and within the patients, scores with head still differed from scores with head pitch ($P < .04$ to $P < .03$). For AY, controls and patients differed significantly regardless of head movement condition. For AY, within groups, both the control group and the patient group differed between head still and pitch conditions ($P = .001$ and $P = .01$, respectively). Data from normal subjects were not significantly correlated with age (Table VI).

For R with head still, controls did not differ significantly from BPPV patients but did differ significantly from the combined UW/AN group ($P = .02$). Controls did not differ significantly from the combined patient group during head pitch. When the BPPV group was combined with the UW/AN group with head still, controls differed significantly from patients ($P = .02$), but the groups did not differ with head pitch. Controls differed between the head still and head pitch conditions ($P = .03$), and the BPPV group differed between head still and head pitch ($P = .05$), but the combined UW/AN group did not differ significantly between head still and head pitch. Data from normal subjects were not significantly correlated with age.

TABLE IV.
Sensitivity, Specificity, and Related Cut-Points (Time in Seconds) for Eyes Closed on Foam, Head Still and Head Pitch, by Age Group.

	Still			Pitch		
Group	Sensitivity	Specificity	Cut-Point	Sensitivity	Specificity	Cut-Point
Aged 21–59 years, n = 123	0.50	0.99	9.8	0.81	0.58	24.8
	0.55	0.83	29.8*	0.82	0.54	29.9*
	1.0	0	30.0	1.0	0	30
Aged 60–79 years, n = 75	0.70	0.71	6.6	0.78	0.82	5.3
	0.83	0.58	8.1*	0.83	0.79	5.9*
	0.91	0.51	10.55	0.87	0.48	8.8

Three different combinations of sensitivity/specificity/cut-points are shown for each condition and age group so that the reader can see the range of values.
*Best cut-point per condition based on best sensitivity/specificity combinations.
n = number of subjects, controls, and patients combined.

For P, controls differed from the combined patient group ($P < .0001$); controls differed within themselves between head still and pitch ($P = .0025$). No other differences were found. For Y, controls differed significantly between head still and pitch ($P = .01$). No other significant differences were found. Thus, across the five kinematic variables, the parameters of sway in the mediolateral plane showed significant differences between controls and patients as well as among patient groups, indicating that lateral balance control is significantly reduced in these patient groups compared to normal subjects.

ROC values for kinematic measures were not strong (<0.80). When the best ROC values in kinematic measures were combined with the ROC values for time to perform the task, the ROC values were all <0.77. Therefore, sensitivity and specificity values were not computed.

DISCUSSION

The goal of this study was to improve the usefulness of the CTSIB for screening standing balance in people suspected of having vestibular impairments, in general. The analyses of the diagnostic subgroups were secondary and exploratory, and should be considered with caution.

Time

The finding of age-related changes on the time performing the test confirms and extends the earlier work.[6,13,14] Unlike previous studies that arbitrarily divided the age range into equal age bins, we allowed the data, shown in Figure 1, to dictate the cuts in the age range. This process provided three groups of different sizes—ages 21 to 59, 60 to 79, and ≥80 years—but the members within the groups were statistically similar. A larger sample might have allowed for finer-grained analyses and might have found more subgroups. Thus, adding to the normal database may be a focus of future work.

The finding that the conditions with eyes closed on foam are the most sensitive to patients replicates previous work. We have extended this work by examining more challenging conditions with head moving in yaw and pitch. As Table IV shows, using time as the dependent measure, ECF pitch is the condition most likely to differentiate patients from controls, for subjects aged 60 to 79 years, because that condition has the best combination of sensitivity and specificity. The conditions on the floor and with eyes open are too easy for many patients, especially younger people.

TABLE V.
Percentages of Subjects per Group Who Could Perform at Least Five Cycles of Head Movements on Foam With Eyes Closed: Head Still, Head Pitch, Head Yaw.

Group	Still	Pitch	Yaw
Normal controls	85	57	39
BPPV	73	19	19
AN	32	5	16
UW	67	24	6

AN = acoustic neuroma; BPPV = benign paroxysmal positional vertigo; UW = unilateral weakness.

TABLE VI.
Kinematic Data for Eyes Closed on Foam, Head Still and Head Moving in Pitch, for Controls and Patient Groups.

Measure	Head Condition	Controls	AN	BPPV	UW
AX, m/s^2	Still	0.15 (0.12)	0.22 (0.16)	0.18 (0.10)	0.12 (0.30)
	Pitch	0.18 (0.07)	0.50*	0.30 (0.13)	0.21 (0.13)
AY, m/s^2	Still	0.18 (0.13)	0.27 (0.17)	0.24 (0.12)	0.26 (0.25)
	Pitch	0.20 (0.10)	0.51*	0.34 (0.13)	0.24 (0.19)
R, rad/s	Still	0.04 (0.04)	0.06 (0.03	0.06 (0.05)	0.08 (0.12)
	Pitch	0.05 (0.03)	0.15*	0.09 (0.05)	0.06 (0.40)
P, rad/s	Still	0.04 (0.04)	0.07 (0.04)	0.05 (0.03)	0.09 (0.18)
	Pitch	0.07 (0.03)	0.27*	0.13 (0.09)	0.07 (0.03)
Y, rad/s	Still	0.05 (0.04)	0.06 (0.03)	0.06 (0.02)	0.08 (0.08)
	Pitch	0.06 (0.03)	0.12*	0.08 (0.03)	0.07 (0.05)

Data are shown as means (standard deviation).
*Represents only one subject.
AN = acoustic neuroma; AX = RMS anteroposterior acceleration; AY = RMS mediolateral acceleration; BPPV = benign paroxysmal positional vertigo; P = RMS pitch angular velocity; R = RMS roll angular velocity; RMS = root mean square; UW = unilateral weakness; Y = RMS yaw angular velocity.

ECF still is challenging but not as challenging as ECF pitch. Also, controls aged 60 to 79 years had poorer specificity with head still than with head pitch. These findings are supported by previous work in the literature; Jacobson et al. reported poor sensitivity and specificity for eyes open and eyes closed conditions with head still.[15]

Analysis of Head Movements

The finding that patients could perform a reduced number of head movements is relatively new, supports our previous study,[9] and provides another measure that clinicians can use during testing. Similar to the finding regarding time, as shown in Table V the number of head movements is a more challenging measure, especially in ECF pitch. This measure is easily observed in the clinic during head pitch and can augment testing. For example, a strong 65-year-old male might perform the condition for 9 seconds but might make only three head motions. Thus, he would be considered abnormal.

The finding that the patient groups had difficulty performing head motions is consistent with the underlying pathophysiology. Even the head still conditions were challenging for some subjects, and many of these subjects could not perform enough head movements. The differences among the subgroups in time and number of head movements are interesting, but the subgroup sizes were too small to draw any conclusions. Future research might address this problem.

Kinematics of Trunk Movements

As expected, we found kinematic differences between the patients and controls with increased scores on kinematic variables in the patient groups. Previous work showed increased trunk sway and other parameters in patients compared to controls,[7,16–18] but we had different percentages of subjects who provided kinematic data. Notably, our patient groups differed from controls in maintaining mediolateral stability. This finding has implications for performance of functional motor skills. Thus, if the necessary hardware and software are available, kinematics provide a useful third level of analysis. These data should be interpreted with caution, however, due to the decreased sample size.

CONCLUSION

Time is a good primary measure, especially for older subjects. The ability to make at least five cycles of head movements during each ECF condition is a good secondary measure. If the equipment is available, kinematics are useful tertiary measures. The data from controls indicate that a few false postives might still be detected. Balance screening with CTSIB is useful to indicate vestibular function and perhaps to indicate functional skill. It is very inexpensive and useful where computerized dynamic posturography is not available. It should not, however, be the only determinant of whether someone has normal vestibular function. Other screening measures should also be used.

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