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The relevance of clinical balance assessment tools to differentiate balance deficits

M. MANCINI, F. B. HORAK

Balance Disorder Laboratory
Oregon Health and Sciences
University, Beaverton, OR, USA

Control of balance is complex and involves maintaining postures, facilitating movement, and recovering equilibrium. Balance control consists of controlling the body center of mass over its limits of stability. Clinical balance assessment can help to assess fall risk and/or determine the underlying reasons for balance disorders. Most functional balance assessment scales assess fall risk and the need for balance rehabilitation but do not differentiate types of balance deficits. A system approach to clinical balance assessment can differentiate different kinds of balance disorders and a physiological approach can determine underlying sensorimotor mechanisms contributing to balance disorders. Objective measures of balance using computerized systems and wearable inertial sensors can bring more sensitive, specific and responsive balance testing to clinical practice.

Key words: Postural balance - Movement - Motor skills.

One-third to one-half of the population over age 65 reports some difficulties with balance or ambulation. Patients with neurological or musculoskeletal disorders are even more likely to have balance problems that affect their safe mobility. The complexity of balance control results in many different types of balance problems that need systematic clinical assessment for effective treatment.

Balance is achieved by the complex integration and coordination of multiple body systems including the vestibular, visual, auditory, motor, and higher level premotor systems. Information from sensory systems is interpreted in the central nervous system based on an internal body schema, an appropriate response is formulated, and the postural muscle synergies are activated to perform the appropriate head, eye, trunk, and limb movements to maintain posture.[1-4]

Maintaining balance encompasses the acts of maintaining, achieving or restoring the body center of mass relative to the base of support, or more generally, within the limits of stability.[5, 6] The functional goals of the balance system includes: 1) maintenance of a specific postural alignment, such as sitting or standing; 2) facilitation of voluntary movement, such as the movement transitions between postures, and 3) reactions that recover equilibrium to external disturbances, such as a trip, slip, or push.

It is important to remember that intact balance control is required not only to maintain postural stability but also to assure safe mobility-related activities during daily life, such as standing while performing manual tasks, rising from a chair, walking and turning. Disorders of balance can be of the result of pathologies, such as neurological disease, sensory deficits or muscle weakness. The postural control system can also be affected by aging (decline in muscle strength, sensory functioning, or in speed of sensorimotor responses), reaching an optimum in early adult life and deteriorating from approximately the age of 50 onwards.[7, 8]

A comprehensive clinical balance assessment is important for both diagnostic and therapeutic reasons in clinical practice. Balance disorders can have serious

Corresponding author: F. B. Horak, PhD, Professor of Neurology, Balance Disorders Laboratory, Oregon Health and Science University, 505 NW 185th Ave, Beaverton, OR 97209, USA. E-mail: horakf@ohsu.edu

consequences for physical function (leading to fall-related injuries) as well as social function (fear of falls leading to activity restriction and social isolation). Falls and immobility to avoid falls are associated with significant morbidity, trauma, inactivity and depression. For these reasons, the impact of balance disorders is enormous, both for affected individuals (markedly diminished quality of life) and for society at large. Thus, a comprehensive clinical assessment of balance is important for both diagnostic and therapeutic purposes in clinical practice.[9, 10]

This review does not intend to provide a comprehensive list of all available balance assessment tools, but rather summarizes the most commonly used approaches to assess balance, discusses the advantages and limitations of each, and presents new computerized tools to objectively and quantitatively evaluate balance and mobility performance in a clinical setting.

Balance evaluation

The primary purposes of clinical balance assessments are: 1) to identify whether or not a balance problem exists and 2) to determine the underlying cause of the balance problem. It is helpful to determine whether a balance problem exists in order to predict risk of falls and to determine effectiveness of intervention. Balance assessment tools that differentiate among types and reasons for balance problem can help directing in the type of intervention for more effective management or treatment of the balance disorder. Ideally, quantitative, norm-referenced tools to assess postural control in the clinic should include measures that are: 1) reflective of both the functional capabilities and quality of postural strategies; 2) sensitive and selective for postural control abnormalities; 3) reliable and valid, and 4) practical, *i.e.*, easy to use and inexpensive.[2]

Clinical balance assessments can be divided into three main approaches: functional assessments, systems/physiological assessments, and quantitative assessments.[1]

Functional assessments

Functional balance tests are helpful to document balance status and changes with intervention. Functional balance tests usually rate performance on a set of motor tasks on a three to five point scale or use a stop-watch to time how long the subject can maintain balance in a particular posture.[1] Table I summarizes commonly used specialized clinical tests to assess balance with their advantages and disadvantages.

The Activities of Balance Confidence (ABC) is a useful questionnaire that evaluates self-perceived balance confidence while attempting 16 different activities of daily living. However, it has been shown to relate better to what activities people actually avoid than to future falls.[21]

The Tinetti Balance and Gait Test [14] is the oldest clinical balance assessment tool and the widest used among older people.[22] The advantages of Tinetti's balance assessment tool are its inclusion of both balance and gait and its good inter-rater reliability (85% agreement between raters) and excellent sensitivity (93% of fallers are identified).[23, 24] However, many items are difficult to assess on a three-point scale and it has poor specificity (only 11% of non-fallers were identified). Despite being widely used in gerontology, the gait section is seldom used and it has ceiling effects for younger people with balance deficits.[22]

In contrast to the Tinetti's test, the inter-rater reliability of the Berg Balance Scale is excellent but its sensitivity is poor to moderate.[12, 25] The BBS was also developed for older people, in whom a score >45 was related to a low risk of fall history.[26] However, a recent study showed that a change of eight points is required to reveal a clinically significant change in function among non self-sufficient older people in activities of daily living.[22] The BBS is easy to use and can be performed in only 10 to 15 minutes, but uncertainty between two close scores is frequent. It has also been validated for vestibular and poststroke patients who can walk independently,[24] although with poor sensitivity.[22]

The Timed "Up and Go Test" (TUG),[15] is the shortest, simplest clinical balance test, and probably the most reliable because it uses agreement in stop-watch durations rather than rating scales.[22] The TUG is widely used because of the ease with which it can be performed in the clinic.[27] In addition, the TUG test has been shown to predict risk of falls in the elderly.[28, 29] The TUG duration correlates with severity of moderate-to-severe Parkinson's disease,[30, 31] and is sensitive to therapeutic intervention in Parkinson's disease subjects [32] but is not sensitive to early PD.[33] Recently, the TUG has been modified to add a secondary task. The TUG cognitive consists of completing the TUG while counting backward from a number between 80 and 100 and the TUG manual consists of completing the TUG while carrying a cup of water. A score of 15 seconds on the

TABLE I.—*Commonly used specialized clinical tests to assess balance.*

Scales	Advantages	Disadvantages
Activities-Specific Balance Confidence Scale (ABC; Powell and Meyers, 1995) [11] 16-item questionnaire in which respondents rate their confidence that they can maintain their balance in the course of daily activities. Items are rated from 0% (no confidence) to 100% (complete confidence) and averaged.	– Relates to activities subjects actually perform – Only 15 minutes – Good test-retest reliability (ICC ranging from 0.7 to 0.92)	– Not objective – No identification of the type of balance problem – Not related to falls
Berg Functional Balance Scale (Berg *et al.*1992, 1996) [12, 13] Clinicians rate 14-item functional activities including sitting, standing, and postural transitions. Items scored from 0 to 4 points with a maximum score of 56. A score less than 45 is associated with increased risk of falling.	– Only 15 minutes to perform – High inter-rater reliability (98% agreement) – Good specificity (96% of non-fallers were classified correctly)	– Poor sensitivity (only 53% of fallers were identified) – Ceiling effect – No identification of the type of balance problem – No dynamic balance during gait or sensory conditions
Tinetti Balance and Gait Assessment (Tinetti, 1986) [14] Clinicians rate a 14-item balance and 10-item gait test. Predicts elderly individuals who will fall at least once during the following year. Maximum score is 40. Individuals scoring less than 36 are at greater risk of falling.	– Only 20 minutes to perform – Good inter-rater reliability (85% agreement) – Good sensitivity (93% of fallers were identified)	– Poor specificity (only 11% of non-fallers were identified) – Ceiling effect – No identification of the type of balance problem
Timed Up and Go (TUG) (Mathias, 1986) [15] A stop-watch is used to measure the duration of functional task performed at a comfortable rate: from sitting in a chair, stand up, walk 3 m, turn around, walk back, and sit down. Participants taking longer than 13.5 to complete the TUG are at increased risk for falls.	– Only 3 minutes to perform – Widely used because simple – Excellent inter-rater (ICC=0.99) and test-retest (ICC=0.99) reliability. – Predicts falls – Correlated with the Berg Balance Scale (r=–0.72) and the Barthel Activities of Daily Living Index (r=–0.51)	– Ceiling effect – Not comprehensive, only 1 functional task – No identification of the type of balance problem
One-leg stance (Fregly, 1968) [16] Performed with eyes open and arms on the hips, the participants must stand unassisted on one leg and is timed in seconds from the time one foot is flexed off the floor to the time when it touches the ground or the standing leg or an arm leaves the hips. Participants unable to perform the one-leg stand for at least 5 s are at increased risk for injurious fall.	– Only one minute to perform and score – Good Inter-rater reliability (ICC=0.75 in older without disability and ICC=0.85 in older with disability. – Inter-subject reliability ICC=0.73.	– Only one task of static balance is evaluated – No identification of the type of balance problem – Not continuously related to falls
Functional reach (Duncan *et al.* 1990) [17] Objectively assesses limits of stability by measuring the maximal distance a person can reach beyond the length of their arm while maintaining a fixed base of support in the standing position. A reach less than or equal to 6 inches predicts fall.	– Only one minute to perform and score – Excellent predictive validity of subjects at risk of falls – Good inter-rater reliability (ICC=0.98) and test-retest reliability (ICC=0.92).	– Only one task is evaluated – Not related to CoM or CoP limits of stability – No identification of the type of balance problem
Balance Evaluation Systems Test (BESTest; Horak *et al.*, 2009) [18, 19] Consists of 36 items, grouped into six systems: "Biomechanical Constraints", "Stability Limits/ Verticality", "Anticipatory Postural Adjustments", "Postural Responses", "Sensory Orientation", and	– Determines the underlying causes of balance deficits, focusing on systems – Focuses treatment based on different types of balance problems – Good inter-rater reliability (ICC=0.91 – Correlation with ABC Scale was r=.636, P<.01	– Long to perform: 30 min – No studies of fall risk – Equipment is needed – Short version (10 min, miniBESTest) now available

(Continued)

TABLE I.—*Commonly used specialized clinical tests to assess balance. (Continued)*

Scales	Advantages	Disadvantages
"Stability in Gait". Each item is scored on a 4-level, ordinal scale from 0 (worst performance) to 3 (best performance). Scores for the total test, as well as for each section, are provided as a percentage of total points.		
Physiological Profile Approach (PPA) (Lord, 1996) [20] Consists of simple, clinical tests of vision, cutaneous sensation of the feet, leg muscle force, step reaction time, and postural sway. Composite PPA scores below 0 indicate a low risk for falling, scores between 0 and 1 indicate a mild risk for falling, scores between 1 and 2 indicate a moderate risk for falling, and scores above 2 indicate a high risk for falling.	– Determine the underlying physiological causes of the balance deficits – Accuracy of 75% in classifying subjects into a multiple falls group - Test-retest reliability 0.51 to 0.97 (ICC) – Inter-rater reliability OK (ie; 0.70 for proprioception and 0.81 for tactile sensitivity)	– Long to perform: 30 min – Equipment is needed – Imprecise measure of physiological mechanisms – Not measuring functional tasks or balance control systems

TUG- cognitive and 14.5 seconds on the TUG-manual is associated with increased risk of falls. The clinical success of the TUG is likely related to sequencing of several important mobility skills, such as turning and sit-to-stand transitions that require balance control, as well as straight-ahead gait.[34] However, the TUG suffers from the same limitations as the other functional clinical scales, since it is not possible to separate which balance and gait subcomponents are affected.[33]

One-leg stance duration is the oldest reported test of balance and it has normative data available from the military.[16, 35] One-leg stance with eyes closed is too difficult and variable in people without obvious balance disorders to serve as a useful clinical test so the eyes open version is generally used. Advantages of the one-leg stance test are 1) excellent reliability because a stop-watch is used to evaluate performance with specific criteria for stopping the timed test and 2) continuous outcomes from 0-30 s. The disadvantage is the difficulty of the test and limitation to evaluation of static balance control.[18]

The Functional Reach Test was developed to evaluate the maximum limits of stability in stance.[17] Subjects are asked to reach as far forward as they can while standing independently. Reaching in the lateral and backwards directions have also been added. Although thought to represent how far subjects can move their center of body mass over their base of foot support, laboratory measurements have shown that the center of mass displacement is not well correlated with the functional reach distance, probably because of the availability of compensatory strategies to reach involving the scapular-shoulder complex.[36] Nevertheless, the forward functional reach performance can predict fall risk.[37]

Clinical assessments of balance are easy to use, do not require expensive equipment, are usually quick to administer, and have also been shown to predict fall risk and, thus, need for therapy.[13, 38] However, the results obtained are subjective, show ceiling effects, are usually not responsive enough to measure small progress or deterioration in a subject's ability to balance.[39] The biggest limitation of functional approach to rating balance is that is cannot specify what type of balance problem a subject has in order to direct treatment.

System assessments

While a functional approach to clinical balance assessment is used to determine whether or not a balance problem exists, a system approach is helpful when the purpose of the assessment is to determine the underlying causes of the balance deficit in order to treat it effectively.[1] Although the previously described tests have proven valid in predicting the likelihood of future falls, the tests do not help clinicians to direct treatment.[19] Two recent clinical balance tests use a systems approach to characterize the underlying reasons for impaired balance control: 1) the Balance Evaluation Systems Test (BESTest) [19] and 2) the Physiological Balance Profile (PPA).[20] Horak's BESTest focuses on differentiating the balance systems affected whereas

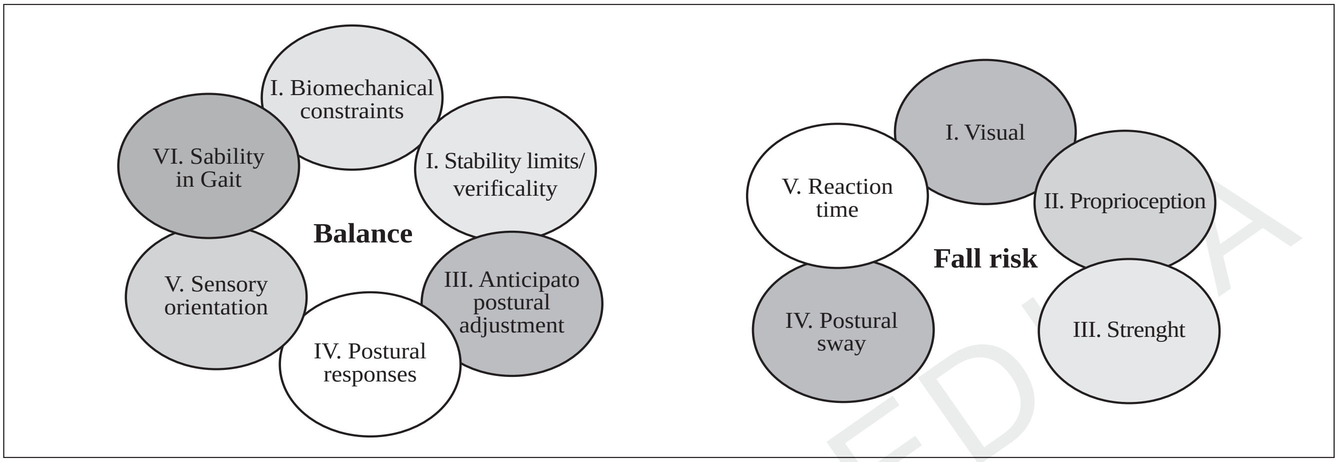

Figure 1.— The six different balance control systems evaluated with the BESTest (A) and the five physiological mechanisms evaluated with the PPA (B).

Lord's Physiological Profile focuses on identifying the physiological mechanisms underlying balance disorders (Figure 1).

The BESTest targets six different balance control systems so that specific rehabilitation approaches can be designed for different types of balance deficits (Figure 1). The BESTest consists of 36 items, grouped into six systems: 1) Biomechanical constraints, 2) Stability limits/verticality, 3) Anticipatory postural adjustments, 4) Postural responses, 5) Sensory orientationî, and 6) Stability in gait. Based on laboratory research, each system is known to represent relatively independent neural mechanisms underlying control of postural equilibrium.[1, 2, 19]

The BESTest has similar inter-rater reliability as the functional balance tests (ICC of 0.91).[19] It is the only clinical balance test to include tests of postural responses to external perturbations and perception of postural vertical. It also combines items from other popular tests such as the Clinical Test of Sensory Integration for Balance,[28] the Berg Balance Scale, the Functional Reach Test,[17] and the Get Up and Go test.[15] The BESTest is unique in allowing clinicians to determine the type of balance problems to direct specific treatments for their patients. The major limitation of the BESTest is the 30 minutes needed to complete the test. Recently, a short, 10-minute version of the BESTest has been developed by eliminating redundant and insensitive items from the BESTtest.[18]

In contrast to the BESTest that is organized around systems underlining balance control, the PPA is organized around the physiological impairments that lead to fall risk.[20] The PPA involves a series of simple tests of vision, cutaneous sensation on the feet, leg muscle force, reaction time, and postural sway in stance. The PPA has two versions: a comprehensive (or long) version and a screening (or short) version.[20] Although the comprehensive version provides information on a broader array of physiological functions than the short form, both versions provide a composite, fall-risk score. The short form takes 15 minutes to administer and includes: 1) postural sway; 2) hand reaction time; 3) knee extension strength; 4) leg proprioception, and 5) visual edge contrast sensitivity. These five physiological functions were identified to discriminate between fallers and non-fallers in both institutional and community settings.[20, 40, 41] The PPA is a valid and reliable measure of fall risk in older people.[20] In fact, based on a participant's performance, the fall risk score (standardized score) has a 75% predictive accuracy for falls in older people. The composite PPA score is derived from discriminate function analysis using data from large-scale studies.[20, 40, 41] The function is made up of weighted scores of the five key components. These weightings are -0.33 for edge contrast sensitivity, 0.20 for joint position sense, -0.16 for isometric quadriceps femoris muscle strength, 0.47 for hand reaction time, and 0.51 for postural sway on a foam-rubber mat with eyes open. Composite PPA scores below 0 indicate a low risk for falling, scores between 0 and 1 indicate a mild risk for falling, scores between 1 and 2 indicate a moderate risk for falling, and scores above 2 indicate a high risk for falling. The test-retest reliability (*i.e.*, intraclass correlation coefficient) for the five key PPA components is

0.57 for postural sway, 0.69 for hand reaction time, 0.97 for knee extension strength, 0.50 for proprioception, and 0.81 for edge contrast sensitivity.[20]

Although PPA has been proven valid in predicting falls with high sensitivity and specificity, the test results do not help therapists to direct the treatment. Identification of impairments, however, may help to identify the pathology, such as peripheral neuropathy or visual disorders, that may contribute to the balance problem. However, therapeutic rehabilitation is not best designed based on pathology, because the functional ability of each patient is multifactorial and depends not only on the patient's pathology but also on the patient's compensation, remaining resources, exposure, experience, motivation, age, and other factors.[20]

Issues about qualitative clinical scales

Unfortunately, all balance rating scales are relatively coarse measures of complex motor behavior and all subjective assessments can easily suffer from tester bias.

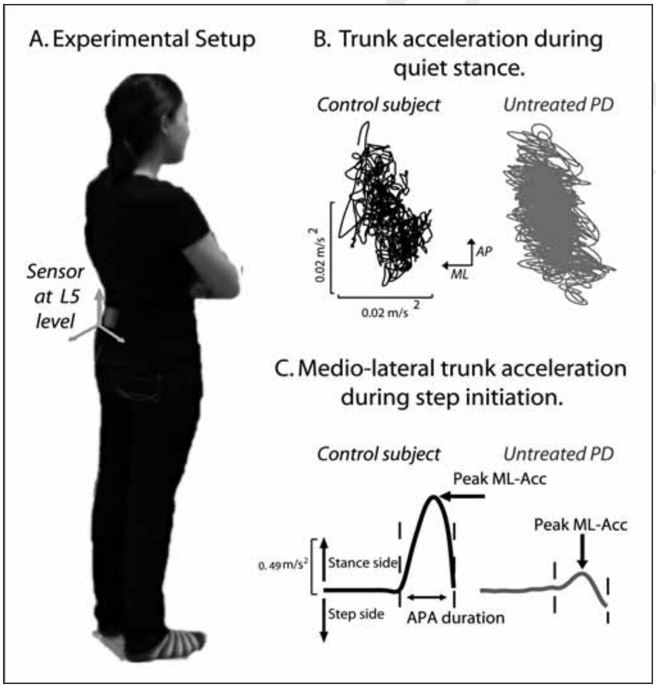

Figure 2.—Photo of subject wearing an inertial sensor on the lower trunk with arms and feet in a prescribed posture (A) and horizontal acceleration trajectories for two representative subjects, during quiet stance (B) and step initiation (C). Adapted from Mancini *et al.*[45, 73]

The ideal assessment method should provide objective, quantitative measurements that could be easily translated into simple and useful information. Advances in computerized technology have made objective assessments of balance more and more practical for clinical environments.

Objective assessments

Posturography

In the last decade, quantitative assessment of postural sway during stance have become available as clinical tools and an increasing number of physical therapists and physicians are customizing treatments for their patients based on the information from posturography.[42-44]

Static posturography.-Static posturography aims to quantify postural sway while a subject stands as still as possible. Postural sway is usually quantified by characterizing displacements of the center of foot pressure from a force plate. Recently, however, accelerometers or gyros (angular velocity sensors) placed on the trunk or head are available to measure postural sway. In fact, we have demonstrated that postural sway characterized from accelerometers on the low back or thigh, but not the upper back, can be analyzed to obtain similar sway characteristics as force plate measures of sway. Figure 2 illustrates postural sway as measured from a traditional force plate and from two-axis accelerometers on the low back at the same time.[45-73] Lightweight, wearable inertial sensors provide a less expensive, more practical method for quantifying postural sway in a clinical setting and user-friendly computer interfaces with automatic analysis are recently becoming available. Available posturography techniques and possible applications have recently been reviewed.[10]

Quantitative posturography can overcome the main drawbacks to the functional clinical balance examination such as: 1) variability in test performance (within and across different examiners); 2) the subjective nature of the scoring system; and 3) sensitivity to small changes. In addition, quantitative posturography can be used to evaluate therapeutic efficiency [46, 47] and to predict risk of falls.[48] However, static posturography may not be able to unravel details of the underlying pathophysiology or provide diagnostic information because, despite its excellent sensitivity, postural sway has poor specificity (with some exceptions).[48]

Because postural sway is such a complex behavior that depends on many parts of the central and peripheral nervous system and musculoskeletal system, it is often difficult to determine why sway characteristics have changed. Postural sway is an excellent measure of overall system health, but not a good measure of underlying pathophysiology since so many different disorders result in increased postural sway. For example, higher mean velocity in the COP displacement has been associated with aging, neuropathy, Parkinson's disease, vestibular loss, stroke, etc. [49, 50]

Several manipulations can be introduced to static posturography to render the balancing task more challenging, for example by reducing the size of the base of support, by decreasing visual feedback (eyes closure), by decreasing proprioceptive feedback (compliant surface), or applying a secondary task while subjects maintain their balance. The clinical utility of posturography as an objective and quantitative measure of balance has been discussed recently.

Dynamic posturography.-In contrast to static posturography, dynamic posturography involves the use of external balance perturbations or changing surface and/or visual conditions.[10] Postural perturbations are usually made with a movable, computerized support surface so that induces disequilibrium is induced by sudden horizontal translations or rotations.[10] The latency of postural responses as reflected in surface forces is approximately 150 ms (100 ms in ankle muscles), but latencies depend on the initial acceleration and velocity of the perturbation. Longer postural response latencies are seen with patients who have damage to the proprioceptive pathways, particularly, in large, sensory nerves and the spinal cord, such as from peripheral neuropathy or multiple sclerosis.[51, 52] In contrast to rapid surface perturbations to detect latencies of postural responses, slow and oscillatory movements are used to study postural adaptation, motor learning, stimulus anticipation and feed-forward postural control mechanisms.[, 54]

It is also possible to use sensory perturbations to selectively manipulate one or more specific sensory input for postural control (movements of the visual scene, galvanic vestibular stimulation, tendon vibration to disrupt proprioception). In fact, sensory perturbations help to clarify how each sensory system contributes to balance control, and how well subjects can reweight the available sensory information as necessary to maintain balance in altered environments. A commercially available system, the Sensory Organization Test (SOT) (Neurocom International, Clackamas, OR, USA), makes systematic evaluation of sensory contributions to balance control clinically feasible. In the SOT, either or both the visual surround or support surface can be sway-referenced so they tilt in response to body sway, thereby resulting in conditions in which visual and/or somatosensory inputs suggest that the subject is not swaying. This requires the nervous system to interpret the new sensory conditions and increase reliance on sensory inputs that are more accurately providing useful feedback about body sway. For example, sway-referencing the surface under a subject who has their eyes closed or looking at a sway-reference visual surround, requires a subject to depend more upon vestibular inputs to control balance. In fact, patients with bilateral loss of vestibular information, cannot stand in these conditions.[55, 56] A reduced capacity to centrally weight different sensory inputs has been identified in population with balance deficits, like patients with Parkinson's disease, Alzheimer's disease,[58] peripheral neuropathy,[59] or stroke.[60]

Although dynamic posturography systems provide accurate data about forward-backward body sway and represent a gold-standard in measuring the motor and sensory contributions to balance control, an important drawback is the high cost and time for training and testing, as well as space for the equipment.[9] Although dynamic posturography can shed insight into the type of balance disorder, functional compensation and the likely environments leading to instability for individual subjects, it is not a diagnostic tool.[9] Moreover, dynamic posturography is limited as it does not provide information about dynamic balance during gait and postural transitions such as turning and sit-to-stand transitions.

Wearable inertial sensors

Recently, wearable motion sensors developed for robotics, aerospace and biomedical measurements have been used to measure balance control.[61, 62] These sensors, with wireless data transfer, have the potential to overcome the major drawbacks of cost, size and limited location of computerized testing, as well as enabling objective measurement of postural sway and movements during task performance. In fact, developments in microelectronics have led to a new generation of small, inexpensive and robust sensors with long battery life and large, local data storage to enable ambulatory systems for all-day monitoring of mobility.[43, 63]

Wearable inertial sensors consist of linear accelerometers and/or angular velocity sensors (gyroscopes) that can measure leg, arm and torso motions while people perform clinical balance tasks or go about doing their daily activities. For example, ambulatory gait analysis systems have been design using accelerometers or gyroscopes,[66] and a combination of both.[67] Unfortunately, these systems that automatically calculate parameters of gait such as cadence, stride length, and stride velocity, do not generally evaluate postural stability of the trunk during gait. Postural stability during gait can be estimated, however, from time spent in double support, since subjects with poor balance spend more time with both feet on the ground. However, subjects with poor balance also walk more slowly and slower gait is associated with longer time spent in double support.[68] Wearable sensors have also been used as activity monitors [69] or to determine time spent in various activities such as lying down, walking, sitting, and standing.[70-72]

Recently, we have proposed using wearable sensors to instrument clinical tests of balance and mobility. Algorithms have been developed to automatically, objectively and quantitatively assess balance and mobility, such as: the instrumented test of 1) postural sway (iSWAY); 2) step initiation (iSTEP); and 3) the Timed Up and Go test (iTUG).[33] With the assessment of these three motor tasks, we obtain an objective and systematic evaluation of three different systems underlying balance control: 1) static posturography; 2) anticipatory postural adjustments prior to step initiation and the sit-to-stand transitions; and 3) dynamic stability during turning as well as trunk and arm movement during gait.

Accelerometers can substitute for traditional forceplate measures to characterize both postural sway during stance and anticipatory postural adjustments prior to step initiation.[62, 73] For example, an Xsens inertial sensor with appropriate sensitivity (MTX-49A33G15) placed on the trunk at the L5 level (Figure 2A) can wirelessly transmit trunk sway as well as lateral trunk postural adjustments in anticipation of step initiation. We have recently measured quiet standing and step initiation in 12 untreated subjects with early Parkinson's disease and 12 age-matched control subjects. Sway parameters extracted from the planar acceleration differentiated between untreated PD and con troll subjects (Figure 2B). The most sensitive measure of sway in early PD was the smoothness of lower trunk acceleration, apparent even when clinical observation may not detect balance problems.[44]

Immediately prior to step initiation, anticipatory postural adjustments (APAs) act to accelerate the center of body mass forward and laterally over the stance foot.[75, 76] APAs represent feedforward balance control that help to stabilize or mobilize the body based on anticipation of forces accompanying voluntary movement such as volitional lifting of the foot during step initiation.[75] We have recently demonstrated that the size and duration of APAs can be measured with accelerometer on the trunk just as well as a force plate. For example, compared to elderly control subjects, patients with early, untreated Parkinson's disease show reduced size and increased duration of APA (trunk lateral displacement) to unload the initial stepping leg (Figure 2C).[72] Clinicians cannot observe the size of postural preparation or the velocity of the first step associated with start hesitation. Accelerometry-based detection of postural sway and APA provide a new, sensitive tool for measuring balance control.

Dynamic balance during gait can also be measured during the postural transition phases of the Timed Up and Go test using inertial sensors. We demonstrated how a Physilog portable data-logger [63] with seven inertial sensors (on chest, forearms, thighs and shanks) could quantify an extended, six-meter, Get-Up-and-Go task to automatically identify postural transitions (sit-to-stand, turning, stand-to-sit) as well as gait parameters.[33, 74] Although the total Get-Up-And-Go time did not differ between groups, subjects with untreated PD showed impaired dynamic balance as indicated by slower turn velocities, longer duration of sit-to-stand, as well as slower cadence, slower arm swing speed, more arm swing asymmetry and smaller yaw trunk rotation.

Thus, objective measures of balance using inertial sensors have the potential to provide clinicians with accurate, stable, and sensitive biomarkers for longitudinal testing of posture and gait. What is needed to make quantitative measures of balance feasible for clinical practice are automatic algorithms for quantifying balance control during prescribed tasks, age-corrected normative values, composite scores, and user-friendly computer interfaces so the tests can be accomplished quickly and data stored conveniently in electronic medical records.

Conclusions

Functional clinical balance assessment tools were not developed to distinguish different types of balance deficits but to determine whether or not a patient has a balance problem. Two clinical balance assessment tools, however, the BESTest and the PPA, aim to determine the underlying postural or physiological system underlying a balance problem. Dynamic posturography also aims to distinguish between sensory and motor deficits underlying postural control. In the near future, clinicians will be able to instrument their functional or systems clinical balance assessments using wearable inertial sensors for more precise, sensitive, and comprehensive evaluation of balance in a clinical setting.

Key points

– Balance control involves maintaining posture, facilitating movement, and recovering equilibrium;

– A variety of balance control systems (reactive, anticipatory, sensory, dynamic, and limits of stability) and physiological systems (vestibular, visual, proprioceptive, muscle strength, and reaction time) contribute to balance;

– Clinical functional assessment scales can assess fall risk;

– A system approach to clinical balance assessment can differentiate among different types of balance disorders;

– A physiological approach to clinical balance assessment can determine the underlying sensorimotor mechanisms constraining balance control;

– Objective measures of balance control using computerized systems are becoming feasible and useful for clinical practice.

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