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CHAPTER 19

Computerized postural control assessment[1]

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19.1. Introduction

When patients with complaints of dizziness and balance disorders are being evaluated in the laboratory they are routinely tested for peripheral and central vestibulo-ocular pathway involvement. Additionally, they should receive some assessment of postural control ability. However, just as in the use of electronystamography/videonystamography (ENG/VNG) and rotational chair testing, not all patients need high tech, formal postural control assessment. There are several different general approaches to formal postural control testing, each with specific technical equipment requirements and goals for the testing (Shepard and Telian, 1996; Monsell et al., 1997; Allum and Shepard, 1999). To start the discussion, consideration of the reasons behind the assessment and a brief review of the various parametric options will be provided.

19.1.1. Rationale for postural control assessment

A formal postural control assessment is needed for patients whose only symptom is unsteadiness when standing and walking and/or unexplained falls with or without injury. Given that rehabilitation programs reduce the rate of falls in the elderly (Gillespie et al., 2003), assessing patients for postural control abilities in static and dynamic situations can be useful in order to justify the basis for referral to such a program. In a review of over 2200 consecutive patients there was a group for whom the only complaint was that of imbalance with standing and walking without falls. In that group, those over 60 years of age showed no abnormalities on routine ENG or rotational chair evaluation of the peripheral and central vestibular system, but they did have consistent abnormalities as assessed by computerized dynamic posturography (CDP) (Shepard and Telian, 1996).

However, is there a rationale for the routine use of some form of postural control assessment in the patient with well definable unilateral hypofunction and symptom presentations of spontaneous or head movement provoked events of true vertigo? For this patient group, independent of age, imbalance and a risk of falls is expected during the vertiginous episode, but many will deny significant difficulties between the events. With casual observation of ambulation these patients tend to look normal, but they have a noticeable restriction in head on body movement (Gouveris et al., 2006, 2007). When asked to walk with head movement during a test such as the Dynamic Gait Index (Shumway-Cook et al., 1995) or Functional Gait Index (Wrisley et al., 2004) their imbalance becomes apparent to the examiner and to the patient. There is also good evidence that the rate of falls associated with unilateral hypofunction at any age is greater than the general population and increases with age, especially if the ability to guard or use assistive devices is restricted (Herdman et al., 2000). Therefore, routine assessment of postural control and/or ambulation performance, even at a screening level, is well justified in the patient with unilateral hypofunction for whom vertigo or lightheadedness are active symptoms when imbalance is not reported.

Patients with bilateral hypofunction also fall at a rate higher than that expected by age changes alone (Herdman et al., 2000). Additionally, the protocols used in CDP (to be discussed below) can help determine the extent of the functional impact of bilateral hypofunction. In this group of patients, formal assessment of the ability to maintain upright quiet

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stance when simultaneous disruptions in visual and foot support surface cues are applied reveals the patient's ability to perform when peripheral vestibular system cues are the only accurate sensory input information. Patients displaying severely reduced or even absent caloric responses, suggesting bilateral hypofunction of the horizontal semicircular canals, may still be able to maintain functional performance that is near normal in a situation of compromised sensory input cues. If this is the case, the suggestion clinically is that the extent of their labyrinthine lesion is significantly less than complete. Coupling this type of evaluation with rotational chair and otolith testing provides useful information about the physiological and functional extent of bilateral peripheral lesions. This then can impact the expected effectiveness of vestibular and balance rehabilitative activities routinely used in the management of these patients (Shepard, 2007).

19.1.2. Outcome parameters in objective postural control assessment

When considering formal assessment of postural control, one must decide which outcome parameters characterize the performance. Unlike the restriction to eye movements in assessing the peripheral and central vestibular system, several options are available when monitoring postural control. These options vary in their measurement complexity and the assumptions related to the number of links (body segments available to move differently from other body segments, e.g. between ankle and knee, between knee and hips, arms, etc). In general, as the number of links increases, the more accurately one can assess the performance of postural control during standing tasks. However, when considering the routine clinical assessment of patients, the increase in complexity of the use of multiple link measurements as well as the increase in cost would have to be justified by the additional differentiating information received for characterizing patient performance (Speers et al., 1999). The variation in the complexity of the recorded measurement can also vary the clinical utility of the measurement. Allum and Shepard (1999) contrast the clinical utility between two units, one that provides for site-of-lesion information and the other that provides for functional information but no significant site-of-lesion analysis. The differences in the systems relate dominantly to the specific outcome parameters being used in the stance tasks as opposed to differences in the tasks themselves.

Table 1 gives a simplified progression of increasing complexity of the recording techniques and the specific measurement parameters associated with each. The goal in all of these is to characterize the movement of the body in the anterior-posterior (sagittal) and possibly the medial-lateral (coronal) planes. Even when not appropriate for routine clinical use, the more complex measurement techniques can be used to validate the interpretations from techniques more applicable to the routine clinical setting (Shepard et al., 1993). To orient and assist the reader with the nomenclature used in this chapter and common in the work of assessment of postural control, basic definitions will be provided (Winter, 1995). The reader interested in a basic primer on these types of measurements and the study of gait is referred to Winter (1995).

- Posture – the orientation of the body segments individually or collectively with respect to the pull of gravity (gravitational inertial force – gif) resulting in the maintenance of upright position.
- Balance – the dynamics of body posture in order to prevent a fall.
- Dynamics – the effects of forces on the motion of a body or system of bodies, both external and internally generated (Gu et al., 1996).
- Kinematics – the study of the motion of a body or a system of bodies without consideration given to its mass or the forces acting on it, i.e. how the various segments (links) of the body move relative to one another (Alexander et al., 1992).
- Center of mass – COM is a point equivalent of the total body mass in a three dimensional coordinate system. Each of the body segments, no matter how large or small, has a COM. It is the weighted average of all of these segments that make up the body COM in 3-dimensional space. This is the most commonly discussed outcome measure for postural assessment, especially by commercially available equipment. Yet, it is important to understand that this quantity cannot be measured; it is a metric that has to be calculated from other measured parameters (e.g. center of pressure – see below).
- Center of gravity – COG is used when referring to the vertical projection of the COM onto the ground.

Table 1

Measurement techniques

- **Observations of an individual's sagittal plane sway against a patterned background.** The individual stands lateral to a wall with a striped pattern. The stripes are separated by a known number of degrees of subtended arc distance when the examiner is standing at a prescribed location. This method provides an estimate of the average angle of sway of the center of mass (COM) using the shoulders as the point of monitoring. In general this method assumes the body is a single link system with a single joint at the ankle.
- **Single sway bar attached at the hip.** This is a rigid bar attached at the hip in a loose clip with the other end fastened to a potentiometer across which a low DC voltage is applied. As the person sways in the sagittal plane the movement of the bar through turning of the potentiometer provides a voltage reading that is proportional to the magnitude of the COM sway. This system can be calibrated in degrees of sway. Again the assumption is that the body is a single link system with the only moveable joint at the ankles.
- **Dual sway bars attached at hips and the shoulders.** This works in the same manner as the single sway bar but has the advantage of no longer having to assume a single link system. In this situation you have a t-link system with joint movement at the ankle and the hip. With this system you can get estimates of the angle of movement of the lower body from the hip bar and estimates of the upper body sway (from the hips to the shoulders) by the difference between the movement of the shoulder bar and the hip bar. Both the dual and single sway bar systems can have varying voltages as a result of the movements of the bars fed into a computer system that can then provide a real time monitor of the sway movements. Calculation of the COM sway can then be made using certain anthropometric and simplifying assumptions (Speers et al., 1999).
- **Single force plate.** In this system a string gage force plate that provides a current output proportional to changes detected in vertical force is the measurement tool. Unlike the methods discussed above, the outcome parameter is the floor reaction force against the force plate with the feet. The floor reaction force is then used to calculate the center of pressure (COP) and monitor its movement on the surface of the force plate. The movement of the COP is used with assumed anthropometric data to calculate the movement of the COM in the sagittal and/or the medial-lateral planes. Here the assumption is that the body is a single link system.
- **Dual force plate.** To increase the accuracy, a pair of force plates are used, one under each foot. In this system the COP is monitored under each foot and then used to calculate the COP movement of the body. The resolved COP is then used to estimate the body COM sway. Here again the assumption is that of single link body movement with the only active joint at the ankle. This method is what is used commercially by the system that is the most prevalent in the United States (Shepard et al., 1993).
- **Dual force plates with one or more sway bars.** This would be the next level of technical sophistication to increase the accuracy of characterizing maintenance of static and dynamic postural control. With the combination of techniques the analysis is not restricted to a single link assumption but can expand to a multi-link model (typically two or three links based on the use of one or two sway bars). This technique does appear to provide for increased differentiation of abilities based on work on normal subjects across age (Speers et al., 1999).
- **Wearable sensor.** This technique and the ones to follow allow for assessment of not only static and dynamic postural control but also afford the opportunity to monitor postural control during ambulation. This scheme typically uses one or more lightweight sensors that can detect movement in the sagittal, coronal and/or horizontal planes. These data can be obtained during a variety of tasks (especially if the data are transferred by telemetry technology instead of sensors hard wired to the receiving computer) in addition to maintenance of stance. In its simplest configuration this technique would assume a single link body model. This is not limited since the use of multiple sensors in different locations would provide for the ability to monitor multiple links independently.
- **Digital motion analysis systems.** While this technique is more restrictive than a wearable sensor scheme, it still allows for assessment of postural control to ambulation and other movement tasks. The technique using digital camera recordings of active or passive markers placed at various locations on the body and then reconstructing the body by the computer model is an advancement in the detail of assessment that can be made using multiple link models. This technology can provide for powerful analysis of the relative movements of the various body links (kinematics) and calculations of the forces generated by limbs and at the joints (dynamics). When combined with force plates built into the walk path, significant information in both kinematics and dynamics can be obtained. This technique allows for analysis in full three dimensions, whereas the others above are restricted to one or two planes of analysis.

- Floor reaction force – the force of the feet in contact with the support surface that reacts to an action force of the pull of gravity. The amount of this force is a result of the strength of the gravitational force and the density of the body.
- Center of pressure – COP is the point location of the weighted average of all of the floor reaction forces from the body parts in contact with the support surface (e.g. the foot in contact with a force plate). This is a measurable quantity and is the most common direct outcome measure used in conjunction with force plate technology. Two force plates are required to resolve the COP under each foot. The movement of the COM and the COP are related in such a way that with general anthropometric assumptions the COP can be used to estimate the position of the COM over time. This estimate becomes less accurate as the frequency of sway increases above 1 Hz (Gu et al., 1992).

19.1.3. Protocols

The next decision related to postural control assessment deals with what single test or group of tests would be appropriate to provide the opportunity to challenge an individual sufficiently in order to assess his ability. As with the outcome parameter techniques given in Table 1, there is a range of tasks from simple standing to complex perturbations of standing posture to assess reactions. From the clinical perspective, what information can be gained from a given protocol that would allow for differentiation between patients, and what information can be gained that would functionally characterize an individual patient to predict daily performance and/or falls risk?

Given the complex nature of maintaining the COM over the base of support, which involves integrated use of vestibular, visual and proprioceptive/somatosensory cues (Nashner, 1976; Nashner et al., 1982; Allum and Honegger, 1992; Allum et al., 1993), a protocol that attempts to isolate the influence of these sensory inputs would be appropriate. This type of protocol is done with the subject given the task of simply maintaining quiet upright stance. Two approaches are possible. The first provides for assessing the contribution each of these inputs makes to quiet stance in a site-of-lesion manner (Allum, 1993; Allum and Shepard, 1999). However, in a protocol of that type, if the patient is fully compensated centrally for the lesion, the test would still be abnormal, thus providing no or little functional information (Allum and Shepard, 1999). In contrast the common protocol of sensory organization testing (SOT, described in detail below) provides assessment of the ability to use in combination or individually the sensory inputs during maintenance of stance (Nashner, 1993a; Shepard et al., 1993; Allum and Shepard, 1999). In this second protocol functional information is available without site-of-lesion suggestions. As such, the performance changes with the compensation status of the patient. When symptoms improve due to postural control, then expected improvement in performance is seen (Cass et al., 1996). Therefore, the SOT can indicate normal performance maintaining quiet stance even when peripheral vestibular involvement is causing other active symptoms, as long as these symptoms do not impact postural control – a functional evaluation.

A second line of investigation is the characterization of a subject's reaction to a sudden, unexpected perturbation in the position of the COM. The outcome parameters for this type of protocol involve the latency to active recovery of the desired COM position over the base of support together with various aspects of how the body segments are coordinated during the recovery process. Typically in this protocol, translational stimuli in the anterior/posterior plane (referred to as motor control test by one manufacturer) or rotations of the support surface co-linear with the ankle in the sagittal plane, or simultaneous use of translation and rotation would be employed (Nashner, 1977; Nashner and Grimm, 1978; Allum, 1983; Horak and Nashner, 1986; Shepard et al., 1993; Allum and Shepard, 1999; Shepard, 2000). This protocol is not used as widely in routine clinical assessments but finds frequent use in research. In this protocol the primary outcome measure is the latency to onset of recovery. Additionally, recording surface muscle activity during recovery and monitoring the sway trajectory of the COM are also used in facilities (Allum, 1983).

The third approach is to use the rotational perturbation but change the outcome measurement to that of electromyographic data from the muscle groups of the lower limbs (discussed further later in the chapter). In this protocol, referred to as postural evoked responses (PER), the monitoring of the movement of the COM is less important (Lawson et al., 1994). While not used on a wide scale clinically, significant site-of-lesion information is potentially available with this protocol (Diener et al., 1984; Dichgans and Diener, 1987; Friedmann et al., 1987; Shepard, 2000).

A more recent attempt to improve the clinical differentiation of patients has been stimulated by the awareness that in the SOT protocol, patients may have normal results yet be experiencing significant problems with postural control and ambulation. The dichotomy occurs because the SOT has the head in a primary position and still during the testing. The patient complaints are noted when the individual moves the head. When you consider that one of the most frequent maneuvers performed during daily routines is that of a step turn (Glaister et al., 2007) and that turns during walking are guided by eye/head movement (Hollands et al., 2002), testing patients with specific head orientations or during dynamic head movements could be clinically productive. To date the use of static head position has not been shown to be of significant value (Chandra and Shepard, 1996). Therefore, attention has turned to dynamic head movements during aspects of the SOT (Paloski et al., 2006; Mishra et al., 2009). While these protocols show promise they are still in the developmental stages.

19.1.4. Clinical perspective – routine postural control assessment

Given the many options and combinations discussed above it is possible to provide a very accurate and detailed assessment of postural control under a variety of conditions and go on for full formal assessment of gait. However, as stated in the Introduction, one must look at the cost/benefit relationship between very detailed assessments and the extensive amount of time and money involved with that approach compared to a simpler assessment that has the sensitivity to assess differences in patients from normal subjects yet be practical in a busy balance center environment. With that concept in mind, the use of a force plate system, assuming a single link model in a protocol that provides a quantification (calculated COM from COP measurements) of the patient's use of the sensory input cues (SOT or similar techniques), has been shown to be of clinical utility and representative of the general information gathered with more complex techniques; for details the reader is referred to a representative sample of the literature (Nashner, 1993b; Shepard et al., 1993; Weber and Cass, 1993; Shepard and Telian, 1996; Monsell et al., 1997; Allum and Shepard, 1999; Rose and Clark, 2000; Jacobson, 2002; Barclay-Goddard et al., 2004; Furman et al., 2005; Longridge and Mallinson, 2005; Mallinson and Longridge, 2005; Fife et al., 2006; Gouveris et al., 2006, 2007; Whitney et al., 2006). It is also of importance that this technique is applicable to patients of all ages with normative data available for population comparison. The data obtained should be available for further post hoc analysis and the test be able to be altered so the protocol can be used to expand particular investigations (Shepard, 1989; Rine et al., 1998, 2004; Speers et al., 1999; Gabriel and Muk, 2002; Medeiros et al., 2005; Mirovsky et al., 2006; Peterson et al., 2006; Rosengren et al., 2007; Mishra et al., 2009). While the SOT protocol is available on more than one commercial piece of equipment it also has the additional benefit of being emulated in a simple office examination manner (Shumway-Cook and Horak, 1986). This office evaluation, the Clinical Test of Sensory Interaction in Balance (CTSIB), has been shown to have a predictive relationship to the formal SOT (El-Kashlan et al., 1998).

The other protocols using unexpected perturbations and perturbations combined with electromyographic (EMG) recordings are much less frequently utilized in a routine clinic for balance and dizziness assessment. However, these protocols, which can be of use in a practical manner in routine clinical assessment (Shepard, 2000), are available on one commercial piece of laboratory equipment and will therefore, be considered in detail below.

19.2. Protocols

From the above discussion of what protocols and measurement techniques appear to be readily available and practical for use in a routine clinic, a more detailed presentation of these protocols is in order. We will start with the SOT paradigm since it is the most widely utilized and has the largest body of literature relating to its clinical utility. Following SOT a presentation of the protocols for determining reaction to sudden perturbations and the use of EMG recordings will be provided.

19.2.1. Sensory organization protocol

There are two commercially available pieces of clinical equipment that provide for formal evaluation of the SOT protocol. The original device that introduced the SOT as a means for assessing static and dynamic balance, EquiTest® by NeuroCom International, is the most commonly used equipment in the United States (see Fig. 1). The Balance Quest® by MicroMedical Corporation (see Fig. 2) is a more recent alternative for postural control assessment using the SOT protocol. Extensive normative data across age are currently available for only the EquiTest®, with that for the Balance Quest® in development. In both cases the measured quantity is the COP from dual force plates on the EquiTest® and a single force plate on the Balance Quest®. The COP data are then used to calculate movement of the COM. The systems use different overall outcome presentations of the calculated COM sway given below.

The SOT measures the ability to perform volitional, quiet stance during a series of six specific conditions (see Figs 3 and 4). The first three provide for uninterrupted, accurate foot support surface information on a surface with adequate friction that is larger than the foot size. Condition 1 has eyes open, while in Condition 2, the eyes are closed. Under Condition 3, the visual scene moves in a pattern that is stimulated by the anterior/posterior sway movements of the patient for the EquiTest®. In the situation of the Balance Quest® the moving visual scene is produced by a visual projection system in an otherwise completely darkened room. Condition 3 presents a situation of visual conflict, where visually accurate information is provided that is of no significant help in maintaining quiet stance. Condition 3 presents misleading optokinetic and foveal visual cues about the position of the body in space. Conditions

Fig. 1. Picture of the EquiTest® system with a subject just completing the SOT portion of the testing protocol.

Fig. 2. Picture of the Balance Quest® system. See text for further description of the equipment.

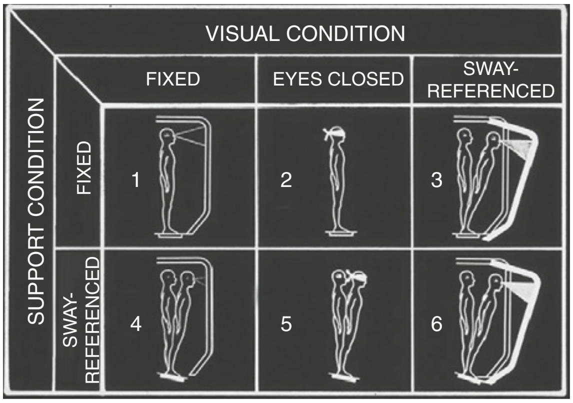


Fig. 3. Shown are the six conditions associated with the sensory organization test. See the text for description of each of the conditions.

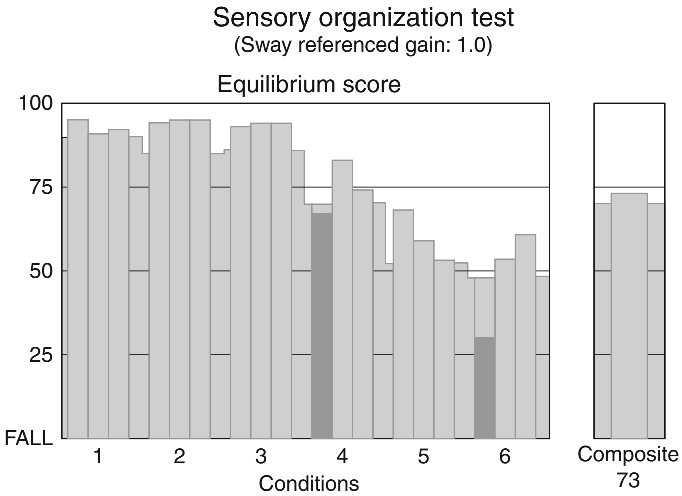


Fig. 4. Graphical printout of the SOT from the EquiTest® system. Conditions 1–6 are shown, each with three trials per condition. The bars of the graph represent the performance in a percentage (equilibrium score) for each of the trials. Note that the first trial of Condition 4 and that of Condition 6 fall into the background stippled area that represents the fifth percentile cut-off age-related normal range, indicating an abnormal performance on those two trials. The separate bar graph labeled 'Composite' at the far right of the figure is a weighted average of all conditions tested. As shown in this example, even though there are two trials that fall outside the normal range, the overall performance is considered normal.

4, 5, and 6 utilize the same sequence of the three visual conditions, but with the foot support surface giving misleading information. As with the movement of the visual surround in Condition 3 for the EquiTest®, when testing under Conditions 4, 5, and 6, sway movements of the patient in the sagittal (anterior/posterior) plane drive the movement of the support surface in a rotational manner about an axis parallel to the ankle joint. For the Balance Quest® system the circular force plate is released from being held rigid and is allowed to be suspended with three springs equally spaced around the circumference of the platform. This allows the movement of the subject in all directions of sway, but the amount of movement will be dependent on the weight of the subject. For either system somatosensory and proprioceptive information is not removed in Conditions 4, 5, and 6, but this information is of limited use in maintaining upright stance in that there is a disrupted relationship between body position and the ankle angle (that angle made between the upper surface of the foot and the anterior portion of the lower leg). The SOT protocol uses three trials each of the conditions. The average performance is taken as representative of the patient's postural control ability under that sensory condition. In the EquiTest® system each trial is fixed at 20 s duration. For the Balance Quest® the duration of each trial is variable.

For the EquiTest® system the reported outcome measure is the equilibrium score. This score is a percentage representing the magnitude of sway (maximum excursion of the COM) in the sagittal plane for each trial of each condition. Movement of the subject in the medial-lateral plane is obtained by the dual force plate system but not reported in a score format. It is available as a calibrated graphic printout that supports the summary information given with the equilibrium score. Details of how this score is obtained will not be repeated here (Nashner, 1993a; Shepard et al., 1993). However, it is important to realize that this score is based on an estimated normal value of 12.5° of anterior/posterior sway about the ankle joint, typically 8° forward and 4.5° backward. It is assumed that this range of sway is available to patients during the test. Some patients may not have this normal range because of physical restrictions at the ankle, or because of limits of sway patients have adopted secondary to their sense of imbalance and fear of a potential fall. It is useful to recognize the patient who has a reduction in limits of sway. If the limits of sway are reduced more than 50%, the interpretation of the patient's results may be inaccurate (Shepard and Telian, 1996).

The Balance Quest® system gives two measures of outcome based on the calculated COM. Each of these uses all the data points collected during the full trial duration. A measure of the area covered by the projection of the COM on to the platform and a measure of the velocity of the movement of the COM characterize the performance in this system.

The general interpretation of the SOT, independent of the system, is that of pattern recognition of abnormal performance across the six conditions. The combinations of the six conditions that are abnormal are used to define a pattern of difficulty that can then be interpreted with regard to the subject's functional ability to use the three sensory inputs in combinations when the visual and proprioceptive/somatosensory inputs are disturbed. Table 2 presents the most common patterns and a commonly used nomenclature. By far the most common pattern is the vestibular dysfunction pattern. The most important aspect of interpretation for the SOT is that it provides information as to which input system cues the patient is unable to utilize for performing the task of maintaining postural control. In other words, it provides a relative measure of the patient's ability to utilize the sensory input cues of vision, vestibular and proprioceptive/somatosensory to maintain quiet upright stance. The test does NOT provide relative information as to which of the sensory systems has lesions, causing postural control abnormalities. Therefore, SOT provides no site-of-lesion information; it is strictly a test of functional ability. The test in no way implies that there exists a central or peripheral vestibular system lesion, nor does it imply central or peripheral pathway lesions in the visual or somatosensory/proprioceptive systems. The information should be interpreted only to reflect which input information the patient is able (or conversely, unable) to use for the task at hand.

Table 2

Patterns of abnormal performance on SOT

- Vestibular dysfunction pattern: Abnormal on Conditions 5 and 6 (alternatively Condition 5 alone).
  Vestibular dysfunction pattern indicates the patient's difficulty in using vestibular information alone for maintenance of stance. When provided with accurate visual and/or foot somatosensory information, stance is within a normal range.
- Visual vestibular dysfunction pattern: Abnormal on Conditions 4, 5 and 6.
  Visual and vestibular dysfunction pattern indicates the patient's difficulty in using accurate visual information with vestibular information, or vestibular information alone for maintenance of stance. When provided with accurate foot support surface cues, stance is within a normal range.
- Visual preference pattern: Abnormal on Conditions 3 and 6 (alternatively Condition 6 alone).
  Visual preference pattern indicates the patient's abnormal reliance on visual information, even when inaccurate. When provided with accurate foot support surface information together with accurate or absent visual cues, or absent vision and vestibular information alone, stance is within a normal range.
- Visual preference/vestibular dysfunction pattern: Abnormal on Conditions 3, 5 and 6.
  Visual preference and vestibular dysfunction pattern indicates the patient's difficulty in using vestibular information alone and the patient's abnormal reliance on visual information, even when inaccurate. When provided with accurate foot support surface information together with accurate or absent visual cues, stance is within a normal range.
- Somatosensory/vestibular dysfunction pattern: Abnormal on Conditions 2, 3, 5 and 6.
  Somatosensory and vestibular dysfunction pattern indicates the patient's difficulty in using foot support surface information with vestibular information, or vestibular information alone for maintenance of stance. When provided with accurate visual information, stance is within a normal range.
- Severe dysfunction pattern: Abnormal on four or more Conditions not covered in the above descriptions, for example, 3, 4, 5, and 6; or 2, 3, 4, 5, and 6; or 1, 2, 3, 4, 5, and 6.
  Severe dysfunction pattern indicates the patient's difficulty with stance independent of the sensory information (vestibular, visual and/or somatosensory) provided. Note that these situations many times involve a dominant feature such as significantly abnormal Conditions 5 and 6, or they may involve equally distributed difficulties on all conditions affected.
- Inconsistent pattern: Abnormal on Conditions 1, 2, 3, 4, or any combination and normal on Conditions 5 and 6.
  Inconsistent pattern indicates that performance of the patient is difficult to explain with normal or typical pathophysiologic conditions and could imply volitional or non-volitional exaggerated results.

19.2.2. Reaction to unexpected perturbation of the COM

There are various philosophies and methods for accomplishing this evaluation of the standing subject (Allum and Shepard, 1999). However, the EquiTest® system is the only commercially available system in the United States with a protocol that has age related normative data for characterizing a subject's reaction to unexpected perturbations. This is referred to as the motor control test (MCT). Therefore, only this protocol and interpretation details will be provided herein.

The center of mass perturbations are created by abrupt anterior or posterior horizontal translations of the support surface with the subject's eyes open. Three translations, increasing in size from small to medium to large (Shepard et al., 1993) are provided in both directions. The increase in size of the translation creates a stimulus intensity series. The profile of the distance of the surface movement is varied for each patient based on height, so that all translations are normalized to a 6-foot tall person (Shepard et al., 1993). For this protocol, as with the sensory organization test, COP detected by the force plates in the support surface is measured. The principal output parameter is the latency to onset of active recovery from the unexpected translations. Other information obtained from the protocol includes weight distribution onto right or left leg, and a relative measure of strength as a function of the size of the perturbation (Shepard et al., 1993).

This study is used less as a functional evaluation than the SOT, and more to evaluate the long-loop pathway. This pathway begins with inputs from the ankle region (tendon and muscle stretch receptors), then projects to the motor cortex and back to the various muscles of postural control, including upper and lower body. When an abnormal latency to onset of active recovery from induced sway is noted, then problems in the long-loop pathway should be considered. The explanation may be as simple as ongoing joint or back pain, a congenital condition of the back or lower limbs, or an acquired lesion involving the neural pathways of the tracts on either the afferent or efferent side. Therefore, abnormalities of the MCT related to latency are non-specific indicators of potential problems in the long-tract or the musculo-skeletal system needed to coordinate recovery from unexpectedly induced sway in the sagittal plane.

There are four separate algorithms that are used to calculate the latency to onset of active recovery from the induced sway in either the forward (backward translation) or backward directions (forward translation). The latency calculations are then compared, and a relative measure of the consistency of the outcome (and ease of recognizing when the active recovery process began) is given by a number from 1 to 4 indicating the number of the calculations that agreed (see Fig. 5). The opportunity for manual determination of the latency from direct viewing of the raw data is provided. As a matter of course, the interpreter should always visually verify the latency measure using the raw data printouts and develop manual scoring numbers as needed.

Other abnormalities from this portion of the testing include inappropriate weight bearing or an inability to properly scale the strength of the response to the increasing size of the perturbations. Such findings may provide information that helps explain the patient's complaints of disequilibrium. These abnormalities are unlikely to directly implicate neurological involvement if the latency findings are normal. In many cases, the weight shift or scaling problems may be maladaptive behaviors developed in response to the initial symptoms of the vestibular disorder (for specific patient examples of this and other SOT/MCT/PER abnormalities, See Chapter 7, Nashner, 1993b; Shepard and Telian, 1996; Shepard, 2000, 2007).

19.2.3. Electromyographic recordings of the lower limb muscles – postural evoked responses

As with MCT only the EquiTest® equipment provides a defined protocol for this study for which normative, age, gender and height related data exists. The concept basis for the test and the details of the normative data development have been presented elsewhere and will not be repeated here (Diener et al., 1984; Dichgans and Diener, 1987; Friedmann et al., 1987; Lawson et al., 1994).

Muscle activity from the distal lower extremities is stimulated by sudden toe up rotations of the support surface (the force plate platform of EquiTest®). The muscle activity stimulated by this dorsiflexion movement at the ankle is recorded with surface EMG electrodes. In this paradigm the EMG response from the medial gastrocnemius and the anterior tibialis is recorded. To improve the signal-to-noise ratio of the evoked EMG activity, the rotation is repeated

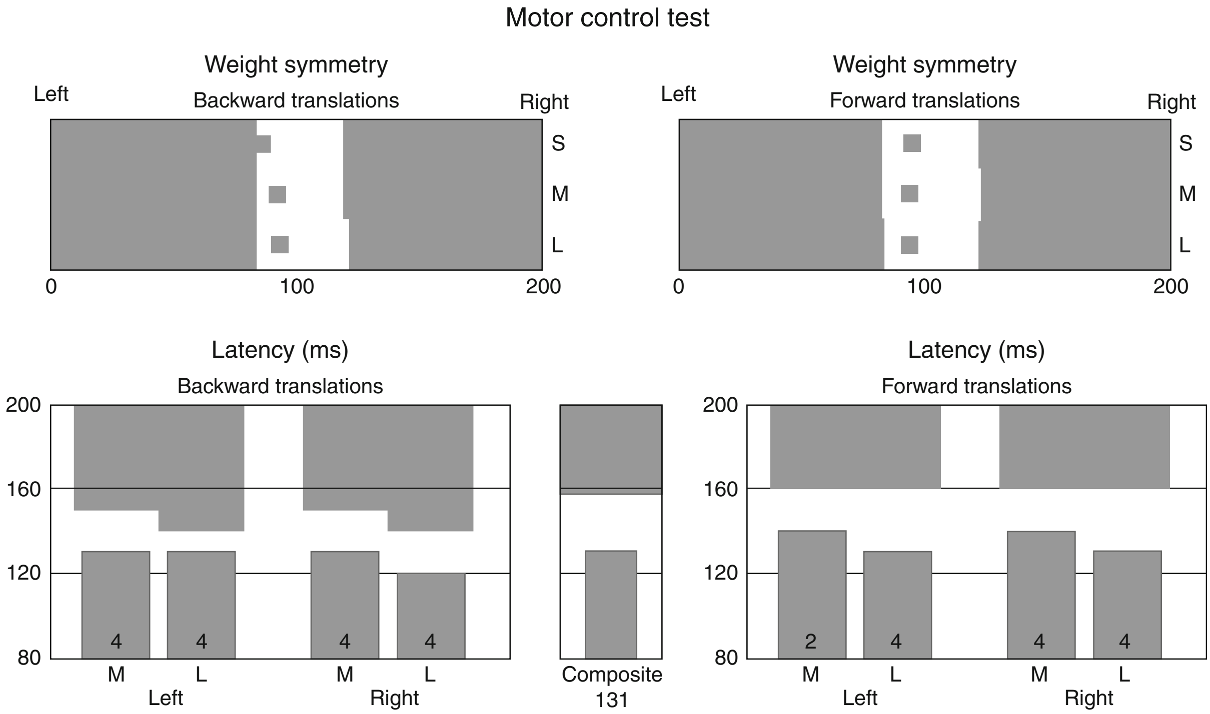
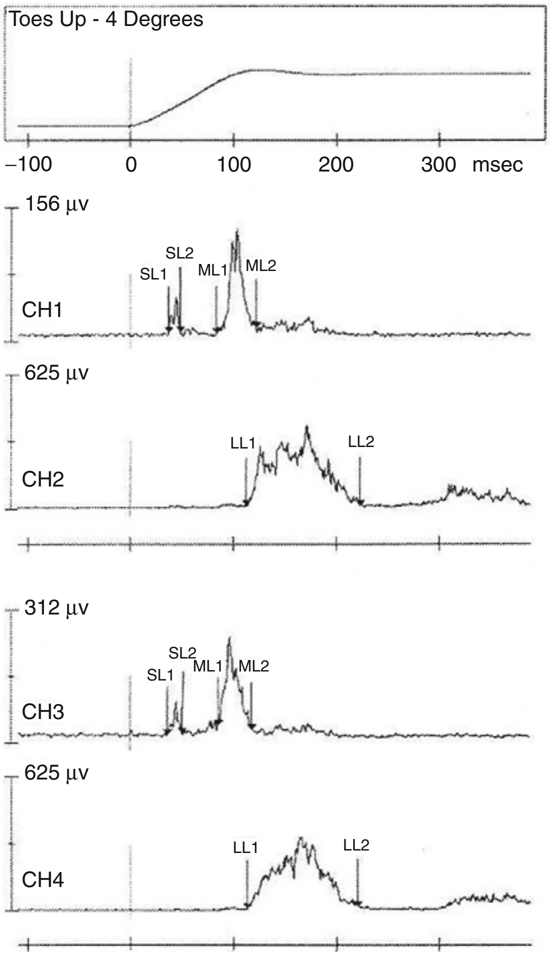


Fig. 5. Graphic printout of two of the aspects of performance of a subject on the motor control test (MCT). The upper plots illustrate weight bearing during each of the three translations (backward surface translations on the left and forward translations on the right). The bottom bar graphs show the latency to active recovery from the sway induced by sudden backward support surface movements (left) and those from forward surface translations (right). While there are three translations forward and backward (as shown by the three markings of weight bearing symmetry in the top graphs), only the medium and large translations are scored for latency. Note the numbers in the bars of the latency graphs. These represent the number of algorithms that gave the same estimate of the latency value illustrated in the graph. See the text for further discussion of the MCT.

with random inter-stimulus intervals and the EMG responses rectified and averaged over 20 events. This allows for clearer identification of onset and offset times of muscle contraction following the stimulus. There are three specific responses obtained, as illustrated in Fig. 6. The short (SL) and medium (ML) latency responses are seen from the contraction of the gastrocnemius shown in traces from channels 1 and 3 (CH1 and CH3) of Fig. 6. The third response is the long latency (LL) response obtained from the contraction of the anterior tibialis, shown in channels 2 and 4 (CH2 and CH4).

The latency and integrated amplitude characterizations of the EMG patterns for contraction from the gastrocnemius and the anterior tibialis muscles are compared to those that have been associated with specific pathologies, such as multiple sclerosis, Parkinson's disease, or for sites-of-lesions in the anterior cerebellum, the basal ganglia, as well as for spinal cord compression and peripheral neuropathies (Diener et al., 1984; Dichgans and Diener, 1987; Friedmann et al., 1987). When the contraction pattern is unrecognized, the interpretation is based upon knowledge of the underlying neural pathways considered responsible for the specific muscle activity. In general, these involve mediation of the short latency response via the spinal cord (H-reflex). The medium latency response is primarily controlled via the spinal cord, with amplitude size determined by the brainstem and basal ganglia. The functional stretch reflex, the long latency response, involves brainstem and cortical activity. Normative results for the paradigm have been developed across age and have been shown to have sensitivity and specificity of 68% and 87%, respectively for identifying the specific disease entities reflected by the defined patterns of abnormal responses (Lawson et al., 1994; Shepard and Telian, 1996, page 150). As with the MCT, the EMG evaluation does not distinguish afferent from efferent disruptions that may underlie the abnormal muscle responses. With additional clinical investigations of sensitivity in the lower limbs,



CH1	SL1	SL2	ML1	ML2
Time(ms)	37	48	83	122
Amp(µv)	10	11	9	16
Peak(µv)	51		128	
IEMG(µvS)	0.3		1.9	

CH2	LL1	LL2		
Time(ms)	112	223		
Amp(µv)	16	17		
Peak(µv)	387			
IEMG(µvS)	19.8			

CH3	SL1	SL2	ML1	ML2
Time(ms)	36	50	85	118
Amp(µv)	20	24	44	32
Peak(µv)	97		246	
IEMG(µvS)	0.7		4.0	

CH4	LL1	LL2		
Time(ms)	113	220		
Amp(µv)	14	23		
Peak(µv)	342			
IEMG(µvS)	17.3			

Fig. 6. A normal postural evoked response (PER) study is shown. CH1 and CH3 show the response for the gastrocnemius of the left and right legs respectively, with CH2 and CH4 showing the response from the tibialis anterior from the left and right legs respectively. SL1 – onset time for the short latency response; SL2 – offset time for the short latency response; ML1 – onset time for the medium response; ML2 – offset time for the medium response; LL1 – onset time for the long latency response; and LL2 – offset time for the long latency response. Latencies for onset and offset times are given in the grids at the right of each trace in milliseconds. The grids also provide for the absolute amplitude of the trace at the time of the onset and offset marks and peak amplitude of the short, medium and long responses in microvolts. Integrated amplitude (IEMG) is given in microvolt-seconds for each response. The trace in the panel at the top left shows the timing of the toe-up rotation of the support surface. Zero time indicates the time of actual start of the platform movement. (With permission from NeuroCom International – Shepard, 2000.)

and/or the use of lower limb somatosensory evoked responses, pathology affecting sensory input can be distinguished from motor output abnormalities.

19.3. Clinical utilization

When considering the clinical utility of formal postural control assessment the primary discussion becomes focused on when tests should be performed. One can make the argument that some level of assessment should be used on all patients complaining of dizziness even if imbalance or falls are not part of the principal symptoms. This argument is supported by the increased likelihood of a fall at all ages with the identification of peripheral vestibular involvement (Herdman et al., 2000). Furthermore, vestibular and balance rehabilitation therapy can reduce the first fall risk and the fall rate in the elderly (Gillespie et al., 2003; Hall et al., 2004; McClure et al., 2007). Do all patients require a full formal postural control analysis? Given the ability to predict whether SOT will be abnormal by first performing the CTSIB (Schumway-Cook and Horak, 1986; El-Kashlan et al., 1998) and then setting specific criteria for use of PERs, a staged protocol could be used. By clinical experience only and not through clinical study, the authors find the MCT assistive in helping to interpret complex patterns of abnormality that can occur on the Sensory Organization Test. Specific clinical examples are outside the scope of this chapter and the reader is referred elsewhere for patient examples (Shepard, 2000).

An example of the staged protocol used by the authors is provided. The criteria were developed based on a study comparing the CTSIB to SOT (El-Kashlan et al., 1998), a large retrospective study of findings in over 2000 patients when all tests were used on all patients (Shepard and Telian, 1996), and two prospective studies, one on false positive findings of the MCT and one on sensitivity/specificity of PERs (Shepard, 2000). Indications for SOT and MCT (both performed together) are given below. These are applied in a parallel loose format such that if any one of the criteria is met the patient goes on for full postural control evaluation.

(1) Abnormal performance on the modified CTSIB. The CTSIB, in its original form using six conditions, was used to investigate the relationship to SOT. Subsequently, this study in a modified manner of performing four conditions of eyes open and eye closed on a flat firm surface and a compliant surface (foam) is used for postural control screening. Normative data across age exist for this study performed in a semi-qualitative manner or via the use of a fixed force plate (Schumway-Cook and Horak, 1986; Weber and Cass, 1993; El-Kashlan et al., 1998; Rose and Clark, 2000).
(2) A major complaint in the presenting symptoms of unsteadiness or imbalance in standing and/or walking (constant or episodic) in the absence of vertigo at the same time.
(3) Known or suggested pathologic involvement of the pyramidal/extrapyramidal tracts or involvement in spinal tracts or suggestion of sensory and/or motor neuropathy via the patient's presenting symptoms or past medical history.

The basis for the criteria for performing postural evoked responses and the normative data for this procedure are provided in published studies (Lawson et al., 1994; Shepard and Telian, 1996). The criteria are:

(1) Abnormally increased latencies on motor control test – this is focused on the latency to active recovery from the forward translation of the support surface independent of the results of the backward translation.
(2) Symptom complaints of constant unsteadiness standing and/or walking independent of other test results or other symptom presentation.

As with the criteria for SOT/MCT, these are also applied in a parallel loose format such that either being positive is sufficient for going on for PERs. For the interested reader specific case examples of the use of this scheme applied to postural control testing together with the use of other laboratory studies used on the dizzy patient are available (Shepard, 2007).

The above discussions are to provide the reader with a general orientation to the clinical assessment of postural control in the dizzy and balance disordered patient and the options available to accomplish this task. Chapter 26 on bilateral peripheral vestibulopathy gives examples of the clinical utility of these studies and their integration with other investigations for diagnosis and management of the dizzy patient.

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