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Stocktaking on the development of posturography for clinical use

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Abstract. This report identifies fundamental problems to be addressed in order to build relevant clinical tests of human balance while standing. The stated purpose of these tests is identification of lesion site and/or definition of functional balance deficits in a specific patient. During a recent consensus meeting (ESCEBD), 60 researchers and experienced clinical users of posturography (14 European countries, 9 different disciplines) inventoried and critically analyzed the various methodologies of posturography currently used for clinical evaluation. To complement posturography, alternative methods of assessment of balance control were considered. The indications for the clinical use of posturography were defined as well as recommendations regarding measurement parameters, type of perturbations and signal analysis techniques to improve assessment of balance control. Consensus was reached that a force platform cannot be considered as a technique which is sufficient on its own to perform a clinically relevant test for the assessment of neuro-otological and musculo-skeletal conditions, evaluation of compensation or treatment (rehabilitation) or prediction of falls. It should be supported by complementary methods, such as segment motion analysis, body-fixed 2D or 3D accelerometer-gyroscope or electromyography. At present, no generally applicable posturography test is available with reasonable sensitivity and specificity for the diagnosis of balance disorders. Perturbation techniques are most likely needed to enhance the diagnostic yield of posturography.

Keywords: Balance control, clinical evaluation, posturography

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1. Introduction

World wide, generally accepted standards for the clinical application of posturography for the assessment of patients with impaired balance are not yet available. Recent reviews illustrate the different opinions on the topic [18,24,42]. Generally two types of posturography are distinguished: static and dynamic posturography. In static posturography or stabilometry, body orientation and body movements of a subject are detected while the subject stands on an earth fixed base of support with a fixed orientation with respect to gravity (e.g. quiet stance on a fixed horizontal or tilted platform). Static posturography may study one or two feet stance and evaluate the impact on balance of instruction, mental set and perturbations like visual stimuli, foam support, vibration, galvanic stimulation, etc. In dynamic posturography, the subject is standing on a moving base of support. The term computerized dynamic posturography refers to computer controlled platform movements and perturbations.

Although static posturography has been used successfully by researchers and clinicians for over 35 years, there is no consensus yet on the precise aims of posturography or on the optimal body movement detection method, the required perturbation techniques, the relevant output parameters and optimal signal analysis of postural sway on force plates. Therefore, a European group of experienced users of clinical posturography held a meeting from which resulted the following report on reproducible and clinical relevant posturography methods to evaluate balance control in patients.

In a review from 1981, Stockwell concluded that the posturography tests available at that time might be useful to otologists, but that there was no proof of an added value beyond other diagnostic procedures; more powerful techniques were under development, but methodological problems remained, and none was yet ready for routine clinical use [53]. A detailed review of the extensive literature since then revealed a large number of publications that promote posturography in various forms for routine clinical use, and a minority of papers being skeptical about its clinical relevance. Diener and Dichgans were amongst the first to develop a standardized technique of toe-up rotation to measure motor reflexes of the *tibialis anterior* and *triceps surae*, and also implemented a sinusoidal platform stimulus technique. The sinusoidal stimulus allowed discrimination between the anticipatory and reactional strategies that are used by subjects to control the centre of mass over the base of support. These ideas were implemented in the computerized moving platforms (T-Post) that were very popular in Europe. The typical 3Hz tremor of Friedrich's ataxia during stabilometry was also mentioned in their studies. In 1988, Diener et al. stated that this type of dynamic posturography helped to identify and localize cerebellar lesions [22]. But the discriminative power of posturography has been contested. Ten years later, Baloh et al. found that posturography does not allow discrimination between patients with cerebellar atrophy or bilateral vestibular loss [4].

Nashner, Black and Horak made a substantial contribution to the analysis of the impact of the various sensory subsystems on postural control in order to get more insight in the processes of sensory substitution and central compensation, and to optimise revalidation. A spin-off out of this research was the still frequently used Computerized Dynamic Posturography (CDP), in particular the 'Sensory Organisation Test (SOT)'. Here the proprioceptive and visual inputs to the postural control system are manipulated by ingenious technology to evaluate their respective contributions. Body sway in the SOT is evaluated in six sensory conditions: 1 stable platform, eyes open; 2 stable platform, eyes closed; 3 stable platform, sway referenced visual surround; 4 sway referenced platform, eyes open; 5 sway referenced platform, eyes closed; 6 sway referenced platform and visual surround. In each condition, an equilibrium score is calculated by comparing the angular difference between the person's calculated maximum anterior to posterior centre of gravity (CoG) displacement relative to a theoretical maximum displacement. In the SOT, the proprioceptive sensory input is assumed to be affected by a technique called sway referencing [9,10], where the supporting surface moves according to the filtered anterior-posterior ankle torque (difference between fore and aft strain gauges) to null out the ankle input within the sway limits of 8° forwards and 4.5° backwards. Shumway-Cook and Horak [51] and many others used a comparable technique by placing the patients on a support surface covered with foam rubber. These techniques make the contribution of the foot-ankle proprioception and the pressure receptors in the feet less adequate [43,44]. Other techniques used to disturb the proprioceptive receptors during posturography are vibration of the calf muscles or Achilles tendons [47,48,52], or chilling the foot soles [36,37]. Vibration of the calf muscles or Achilles tendons induces instability and an illusion of body movements [43]. The vibration induced body sway is thought to result from the saturation of group I afferents and the activation of the secondary endings of the muscle spindles, leading to misleading information of the actual muscle length [39,47]. Chilling the foot soles is believed to anaesthetize the pressure receptors of the footsole and enhances body sway too [36,37]. Although it is possible to abolish the visual input to the postural control system simply by closing the eyes [15, 44], the previously mentioned SOT also incorporates a visual sway referencing technique (also called stabilised vision) where the visual surround moves with low-pass filtered anterior-posterior torques, which may be an estimate of CoG movement. The rational behind this addition is that the postural control system in some vestibular deficient patients is believed to respond inappropriately to *conflicting* or *inaccurate* visual inputs [8]. Less sophisticated but comparable techniques are described where body sway is examined in subjects wearing a head mounted visual conflict dome or specially designed goggles [30].

Despite intensive research, it remained controversial which method is the most effective to disturb proprioceptive or visual input for postural control. However this is essential to quantify their impact in the individual. One of the problems encountered is that any effort to determine the contribution of any sensory input to postural stability is hampered by the fact that stabilisation and orientation of the head and body in space depends on learning and habituation processes and on a complex integrative processing of vestibular, visual and proprioceptive-somatosensory inputs [46]. The complex, most likely non-linear, integrative processes complicate the interpretation of the manipulation of the sensory inputs. Habituation, fatigue, the instructions by the examiner, motivation and subject naivety affect the reproducibility of most balance tests. Particularly, pre-knowledge introduces a methodological problem as poor reproducibility hinders a quantitative comparison between successive tests with different sensory conditions. As a consequence sensitivity and specificity of, for example, the SOT were and still are subject of debate [11,19,23]. It has been reported that the SOT detects decreased postural control in patients with otolith disorders [6], but some studies indicate that already reproducibility of the test results is uncertain [25,58]. Identification of malingerers from vertiginous patients by trained observation seems to be equal or more reliable than by analysis of the posturography outcome measures [55]. Limited clinical value of posturography is also mentioned by many authors [19,25,27,50] and dynamic posturography could not replace a skilled clinical judgment of impaired fitness to work [50].

A large variety of sophisticated stimulation or perturbation techniques are used world wide, and special equipment has been developed and has partially been commercialized [1,21,32,34,41,52,57]. It has also been claimed that standing on a simple piece of foam rubber is as good as standing on a sophisticated computer controlled dynamic posturography system for study of balance control [59]. No real true progress in the predictability of falls on an individual basis could be reported in a review by Bloem et al. [13]. In 1998, Baloh et al. still observed that posturography data did not correlate with frequency of falls or provided information about the cause of the imbalance in an individual patient [5]. O'Neill et al. indicate that CDP alone is not a useful tool to assess balance and functional changes in patients with vestibular hypofunction [45]. Ultimately the outcome of many analyses was not very successful: CDP did not correlate with Dizziness handicap scores [49]. Buatois et al. however concluded that dynamic posturography is a sensitive test to identify those at high risk of recurrent falls [17].

Body sway and position parameters depend on many factors, which indicate the need for standardization of the precise test condition, data-acquisition and analysis, including clinically relevant output parameters. Regarding measurement and stimulus conditions, many aspects have been discussed. The distance between the heels, and not the angle between the feet, appears to be important and requires standardization during the test [54]. Various complex mathematical models have been developed to adequately describe postural control and adaptation in humans using posturography data [26, 32] but consensus about the most appropriate analysis has not yet been reached. Research is still ongoing to identify the output parameters that allow making differential diagnosis by using dynamic posturography [2, 34,40,57].

Most reviews by experts in the field indicate that not that much has changed since Stockwell et al., 1981 [53] and that posturography has an additional but limited value compared to the standard vestibular test battery [1,12,31,41,53]. Through the years it became clearer that, like static posturography, CDP evaluates a complex function and gives a quantitative measurement of the impact of interventions and rehabilitation on balance [19,25,28,34].

2. Methods

An extensive survey of the literature served as a basis for the organization of a special meeting (ESCEBD) in Nancy (N.E. France) to gain insight in the current opinion of clinicians regarding posturography as a clinical tool. Sixty highly experienced users of clinical posturography and specialists in balance control from fourteen different European countries participated in the meeting with various clinical backgrounds: ENT, neurology, ophthalmology, physical medicine and rehabilitation, geriatrics, cardiology, sports medicine and (clinical) physics.

The problems encountered with posturography for clinical diagnostics were first listed by asking each attendant to indicate two major problems or interesting topics that had to be addressed. Subsequently seven critical reviews were given regarding the following topics to stimulate discussion: overview of the different types of posturography (including detection techniques) currently used for clinical evaluation; overview of various techniques of balance perturbation and signal analysis; review of data regarding clinical relevance of various posturography methods to assess vestibular pathology; multi-factorial assessment of imbalance in the elderly by posturography; predictive values of posturography in relation to risk of falls; ability of posturography to reveal malingering; and assessment of rehabilitation of balance control after stroke.

The discussion was subsequently focused on the following major topics: purpose of posturography in health care; definition of the minimally required techniques for body movement detection; definition of the minimally required perturbation techniques; and definition of the most clinically relevant balance control parameters.

3. Considerations

3.1. *Statement regarding the clinical relevance and diagnostic value of static and dynamic posturography*

Posturography is considered as the general term for techniques to quantify postural control in upright stance in either static or dynamic conditions.

Static Posturography or stabilometry is a technique using a force platform to quantify postural equilibrium in man by measuring position and the movements of the centre of foot pressure during stance. Stabilometry shows clear abnormalities in case of acute peripheral vestibular deficits (but normalizes after compensation) and in case of central nervous system pathology. In the opinion of all attendants, recent literature and current clinical experience indicate that the poor sensitivity and specificity of stabilometry do not allow recommendations of stabilometry on its own as a valuable standard clinical test for the identification of the etiology of poor balance control. Following this conclusion, many attempts have been made to increase sensitivity and specificity of posturography: introduction of more challenging testing conditions during stance, using a wide range of perturbation techniques; by developing (computerized) dynamic posturography; by detection and analysis of a wider array of parameters instead of using only center of foot pressure as in stabilometry.

Computerized Dynamic Posturography is a way to enhance the yield of postural measurements by using a movable platform and / or visual surround, included in the Sensory Organization Test (SOT), the Motor Control Test (MCT) and Adaptation Test (AT). The CDP measures postural stability in case of absence or conflicting sensory information, motor responses to perturbations (MCT) and adaptive behavior (AT). Because of redundancies in the postural control system and interindividual variability in the organization of sufficient balance control and in the ability to compensate for sensory losses, CDP has not been considered to be a localizing diagnostic test but as a functional test of balance, assessing mainly the effects of adaptation, rehabilitation and training.

In conclusion, no sensitive or specific platform posturography is presently available to detect postural deficits in a way which has localizing diagnostic value in balance disorders. As a consequence a critical discussion continued about the aim of posturography, the optimal equipment to assess balance control, the testing conditions and perturbations, the relevant output parameters and signal analysis. Alternative methods for the assessment of balance control like body-fixed sensors, subjective proprioceptive horizontal or analysis of gait will also have to be considered as complements to posturography.

3.2. *The aim of posturography*

Table 1 lists the aims of posturography proposed by the participants. Key demands are identification, localization and quantification of the deficits that account for impaired balance. It is questionable whether all aspects in Table 1 ever will be achieved by one single test. More likely is a battery of tests, which might be different for infants, adults and the elderly.

The first major step to be made is the design of a test that allows a reproducible quantification of balance control *per se*. Posturography should investigate and

Table 1
Aims of posturography put forward by the participants

– An up to date statement is needed regarding the clinical relevance and diagnostic value of static and dynamic posturography (stabilometry, dynamic posturography (Sensory Organization Test, Motor Control Test), etc.)

– Definition of the aim of posturography
  * to objectively quantify balance control
  * to identify and describe deficits and functional loss (vestibular, motor-ability, impact of deformations (orthopedic pathology (e.g. scoliosis, limitation of mobility in joints), non-organic diseases, simulation or aggravation))
  * to quantify handicap in daily life
  * to predict falls and balance problems
  * to guide rehabilitation programs for balance
  * to propose a relevant assessment tool for the development and regression of motor control and gait

– Which measurement techniques are optimal and required to assess balance control?
  * evaluation of various assessment techniques of measurement of body posture and body movement (e.g. force-platform, accelerometers and/or gyroscopes, video techniques)
  * need for 2D or 3D evaluation of movement, need for separation into anterior-posterior and/or lateral sway

– Which test conditions and perturbation techniques could be recommended?
  * position of feet, arms and head
  * simultaneous cognitive tasks (dual task paradigm) or distraction of attention, mental set and instructions
  * relevance of assessment of posture with eyes open, eyes closed or sway referenced vision necessary
  * optokinetic stimulation including sway referenced vision
  * platform movements including sway referenced platform
  * vibrations of neck and calf muscles
  * impact of habituation and adaptation
  * balance during gait or equivalents

– Analysis techniques and definition of clinically relevant output parameters
  * spatial orientation of body (segment) / sway path / sway velocity / sway acceleration / sway area, etc
  * muscle activity (electromyography)
  * spectral analysis / Fourier Transform (FFT-FFIT) / Wavelet transform of position or movement
  * timing between stimulus and response (reaction times, latencies, phase)
  * timing and sequence of movement of body segments (reaction times, latencies, phase)
  * psycho-physics, perception of movement or body orientation

– Standardization needed for the measurement technique of choice, the procedure, data analysis and display
  * evaluation of sensitivity and specificity of complete test procedure with respect to various balance disorders
  * tests need to be reproducible and adaptable to individual patients
  * are there specific response patterns for specific pathologies?
  * definition how to deal with failures to complete a test and falls
  * dependence of posturography data on age, gender, motor training and experience
  * what are the pitfalls or practical limitations of the test?

– Comparison of posturography with other methods of assessment of balance control
  (subjective proprioceptive horizontal, balance analysis during gait)

describe individual balance strategies and the impact of and the dependence from the various sensory modalities. The objective to localize anatomically a disorder of the postural system or to trace its etiology is not realistic. The goal is rather to characterize the sensory and motor deficits in relation to complaints, to contribute to a customized rehabilitation program and to have a meaningful and discriminative estimate of the deficits of an individual patient as opposed to parameters with merely group differences with large overlaps between patients and controls [56]. Psychophysical parameters like perceptions of movement or body orientation in space could be evaluated. A recent example is the report that an unilateral loss of otolithic input impairs the ability to judge whether a support surface is horizontal [7].

In conclusion, in order to be clinically relevant, posturography should be able to identify and quantify the postural and balance deficits related to the complaints, trace sensory deficits in an individual patient and provide information to guide optimal rehabilitation.

3.3. Which measurement techniques are optimal and required to assess balance control?

Force platforms are easy to use, low cost and provide a crude estimate of body posture and movement (estimation of the position of the centre of body mass (CoM) based on the filtered centre of foot pressure (CoP)), in conditions where no substantial shear (reaction) forces are induced. However, different body postures can lead to the same position of the centre of foot pressure and therefore provide ambiguous information. Under dynamic conditions the presence of shear forces complicates an accurate reconstruction of the body posture and movements. This is partially solved by use of advanced force platforms that allow detection of shear forces which by themselves may provide information on the work carried out by the body to maintain stance. Ground reaction force might also be a relevant element for gait analysis. Force platforms do only allow the assessment of balance control within a restricted space. Due to these limitations, stabilometry without perturbations is not considered as a sufficient technology for posturography.

Three-dimensional (3D) video-techniques using body-fixed markers as used in gait analysis allow a detailed reconstruction of body posture and movements with good spatial and temporal resolution. This technique is accurate for the detection of absolute body position. However, pre-calibration and installation is time consuming and abnormal dimensions of body segments (prostheses, spasticity in children) and markers outside the camera's field or hidden from the cameras (by, for example, wrist pronation for a wrist marker) can create problems when reconstructing body movements. Also substantial muscle action may be present to maintain position, which might not be detectable when just recording movements. The video technique does not allow the calculation of amplitude and direction of ground reaction forces, unless the kinematics and body masses are exactly known.

Body-fixed 3D accelerometers and gyroscopes are robust movement sensors that allow detection of posture and movement of several body segments. Depending on the complexity of body movements one or more sensors will have to be used. Wireless transmittance, a large free range of motion and sufficient acquisition time is already possible. Unfortunately, drift can induce substantial inaccuracies in the detection of absolute body posture, which makes the technique better for detection of body motion than body position or orientation. Recently, sensors with virtually no drift have become available and overcome some of these problems. Installation and use is simple compared to 3D video techniques but more complex than the use of a force platform. Positioning of a 2D or 3D sensor on the trunk close to the CoM is a simple, low cost and an ambulatory alternative for a force platform. Different body postures can however lead to identical output patterns of the sensor, leading to ambiguous information about the real movements. Nevertheless, some interesting developments make use of this kind of technology and show promising results [14,16,33,34,57]. These developments showed that in static conditions only one body-fixed sensor at the lower back is sufficient to monitor the position of the centre of body mass. However, as soon as different body segments move relative to each other (limbs, upper or lower trunk, head) additional sensors on the moving body segments are needed to correct for the impact of segment motion upon the COM position. The general question is often raised whether body movement analysis with body fixed sensors will supercede platform posturography and 3D video techniques. It is clear that – in comparison- the application of body fixed sensors is not restricted to a certain environment. For example body fixed sensors can be applied easily during gait in a natural environment, where the application platform or video posturography or gait analysis is very limited or impossible. Several promising applications are in development that do indeed indicate that body fixed sensors might have a broader clinical and scientific application [14,16,57].

Postural control mechanisms seem to be organized differently for the pitch and roll planes and pathology seems to affect anterior-posterior sway differently than lateral sway [3,35]. This shows the relevance of an analysis of body sway in various directions. So far several posturography tests only analyze anterior-posterior and lateral sway and movements in other directions are not taken into account. As postural sway may occur in any direction a complete analysis needs a full 2D vector-analysis with for example movement direction and body velocity as possible relevant parameters including an analysis in the pitch and roll planes.

Apart from body or CoP movements, muscle activity induced by movements of the support surface (rotations or translations) can be monitored by standard electromyography techniques to determine postural response latencies. Diener, Dichgans and Allum pioneered this work; unfortunately they also showed how complicated the clinical interpretations are and that the diagnostic value is limited.

In conclusion, a force platform in combination with complementary methods such as a motion analysis, 3–5 body-fixed 2D or 3D accelerometer-gyroscopes or electromyography could be considered as a necessary technology for the development of a relevant clinical posturography test with a wide range of applications.

3.4. Which test conditions and perturbation techniques may be pursued?

In posturography, body sway parameters depend on foot position, shoes, support surface, head orientation, mental set, instructions, alertness and visual fixation distance. Habituation (learning effect), anxiety, fatigue and drug usage are also factors that affect test outcome. This becomes even more important when complex perturbation techniques are used. As all these factors affect test reproducibility, strict standardization of all test conditions for each patient is needed. On the other hand however, the large range of postural control and motor abilities among healthy subjects and patients might force us to adapt test conditions to individual abilities. These aspects may best be overcome if each patient acts as his/her own control in a series of different test conditions as done in the Romberg test (eyes closed versus eyes open) and the SOT concept.

So far, various perturbation techniques have been applied either to create a stimulus-response test condition (e.g. MCT) to enhance test specificity or to reduce or manipulate the input of a specific sensory system (eyes closed, optokinetic stimulation, sway referenced vision, foam rubber, vibration of postural muscles, cooling of foot soles, sway referenced platforms, caloric or galvanic stimulation, etc.). It seems, however, that sensory substitution strategies and selective attention are quite variable among healthy subjects and patients, not allowing an easy identification of sensory deficits in an individual patient with these techniques. Another suggestion is that perturbation techniques should mimic frequently occurring sensory conditions in daily life to allow extrapolation of the test-results into terms of handicap in daily life and to allow definition of effective personalized rehabilitation programs.

In conclusion, a perturbation technique is necessary to enhance the sensitivity and specificity of posturography and to be able to trace the motor and sensory deficits causing a possible balance disorder. However no optimal solution could be proposed yet.

3.5. Analysis techniques and definition of clinical relevant output parameters

Position and movement of the body or body segments and the CoP or electromyography of postural muscles can be used to analyze posture control in many ways. Here, variance of the CoP is considered to reflect the energy associated with postural sway. CoP sway area is associated with precision of sway control, sway velocity and sway path are parameters associated with the efficiency of postural control. Analysis of the timing between responses and stimulus reveal reaction times, latencies and phases and may have a clear clinical interpretation. Frequency analysis can inform about the transfer functions and the dynamics of the control mechanisms involved and allow the display of tremors that are characteristic for cerebellar ataxia, etc. More modern frequency analysis techniques (among them wavelet transforms) allow an observation of the frequency content of the response signals as a function of time. They seem to provide more detailed information than the traditional techniques that calculate the frequency content averaged over time (Fast Fourier Transformation or FFT). However, wavelet analysis, time-variant alternatives for the Fourier Transformation (FFIT), have been developed as well. Using these or similar techniques, the parameters that describe the transfer functions related to balance control can be estimated.

In conclusion, no consensus presently exists which analysis techniques provide the most clinically relevant output parameters. The choice of analysis and the choice of output parameters depend on the stimulation or perturbation applied. It is not possible to come up with a clear recommendation. It is also assumed that further developments will appear in the mathematical analysis as it continues to develop in other fields of science.

3.6. Standardization needed of the measurement technique of choice, the procedure, data analysis and output presentation

The complete test procedure (instruction and mental set of the patient, single or double tasks, initial posture, stimulus type and response, analysis technique and output parameters) will have to be evaluated regarding reproducibility, sensitivity and specificity, clinical applicability, costs expressed in money and time [38]. Normative data have to be gathered and systemized considering the large variety (e.g. physical body measures, age, regular physical activities) of patients with balance disorders due to organic or non-organic origin.

3.7. Comparison of posturography with other methods of assessment of balance control

Based upon current understanding, it seems unlikely that one particular posturography test will be able to identify the etiology of every balance disorder. Several studies have shown that the sensitivity and specificity of balance testing can be increased by results from more than one test. It is more likely that a set of specific tests will be needed [20,29,58], including static and dynamic posturography, vestibular caloric and rotational tests and analysis of gait and that a full clinical picture can only be obtained when all tests are evaluated in combination. To complement posturography, alternative methods of assessment of balance control like perception of posture in space and measurements and analysis during gait will have to be considered to allow for an appropriate evaluation of balance control in patients.

4. Conclusion

No sensitive and specific generally applicable posturography test is available yet for the assessment of balance disorders. Ideally, clinical posturography should be able to identify and quantify the postural and balance inabilities related to the complaints and trace the sensory deficits of an individual patient and provide information to perform an optimal rehabilitation. It is unlikely that one standard test will be sufficient to explore balance control in all cases of disturbed postural control. The large range of postural control and motor abilities among healthy subjects and patients might force us to adapt test conditions to individual abilities and to construct various test conditions and comparing the performances within each individual.

A battery of different types of balance tasks, including stabilometry associated with electromyography, motion analysis, body-fixed 2D or 3D accelerometer-gyroscopes, to evaluate stance under a variety of sensory conditions, response to perturbation, postural stability during gait or anticipatory postural adjustments, could be useful for the development of relevant posturography testing with a wide range of application. It is yet unclear which technique of body movements detection is best, e.g. whether body fixed sensors supercede platform posturography, as body fixed sensors can obviously be applied in many more conditions. While perturbation techniques are needed to enhance the specificity of posturography, they should mimic daily life sensory conditions to allow extrapolation of the test-results into terms of handicap in daily life and to design effective personalized rehabilitation programs.

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