The Role of Vision and Spatial Orientation in the Maintenance of Posture

This article reviews and analyzes the role of vision and spatial orientation in maintaining posture and balance. The key issues that relate to the development of postural control across the life span are discussed. Use of vision as a critical source of information that specifies spatial orientation in the environment is considered. We argue that the visual system functions as part of the perception-action cycle as promoted in ecological psychology by James Gibson. We compare and contrast theory and evidence of both standard and ecological accounts of how the visual system perceives the information and the findings relative to the role of the retinal vision in processing and acting on information related to motion. Changes in the ambient optical array (optical flow) as a non-force field are compared with gravity-based perturbations relative to the possible influence of the non-force field to changes in the motor system. Finally, a summary of some of our own work is presented, with comments about implications for further research and possible applications to clinical practice. [Wade MG, Jones G. The role of vision and spatial orientation in the maintenance of posture. *Phys Ther.* 1997;77:619–628.]

Key Words: *Posture, Spatial orientation, Vision.*

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Endurance, power, and high levels of coordination and control are all necessary to execute skilled behavior and are used in a complementary fashion to provide postural stability. The reflexes that an organism possesses at birth provide a short-term safety net that permits the acquisition of nutrients and a limited and constrained connection to the organism's new environment. Without some control of posture, the organism cannot acquire the capacity to optimally explore and interact with its environment. Diminished or absent postural control can greatly disadvantage or threaten the very existence of the organism, or limit its potential to a less-than-optimal level of development. Postural stability is both the anchor and the launching pad for much of the activity of the organism. In humans, postural control provides stability, exhibited in the form of balance in a variety of body configurations (eg, seated, bipedal stance), whether stationary, preparing to move, in motion, or preparing to stop.

Earlier reviews of posture and balance by Williams[1(pp261–281)] separated what is sometimes called "static balance" from "dynamic balance." In a rather simplistic fashion, balance has traditionally been measured either by an individual's stationary position in quiet upright stance (static balance) or by tasks such as locomoting across a balance beam or walking a tightrope (dynamic balance). We view this dichotomy as artificial because it affords few interesting theoretical or practical insights. Instead, we argue that just as the development of postural stability can be defined as a continuum between early infant reflex activity and the maturing human's infinite number of voluntary motor activities, so should assessment of balance and posture be viewed across a continuum from static to dynamic balance, based on context.

Our present task is to describe the role of vision in the control of balance and postural stability. First, we consider critical factors in the role of posture and balance from a life-span developmental perspective, both as an important attribute of the developing organism and as the changes that emerge as a function of age. Second, we discuss the role of posture and balance in a changing environment and then review the way in which vision contributes to posture and balance in the context of what we term the "triad" of posture and locomotion—namely, the somatosensory, vestibular, and visual systems. We argue that of this triad, the visual system is the least well understood and has been the recipient of the least inquiry, compared with the extensive literature on the somatosensory and vestibular systems. Third, we discuss how perceptual systems derive spatial orientation, and we determine how crucial this derivation is with respect to the acquisition of information for postural control and balance. We extend this discussion further by reviewing competing theories of vision and posture.

We contrast the traditional model of a neurologically based system that is essentially computational, viewing the nervous system as a controller of the musculoskeletal system, with another view[2] that posits that information for the coordination of control and movement is directly perceived. This latter perspective views posture and balance as managed by an integrated musculoskeletal system that is heterarchical (shared) rather than hierarchical and advances the theoretical ideas of perception proposed by the late James Gibson.[3,4] Finally, we present, in summary form, data from our own laboratory on the development and maintenance of posture in younger and older adults and individuals with disabilities.

We will use the data from our laboratory to illustrate an overarching framework that seeks a more ecologically valid understanding of the role of the visual system in the control of posture and to argue aggressively for viewing the perceptual systems as the link between the environment and the active organism. With this perspective in mind, we will conclude with some comments regarding implications and possibilities for clinical practice.

Critical Factors in the Development of Posture

Postural stability is essential in the everyday activities involved in leading an independent lifestyle. Early and late in life, postural stability is of great concern because postural problems often result in injuries, especially among elderly persons, and in the expense of care and rehabilitation. Postural stability is modulated by postural control, which is exhibited in the form of postural adjustments.[5–7] These adjustments can occur prior to (anticipatory adjustments) or during (associated adjustments) voluntary movement and are thought to minimize the displacement of the center of gravity caused by voluntary movement[5] and also to affect voluntary movement directly.[6,7] Thus, postural control is dependent, to a large degree, on the goal of the voluntary movement

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and on the contextual setting[8] or environment in which it takes place. Bipedal upright stance and movement are inherently unstable, with about two thirds of the body's mass positioned over the lower extremities.[9] Although this body configuration facilitates actions such as reaching, grasping, and seeing, there are potential drawbacks, such as falling, especially for older individuals who are slower to react to rapid unexpected body perturbations.[10] This may be a factor in the changes in voluntary movement strategies that occur with aging, which can be characterized as slower, stiffer movements, with a wider base of support. For example, elderly persons often reach for objects with one hand while firmly grasping an external support such as a countertop with the other hand. Another example occurs when an elderly person climbs stairs, using a handrail for postural support.

At the other end of the life span, infants who are afforded postural stability and support from "walkers" or parents can produce voluntary movements that would not be possible on their own. Despite the differences in behaviors between infants and elderly persons, one common link is that behavior tends to emerge from intrinsic and extrinsic resources available to an individual. Thus, more often than not, decrements in one component of behavior do not linearly map onto a corresponding decrement in overall behavior. There is a certain degree of exploration that occurs, resulting in a compensation for the decrement. For instance, in infant development, independent upright stance requires adequate musculoskeletal development, which emerges at approximately 12 to 14 months of age.[11] Although infants attempt to explore their environments (crawling and sitting), independent behavior is constrained by the rate of musculoskeletal development.

Numerous studies of postural stability have focused on static, discrete postural tasks such as upright stance[12–14]; however, postural control is also a continuous process that demands responses to a constantly changing environment. Whether postural studies of discrete actions relate to real-world events is sometimes questionable. This is not to say that discrete postural tasks are not useful in developing an understanding of typical and atypical response characteristics, but rather that behavior, expressed via more natural movements, represents adaptive coordinative responses, most based in the context of continuous environmental, biological, and task constraints. Postural control, in our view, should therefore be considered on a continuum between stationary posture and movements. Furthermore, we suggest that this is a more valid approach to studying postural stability, and it can provide greater insight into the processes by which people manipulate and respond to their environments during goal-directed behaviors.

The Relationship Between Posture and Voluntary Movement

The relationship between posture and movement is an inclusive subset of a larger set of relationships between perception and action. Not only do actions within an environment lead to increases in perception, perception in turn leads to knowledge of potential behaviors within the environment (ie, affordances).[3] For example, exploratory behavior within an environment, such as a child playing with a new toy, produces sensory stimulation that is textured by the dynamics of the action-environment cycle and that results in movement modifications based on this feedback.[15,16] Given that the action-perception cycle is critical to the organism-environment interaction, Stoffregen and Riccio[17] have argued that an important goal of postural control is to provide stability to both sensory and motor systems, which optimizes the influx of sensory information while moving. For example, studies have shown that the stabilization of head motion is a fundamental feature of locomotion[18] and upright stance.[19] The ability to maintain an invariant head position relies on the constraining influence of the degrees of freedom available in the skeletal system.

In maintaining upright stance, an organism interacts physically with a surface and is subject to a gravitational force. This interaction (usually occurring on the soles of the feet) can be seen as a pivotal point around which the sum of three-dimensional inertial force vectors acting as torques of segments around joints is minimized[20] such that the gravitational force vector is within a functional base of support. This interpretation can be extended to movements such as locomotion, where although the sum of the gravitational forces is often outside the base of support, it is a deliberate functional behavior and the creation of these forces is used to aid movement progression.[21]

The ability to modulate posture and voluntary movement serves to enhance the acquisition of environmental information, not only from visual mechanisms but also from somatosensory and vestibular mechanisms. Investigation of each of these systems separately is possible; however, in our view, it is the nature of the integration of these systems that holds the key to a better understanding of how the postural system works.

How these three systems integrate across the life span is not well understood. Certain traits, however, are evident. Howard,[22] for example, proposed that the somatosensory and visual systems are primarily sensitive to low-frequency stimulation. Warren[23] has suggested that these systems are associated with postural sway (under 0.5 Hz) and gait (under 1.0 Hz). The visual system affords far more sensitive information than the vestibu-

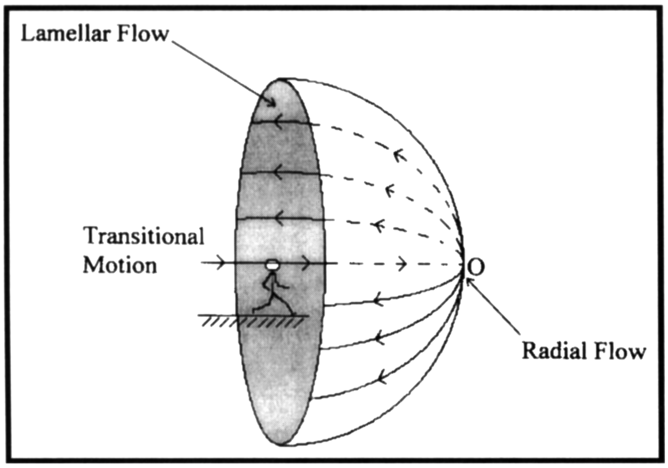

Figure 1.
A three-dimensional representation of the lines of flow of the optical flow field generated by pure transitional movement through the environment. As the flow lines approach the locomoting subject, the optical array close to point "O" flows outward in a radial fashion, transforming into lamellar flow as it passes the subject.

lar system,[24] which itself appears to be more sensitive to high-frequency movement.[22] All three systems specify information that is used for spatial orientation, and there often seems to be a redundancy in the specification of postural state.[4] Nevertheless, the importance of any one perceptual system cannot be underestimated. We believe, for example, that elderly drivers who wear hearing aids appear to be more susceptible to automobile accidents; this may also hold true for the army of cell phone users.

The importance of joint kinesthesia in postural control has also been demonstrated in quiet upright stance, where subjects experienced a loss of upright stability while they stood on compliant[25] and sway-referenced surfaces.[26] The degradation of perceptual and sensory systems has been linked to potential postural problems; accordingly, a large body of research has focused on identifying predictive variables for postural problems.[27,28] This attempt to identify predictive variables has been only moderately successful, with mostly low correlations present between predictor scores and outcome. This finding may be due to factors such as the functional heterogeneity (idiosyncracies) of the subjects studied. The finding stems from compensatory motor strategies, which rely very little on feedback from immature or degraded perceptual and sensory systems, and thus maximize feedback from intact perceptual systems. Such factors make research on atypical populations a daunting task, however, one that carries a potentially high reward.

Theoretical Issues

Vision is the third component of the triad of posture and locomotion (somatosensory, vestibular, and visual systems) and is an important source of information. The visual system acts not only via the clarity with which it "sees" (visual acuity) but also via the information that is generated by the individual's motion through the environment. The acquisition of such dynamic information generates field-of-view information for self-motion, the critical issue being active motion.[29] The traditional model of the visual system (referred to as the "two-mode theory of vision"[30]) asserts that spatially distributed information comes to the individual via the ambient mode, which is responsible for orientation and locomotion, and the focal mode, which is responsible for object recognition and identification.[30] Thus, *focal vision* refers to a system that seeks to answer the question "What is it?" and presumably generates a conscious awareness and registers events predominantly in the central retina.[31]

Ambient vision answers the question "Where is it?" and has been termed by Schmidt[31] as "motor vision." Although stimulation of the peripheral retina generally results in the use of the ambient motor vision, and the focal mode is by and large a consequence of stimulation of the central visual field (foveal), ambient vision is available and can stimulate both the central and peripheral retinal locations.[31] A large body of literature exists on age-related changes within the visual system.[32] Decreased visual acuity, restrictions of the visual field, increased susceptibility to glare, and poorer depth perception as a function of age have all been studied.[32]

The visual system of elderly persons has a decreased sensitivity to low spatial frequencies, and elderly individuals therefore require more contrast to detect spatial differences.[33] This diminished sensitivity to low spatial frequencies may be partly responsible for some problems of decreased postural stability, because locomotion and postural stability are thought to depend in part on low-frequency visual information, mediated by inputs from the peripheral visual system.

The peripheral field of view is known to decrease as a function of age, and the importance of peripheral vision in postural control has been demonstrated in numerous studies.[28,34] The traditional two-mode theory[30] asserts that postural sway, as a specific case of self-motion, is controlled primarily by the ambient visual system. The assumption is that the retinal periphery fails to detect radially structured information from the optical flow that relates to postural control and is sensitive only to lamellar flow. The types of flow are illustrated in Figure 1. This assumption implies that it is not only the retinal region that determines postural stability, but also the nature and structure of the light itself that is perceived by the periphery of the retina.[29]

The late psychologist James Gibson[3] proposed a different perspective from the traditional two-mode theory of vision. Gibson's[3] ecological theory anchors visual perception to the optic array and emphasizes the importance of optical information retrieved from various sectors of the optic array. The ambient optic array is essentially a pattern of differential reflectances that converge at every point in the visual field. For Gibson, perceiving is a "value rich ecological object"[3(p140)] that involves the whole person in the acquisition of information, not just simply the head. Thus, Gibson's theory of ecological optics involves the use of optical variables to specify different types of self-motion. Advocates of the traditional two-mode theory appear to have neglected the value of different types and magnitudes of information available from the optic array, and instead have emphasized that the differential stimulation of different regions of the retinal area can be used to explain the perception of self-motion.

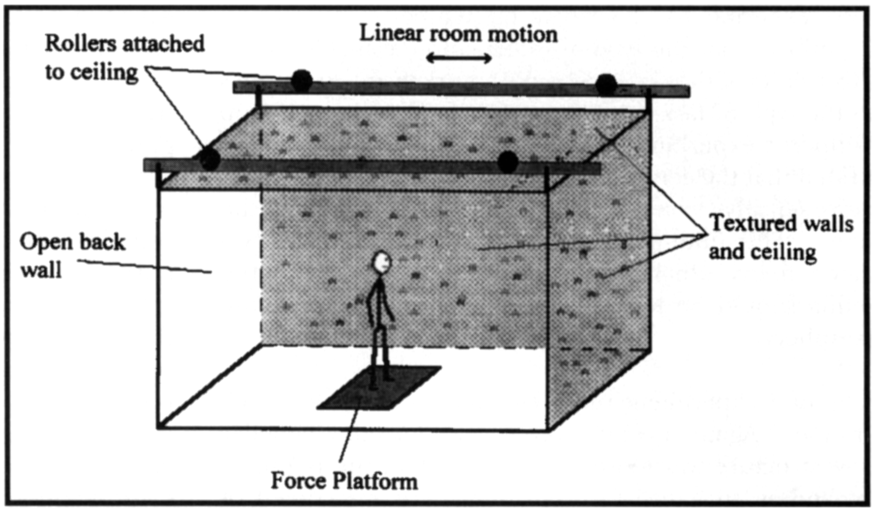

Figure 2.
The moving room with the near side wall removed. The room is attached to rollers mounted on the ceiling, enabling the room to oscillate around a stationary subject.

As we locomote in the world, an optical flow field is generated that contains a variable geometric structure (Fig. 1).[3] Figure 1 illustrates how an optical flow field radiates outward from a point in the optic array that is spatially coincident with the direction of motion[35(p55)] and is projected to the center of the retina. At the peripheral edges of the field of view, the optical flow field is nearly parallel to the line of motion. This flow structure at the periphery has been termed "lamellar flow,"[35] as opposed to radial flow. Thus, optical information for the control of posture is a function not only of retinal location but also of the geometric structure of the light rays that form the optical flow field.[35] This ecological interpretation of visual perception challenges the traditional two-mode theory of vision.

Proponents of the ecological perspective[24,35,36] have demonstrated that the visual system is sensitive to various kinds of optical information. The important point worth noting here is that postural control and the perception of self-motion are concerned not only with the sensitivity of the retina, both at the center and at the periphery, but also with the structure of the light in the optical flow field, which may be either radial or lamellar. A subject's sensitivity to optical information specifying postural state can be evaluated in a experiment using a moving room (Fig. 2).

Subjects assume a quiet upright stance within the room as it is translated or oscillated toward or away from them. This room movement artificially generates an optical flow field pattern that is similar to the pattern experienced when translating through the environment (Fig. 1). Smaller translations of the moving room can also produce optical flow field patterns that are often experienced in upright bipedal stance. Lee and Lishman,[24] in their early work, demonstrated that these translations induce compensatory sway.

A newer feature of some moving rooms is their ability to translate the front and side walls independently, generating special optical flow fields. For example, movement of only the front wall of the moving room will generate only a radial optical flow field, whereas movement of the side wall will generate only a lamellar field. Using this feature of the moving room, we can examine the influence of certain optical flow field patterns on postural state. Lee and Lishman,[24] for example, suggested that compensatory sway corresponding to whole-room movement was controlled primarily via the ambient mode (ie, the periphery).

In examining the nature of the information that is useful for the control of stance or upright posture, Stoffregen[35] has demonstrated that the retinal periphery itself shows no particular facility for detecting posturally relevant information if the information is radially structured. Lamellar flow striking the periphery of the retina, however, provides posturally relevant information—the sensitivity of the periphery to lamellar flow.[36] Thus, the two-mode theory of visual perception, which relies primarily on the location on the retina where the visual information is detected, is an insufficient explanation for visual control of motion.

Two experiments described by Wolpert[37] tested the hypothesis that the type of information available in the two sectors of the optic ray is differentially informative as to the type of task the observer is required to perform. Wolpert's experiments on detection of descent demonstrated that the central region of the retina (the fovea) is more sensitive to self-motion than is the periphery of the retina. This finding contrasts with the traditional two-mode theory, which claims that the central region of the retina should be less sensitive to self-motion than the periphery.

A second experiment required subjects to detect acceleration.[37] Again, a central visual field detecting lamellar flow structure was more informative than the regularly expanding structure for detecting increasing speed of self-motion. The findings in these two experiments question the assumptions of the two-mode theory, because they suggest that peripheral vision is less sensitive than central vision, based on the structure of the optical flow. Of the three systems that influence the control of posture—somatosensory, vestibular, and visual—it is the visual system that seems to be least well understood.

The role of the visual system in maintaining posture and balance has been constrained by the traditional two-mode theory of vision, and this is certainly an area in need of further research. Kugler and Turvey[38] have suggested that postural equilibrium is maintained and influenced by both force flow fields and non-force flow fields (optical flow) acting on an organism.[38] Research using a gravity-based system, such as a hydraulic platform,[39] is more widely published than investigations utilizing a non-force flow field, such as that generated by the visual system in a locomoting animal or human or such as when the environment moves around a stationary organism.

Spatial Orientation

The importance of spatial orientation for the pickup of information is exemplified in an article by Marendaz et al.[40] They showed that subjects in upright, supine, and sitting immobilized postures take different amounts of time to search a visual array and locate targets. This finding suggests that nonvisual information (somatosensory and vestibular) contributes to spatial orientation, which directly affects the acquisition of information.

A knowledge of one's spatial orientation has often been directly associated with a vertical gravitational force vector.[41] Howard[42] has suggested that the gravitational vector is used as a reference for movement. Recently, this view has been challenged by Riccio and Stoffregen,[43,44] who contend that the gravitational force vector is relevant only for the maintenance of balance. For example, gravity acts to accelerate the body downward, which in upright bipedal stance causes loading on joints and stimulation of receptors on the soles of the feet. This loading carries information for balance because deviations of body segments away from being parallel to the gravitational vector result in an increase in torques around some joints.[16] Lee and Aronson[45] suggested that information carried in the form of an optical flow field contains not only information about the environment but also information concerning the body's orientation within that environment. These authors have termed this information "visual exproprioception" and have suggested that it can be used for the maintenance of postural control.

Any comprehensive theory of vision must address how coordination of the eyes with the head and the trunk occurs. Research[3,46] shows that far more information is gained when subjects move than when subjects do not move. Larish and Anderson[46] compared subjects who actively locomoted within an environment with subjects who passively viewed a three-dimensional video display. After a period of time, both displays were blacked out and, after a variable period of time, subjects were asked to describe the orientation. Subjects who actively moved around their environment were more accurate in predicting orientation. These data suggest that active movement not only allows for increases in perception but also permits subjects to extrapolate future events. There also seems to be a link between perception when a subject is active and incidence of motion sickness. Reason and Brand[47] reported that passive observers (airline passengers) are more likely to experience motion sickness and disorientation than pilots flying the plane.

Classical theories of motion sickness are built on the premise that it is caused by conflicts in the information picked up by the different sensory systems.[48] In particular, sensory conflict theory proposes that information from the retinal periphery in provocative situations disagrees with information from other perceptual systems, and thus does not allow individuals to make inferences about their world. Recently, Riccio and Stoffregen[48] challenged this notion, proposing that the perceptual systems display adaptations to the environment and that changes in environmental dynamics result in necessary changes in posture. In their view, motion sickness is the result of prolonged postural instability. It would seem that the degree of disruption is a function of the degree of similarity between the ranges of imposed and natural motion. Riccio and Stoffregen[48] argue that an intact vestibular system may be a prerequisite for motion sickness. This implies that the greatest disturbances in postural control occur when optical information is in the range of postural control frequencies. Thus, while investigating motion sickness, Riccio and Stoffregen[48] make a potentially important connection to postural control. In the case of active perception, controllers (eg, pilots) are able to anticipate environmental changes that minimize postural instability and reduce considerably any nauseating effects.

The environment is richly endowed with information that can be used not only to derive spatial orientation but also to form a reference for coordination of movements.[49,50] For example, successful batters must time the initiation of their swings with the oncoming ball within a small temporal window. Lee et al[51] demonstrated that some patients with left hemiplegia (with no comprehensional or perceptual difficulties), who displayed slow and jerky arm coordination movements, were able to coordinate their movements when provided with an external stimulus, such as hitting or catching a ball that was rolled toward them. This information is derived mainly in the form of visual information, which more often than not is used to anticipate contact with an object.[49,50]

Recent Research and Its Implications for Practice

Traditional theories of cognition view perception in the context of a computer-like information processing system that is much in step with the formal accounts of the "seeing" eye. The computer analogy fits well when describing visual perception in terms of the physics of the eye and its neurological connections. This theoretical approach has merit and a rich history of research, but it has provided no insights into what we refer to as "dynamic visual perception."[32] Dynamic visual perception considers not just the seeing eye and the associated physics and neurology, but rather a visual system that coordinates the anatomical location of the eyes in the head, the head on the shoulders, and an articulated muscle-joint system that has evolved as a special-purpose design for bipedal locomotion. Such an anatomical system requires control of posture across a range of continuous activities that include stopping, starting, locomoting, and changing direction. The ambient optic array is one in which the sight lines move up and down in a sinusoidal or quasi-sinusoidal fashion as the joint system both flexes and dampens to the motion induced by movement, proximal from the point of the seeing eye, to a distal point at the articulators of the ankle-foot joint system. None of these "sight lines" in real-world activities are fixed horizontal points connecting one point of spatial orientation to another. This view has been described by Owen and Lee,[52] and research on problems of posture in the context of natural biological motion requires a different kind of investigative approach (more descriptive than experimental) that seeks a better understanding of the links between the organism and the environment through which it moves. To describe this linkage, Gibson[2] coined the term "perception-action cycle."

When considering perception and action, and the linkages between them, the focus is on a visual system that both perceives and calibrates the movement articulators (the limbs) in response to the totality of the environment in which the organism finds itself. Thus, locomoting through a terrain that continuously changes in both texture and gradient requires continuous calibration of the movement system, based on information received as the individual locomotes. Most people perform these activities with remarkable ease, suggesting that our perceptual systems (ie, the totality of the perceptual landscape) both detect and adjust to the environment directly as they are perceived. Thus, information about changes in surface texture and sound of the air are continuously and directly monitored to maintain stability, safety, and the realization of the specific goal.

In the more immediate context of vision and postural stability, it is the sensitivity of the individual's visual-perceptual system that detects the real-time changes in the dynamical properties of the ongoing event. Thus, when we pose questions about posture and balance that we plan to investigate in the laboratory, we ask how and in what ways is the organism sensitive to visual-perceptual information that mediates and influences postural stability. Using the moving room (Fig. 2) pioneered by Lee and co-workers[24,45] and a force platform acting as a stabliograph, we have tested different groups of subjects in different experimental conditions of optical flow and recorded their responses to these flow fields.

The methods we used required subjects to adopt a standardized upright posture standing on a force platform. From this position, either a rotating disk at eye level[53] or a moving room[54] in which the front (radial flow) and side walls (lamellar flow) could move independently or together (global flow) generated an optical flow field that specified motion to the subject. These methods have been described in more detail by Wade[53] and Wade et al.[54]

Our research suggests that using a moving room protocol and recording changes in center of pressure (COP) as a function of optical flow detects differences between persons without impairments and individuals who have been diagnosed as functionally mentally handicapped[53] and that persons aged 65 years and older are more sensitive to optical flow presented globally compared with persons in their third, fourth, and fifth decades of life.[54] More recently, we have turned our attention to individuals diagnosed with multiple sclerosis at different stages of functioning, as classified by the Tinetti index.[55] Although this work is preliminary,[54] our long-range goal is to determine how changes in sensitivity of the perceptual apparatus might play a role in calibrating the motor system to changes in environmental (perceptual) information. We also hope to map more clearly the specifics of the optical flow field and the sensitivity of the retina to the flow field itself.

For some groups of subjects, sensitivity to the overall perception-action cycle may be present outside the normal range of frequencies. Maintaining upright posture in an essentially stationary mode is normally recorded between 0 and 2 Hz,[56] whereas individuals with cognitive or genetic abnormalities may exhibit different frequency oscillations. Yoneda and Torumasu,[56] using spectral analysis techniques, found differences in the power spectrum of the COP of individuals without impairments and patients with Mènière's disease, benign paroxysmal positional vertigo, and vestibular neuritis in upright quiet stance with eyes open or closed. Current work in our laboratory is focusing on a study of optical flow fields that not only specify motion in the anteroposterior plane but that also can be used to determine sensitivity to the coupling effects on subjects as a moving room oscillates at a particular frequency. Again, the subject stands on a force platform, and we record how tightly the individual can couple his or her postural motion to the oscillatory motion of the room, as recorded by motion of the COP.

Our long-range goal is to determine whether there exists a signature represented by the mechanical state of the postural system measured stabliographically. A signature would be represented or characterized by a somewhat unique set of postural measures, which would differentiate an individual's postural profile as a function of a particular pathology or disease. Such measures (dependent variables) might be direction and range of the movement of the COP or the frequency range of an individual's postural sway while standing upright or responding to an optical flow field perturbation. Frequency, direction, and magnitude of such responses may assist in defining a profile of an individual's postural status as it relates to functional preference. These postural data may provide new insights into the treatment that might be devised for individuals in need of rehabilitation for a cognitive disability or recovering from physical or neurological trauma.

Our work assesses the role of optical flow as a mediator of postural stability in these different groups of subjects with different functional problems. If we can devise a specific clinical profile (postural signature), measured via a response to an optical flow field, there is potential for such a protocol to be used clinically to detect problems of posture and locomotion. This protocol may apply not only to individuals with motor deficits, as a function of birth or genetic pathology, but also those seeking recovery from a stroke or similar neuromuscular deficit that requires rehabilitation. When we suggest the clinical implications of research investigating posture from an ecological perspective, the underlying assumptions are fundamentally different from the responses of subjects perturbed using a gravity-based system.[39] What we have discussed focuses on the subjects' response to a non-force flow field. Although the responses for both force and non-force flow fields can be recorded as either biomechanical or electrophysiological deviations, the origin of the perturbations are very different. Movement of the COP is sensitive to non-force manipulations such as optical flow and requires a different kind of analysis than do the more usual recordings of ground reaction forces and muscle activity when a hydraulic platform perturbs the subject. We are suggesting here that the way subjects respond to the perturbation due to a nongravitational force field should be "food for thought" for clinical practice.

The role of vision in both calibrating and maintaining posture and balance provides support for the dynamical systems theory. This approach views the coordination and control of human locomotion and voluntary motor activity more in terms of an organism's ability to self-organize as a function of task and environment, rather than being controlled by internal mechanisms such as motor programs. This idea, although relatively new to the field of physical therapy,[57,58] is finding increasing theoretical and research support by investigators who are seeking a more complete description of how the system utilizes the many degrees of freedom available in the musculoskeletal system and constrains and organizes these degrees of freedom in such a way as to produce functional and skillful motor activity. This is true for movement across a wide spectrum of activities, from natural locomotion to the fine motor skills and manipulations of expert surgeons and skilled performers.

References

1 Williams HG. *Perceptual and Motor Development.* Englewood Cliffs, NJ: Prentice-Hall Inc; 1983.

2 Epstein W, Sheena R. *Perception of Space and Motion.* New York, NY: Academic Press Inc; 1995.

3 Gibson JJ. *The Ecological Approach to Visual Perception.* Boston, Mass: Houghton Mifflin Co; 1979.

4 Gibson JJ. *The Senses Considered as Perceptual Systems.* Boston, Mass: Houghton Mifflin Co; 1966.

5 Riach CL, Lucy SD, Hayes KC. Adjustments to posture prior to arm movement. In: Johnson B, ed. *International Series on Biomechanics, Biomechanics X-A.* Champaign, Ill: Human Kinetics Inc; 1987:459–463.

6 Cordo PJ, Nashner LM. Properties of postural adjustments associated with rapid arm movements. *J Neurophysiol.* 1982;42:287–302.

7 Nouillot P, Bouisset S, Do MC. Do fast voluntary movements necessitate anticipatory postural adjustments even if equilibrium is unstable? *Neurosci Lett.* 1992;147:1–4.

8 Paillard J. Posture and locomotion: old problems and new concepts. In: Amblard B, Berthoz A, Clarac F, eds. *Posture and Gait: Development, Adaptation, and Modulation: Proceedings of the 9th International Symposium on Postural and Gait Research.* Amsterdam, the Netherlands: Elsevier Science Publishers BV; 1988:v–xii.

9 Winter DA, Patla AE, Frank JS. Assessment of balance control in humans. *Med Prog Technol.* 1990;16:31–51.

10 Kirshen AJ, Cape RDT, Hayes KC, et al. Postural sway and cardiovascular parameters associated with falls in the elderly. *Journal of Clinical Experimental Gerontology.* 1984;6:219–222.

11 Wild D, Nayak USL, Issacs B. Description, classification, and prevention of falls in old people at home. *Rheumatol Rehabil.* 1981;20:153–159.

12 Woollacott MH, von Hosten C, Rosblad B. Relation between muscle response onset and body segmental movements during postural perturbations in humans. *Exp Brain Res.* 1988;72:593–604.

13 Horak FB, Nashner LM, Diener HC. Postural strategies associated with somatosensory and vestibular loss. *Exp Brain Res.* 1990;82:167–177.

14 Maki BE. Biomechanical approach to quantifying anticipatory postural adjustments in the elderly. *Med Biol Eng Comput.* 1993;31:355–362.

15 McDonald PV, Oliver SK, Newell KM. Perceptual-motor exploration as a function of biomechanical and task constraints. *Acta Psychol (Amst).* 1996;88:127–165.

16 Riccio GE. Information in movement variability about the qualitative dynamics of posture and orientation. In: Newell KM, Corcos DM, eds. *Variability and Motor Control.* Champaign, Ill: Human Kinetics Inc; 1994:317–357.

17 Stoffregen TA, Riccio GE. Responses to optical looming in the retinal center and periphery. *Ecological Psychology.* 1990;2:251–274.

18 Grossman GE, Leigh RJ, Bruce EN, et al. Performance of the human vestibuloocular reflex during locomotion. *J Neurophysiol.* 1989; 62:264–272.

19 Riach CL, Starkes JL. Visual fixation and postural sway in children. *Journal of Motor Behavior.* 1989;21:265–276.

20 Riccio GE, Stoffregen TA. Affordances as constraints on the control of stance. *Human Movement Science.* 1988;7:265–300.

21 McMahon TA. *Muscles, Reflexes, and Locomotion.* Princeton, NJ: Princeton University Press; 1984.

22 Howard IP. The perception of posture, self-motion, and the visual vertical. In: Boff KR, Kaufman L, Thomas JP, eds. *Handbook of Perception and Human Performance.* New York, NY: John Wiley & Sons Inc; 1986:18.1–18.62.

23 Warren WH. Self-motion: visual perception and visual control. In: Epstein W, Sheena R, eds. *Perception of Space and Motion.* New York, NY: Academic Press Inc; 1995:263–325.

24 Lee DN, Lishman JR. Visual proprioceptive control of stance. *Journal of Human Movement Studies.* 1975;18:87–95.

25 Ackner SL, Di Fabio RP. Influence of sensory inputs in standing balance in community-dwelling elders with a recent history of falling. *Phys Ther.* 1992;72:575–584.

26 Manchester D, Woollacott MH, Zederbauer-Hylton N, et al. Visual, vestibular, and somatosensory contributions to balance control in the older adult. *J Gerontol.* 1989;44:118–127.

27 Maki BE, Holliday PJ, Fernie GR. A posture control model and balance test for the prediction of relative postural stability. *IEEE Trans Biomed Eng.* 1987;34:797–810.

28 Berg WP, Alessio HM, Mills EM, et al. Correlates of recurrent falling in independent community-dwelling older adults. *Journal of Motor Behavior.* In press.

29 Wolpert L. Field of view information for self-motion perception. In: Warren R, Wertheim AH, eds. *Perception and Control of Self-Motion.* Hillsdale, NJ: Lawrence Erlbaum Associates Inc; 1990:101–122.

30 Held R. Two modes of processing spatially distributed visual stimulation. In: Schmitt FO, ed. *The Neurosciences: Second Study Program.* New York, NY: Rockefeller University Press; 1970:317–323.

31 Schmidt RA. *Motor Control and Learning: A Behavioral Emphasis.* 2nd ed. Champaign, Ill: Human Kinetics Inc; 1988.

32 Brownlee MG, Banks MA, Crosbie WJ, et al. Consideration of spatial orientation mechanisms as related to elderly fallers. *Gerontology.* 1989; 35:323–331.

33 Lord SR, Clark RD, Webster IW. Visual acuity and contrast to sensitivity in relation to falls in an elderly population. *Age Ageing.* 1991;20:175–181.

34 Stoffregen TA. The role of optical velocity in the control of stance. *Perception and Psychophysics.* 1986;39:355–360.

35 Stoffregen TA. Flow structure versus retinal location in the optical control of stance. *J Exp Psychol.* 1985;11:554–565.

36 Koenderink J, Van Doorn A. Exterospecific component of the motion parallax field. *J Opt Soc Am A.* 1981;71:953–957.

37 Wolpert L. *Field of View Versus Retinal Region in the Perception of Self-motion.* Columbus, OH: Ohio State University; 1987. Doctoral dissertation.

38 Kugler PN, Turvey MT. *Information, Natural Law, and the Self-assembly of Rhythmical Movement: Theoretical and Experimental Investigations.* Hillsdale, NJ: Lawrence Erlbaum Associates Inc; 1987.

39 Nashner LM. Strategies for organization of human posture. In: Igarashi M, Black FO, eds. *Vestibular and Visual Control on Posture and Locomotor Equilibrium.* Houston, Tex: Karger & Basel; 1985:1–8.

40 Marendaz C, Stivalet P, Barraclough L, et al. Effect of gravitational cues on visual search for orientation. *J Exp Psychol Hum Percept Perform.* 1993;19:1266–1277.

41 Schone H; Strausfeld C, trans. *Spatial Orientation: The Spatial Control of Behavior in Animals and Man.* Princeton, NJ: Princeton University Press; 1984.

42 Howard IP. *Human Visual Orientation.* New York, NY: John Wiley & Sons Inc; 1982.

43 Riccio GE, Stoffregen TA. Gravitoinertial force versus the direction of balance in the perception and control of orientation. *Psychol Rev.* 1990;97:135–137.

44 Stoffregen TA, Riccio GE. An ecological theory of orientation and the vestibular system. *Psychol Rev.* 1988;95:3–14.

45 Lee DN, Aronson E. Visual proprioceptive control of standing in human infants. *Perception and Psychophysics.* 1974;15:529–532.

46 Larish JF, Anderson GJ. Active control in interrupted dynamic spatial orientation: the detection of orientation change. *Perception and Psychophysics.* 1995;57:533–545.

47 Reason J, Brand JJ. *Motion Sickness.* London, England: Academic Press Inc (London) Ltd; 1975.

48 Riccio GE, Stoffregen TA. An ecological theory of motion sickness and postural instability. *Ecological Psychology.* 1991;3:195–240.

49 Tresilian JR. Visual modulation of interceptive action: a reply to Savelsbergh. *Human Movement Science.* 1994;14:129–132.

50 Lee DN, Young PE, Reddish S, et al. Visual timing in hitting an accelerating ball. *Q J Exp Psychol [A]*. 1983;35:333–346.

51 Lee DN, Lough S, Lough F. Activating the perceptuo-motor system in hemiparesis. *J Physiol (Paris)*. 1984;349:28.

52 Owen BM, Lee DN. Establishing a frame of reference for action. In: Wade MG, Whiting HTA, eds. *Motor Development in Children: Aspects of Coordination and Control.* Boston, Mass: Martinus Nijhoff; 1986:341–360.

53 Wade MG. Impact of optical flow on postural control in normal and mentally handicapped persons. In: Vermeer A, ed. *Motor Development: Adapted Physical Activity and Mental Retardation.* Basel, Switzerland: S Karger AG, Medical and Scientific Publishers; 1990:21–29.

54 Wade MG, Linquist R, Taylor JR, et al. Optical flow, spatial orientation, and the control of posture in the elderly. *J Gerontol.* 1995;50B: P51–P58.

55 Roehrs T. *The Influence of Optical Flow on the Postural Control of Persons With Multiple Sclerosis.* Twin Cities, Minn: University of Minnesota; 1996. Master's thesis.

56 Yoneda S, Tokumasu K. Frequency analysis of body sway in the upright posture. *Acta Otolaryngologica. (Stockh).* 1986;102:87–92.

57 Scholz JP. Dynamic pattern theory: some implications for therapeutics. *Phys Ther.* 1990;70:827–843.

58 Woollacott MH, Shumway-Cook A. Changes in posture control across the life span: a systems approach. *Phys Ther.* 1990;70:799–807.