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Vestibular and Visual Control on Posture and Locomotor Equilibrium

Editors
M. Igarashi, Houston, Tex.
F.O. Black, Portland, Oreg.

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Foreword

The international symposium on Vestibular and Visual Control on Posture and Locomotor Equilibrium: 7th International Symposium of the International Society of Posturography, under the auspices of Baylor College of Medicine, was held in Houston, Texas, from November 30 to December 2, 1983. The symposium concentrated upon contributions of the major sensory inputs to control mechanisms maintaining posture and locomotor equilibrium. In order to set the stage for dialogues on the various issues arising from studies in this field, several distinguished scientists were invited to present summary lectures. These lectures, all of which reflected super-abundant experience and unlimited rich thought on the part of the lecturer, achieved their goals by updating the knowledge as evidenced by the active discussions following the presentations, both formally and informally. These summary presentations greatly contributed to synthesize the meeting into an identification of important concepts of posture and locomotor balance control.

The first portion of the symposium mainly dealt with technical and theoretical advancements which permitted both a synthetic and also an analytical approach to understanding posture and locomotor balance control. Information gained from numerous studies employing advanced technology have contributed enormously to the development of neurophysiological, mathematical, biomechanical and control theory models of postural control. This purpose was successfully achieved by a panel discussion, 'Application of postural control mechanisms to the design of clinical tests'. These studies demonstrated the most critical role of gravito-inertial sensors in the balance control of both normal and abnormal posture. Furthermore, the studies on the interactions between different sensory inputs and the manner of information process also resulted in a vivid exchange of discussions which clarified the importance of the convergence between various sensory modalities on posture and locomotor balance control.

The importance of postural control in space environment was crystalized by a panel discussion, 'Equilibrium physiology and perception in relation to space environment', and several additional contributions which attracted researchers from all around the world. This highlighted section of the symposium examined the altered role of the gravito-inertial sensors toward the postural control in space and further focused upon the importance of sensory interaction and sensory conflict in the production of space motion sickness. The significance of this session was further punctuated by the keen observations made by physician-astronaut Dr. *William E. Thornton* during his recent experience on the Space Shuttle Mission.

Compensation after vestibular lesions has been of great interest both to clinicians for practical reasons and to basic scientists for providing the working model of neural plasticity. The interchange of the opinions between clinicians and researchers on this topic was the most constructive facet of the meeting.

Most importantly, this symposium was ours and successfully fulfilled the purpose of updating participants from various specialties in both technical and conceptual realms of converging sensory control on posture and locomotor balance, as well as evolving much thought about future research targets and designs. The most helpful support was rendered by the National Aeronautics and Space Administration toward the successful execution of this symposium, for which we all express deep appreciation. It is expected that this symposium's proceedings will continuously stimulate more interest and perpetuate the enthusiasm of those established investigators and of developing young researchers in the field of Vestibular and Visual Control on Posture and Locomotor Equilibrium.

Makoto Igarashi
F. Owen Black

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7th Int. Symp. Int. Soc. Posturography, Houston, Tex., 1983, pp. 1–8 (Karger, Basel 1985)

Strategies for Organization of Human Posture

Lewis M. Nashner

Neurological Sciences Institute, Good Samaritan Hospital and Medical Center, Portland, Oreg., USA

Concepts for Experimental Design

In this essay I shall develop a concept of human posture control as a system of distinct strategies for integrating sensory inputs and coordinating muscle contractions. By strategy I mean a specific prescription for mapping interactions among sensory and motor elements of the system. I will argue that sensory and motor strategies are highly interdependent and that balance within a wide variety of environments is achieved by selecting, prior to the execution of an action, environmentally appropriate strategies among a number of alternatives. I then explore some of the implications of this hypothesis with reference to the design of human posture control experiments and the interpretation of the ensuing observations.

The structure of the body, the geometry of muscular actions, and the locations and characteristics of orientation and motion receptors within the body all contribute to creating a menu of alternative sensory and motor strategies for accomplishing a given postural task. This essay describes alternative strategies for correcting anteroposterior sway adjustments, for coordinating head-trunk movements, and for determining the system's vertical orientation reference.

Two Strategies for Coordinating Legs and Trunk

To maintain the body in equilibrium with respect to gravity, the posture control system must compensate for perturbations away from equi-

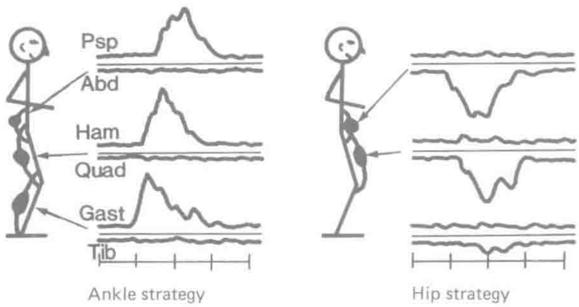

Fig. 1. 'Ankle' and 'hip' strategies for compensation of forward anteroposterior sway displacements: patterns of muscle contractions. Rectified, filtered, and averaged (10 trials) EMG responses of gastrocnemius, anterior tibialis, hamstrings, quadriceps, paraspinals, and abdominal muscles. Records of antagonist muscle pairs are grouped according to ankle, thigh, and trunk segments. At each segment, the functional extensor muscle is displayed positive upward; the functional flexors, positive downward. Forward sway perturbations were imposed at time 0, with divisions thereafter 100 ms each. Psp = Paraspinal; Abd = abdominals; Ham = hamstrings; Quad = quadriceps; Gast = gastrocnemius; Tib = tibialis anterior.

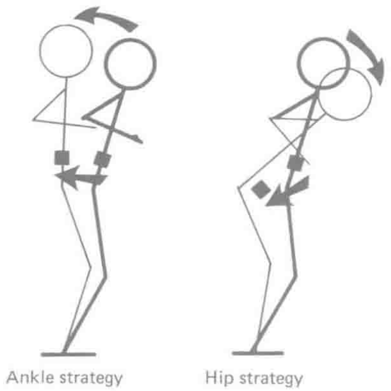

Fig. 2. 'Ankle' and 'hip' strageties: patterns of body movement. The heavy outlines show initial displaced positions; fine outlines, final compensated positions. Outlines were sketched (motions exaggerated for purposes of illustration) from video records of sway. Note that the head and body center of mass (filled squares) move backward together during the ankle strategy. The center of body mass moves backward while the head moves forward and downward during the hip strategy correction.

librium by moving the body center of mass back to a position over the center of foot support. Using a two-joint (ankle and hip) mathematical model of anteroposterior posture, *Golliday* [1975] predicted that two distinct movement patterns could be used to compensate perturbations in the anteroposterior plane. In recent experiments with normal human subjects, *Horak and Nashner* [1983] documented these two patterns of trunk-leg coordination during posture control, including motions of the ankle, knee, and hip joints and their associated patterns of muscle contractions:

(1) When a normal subject standing upon a rigid flat surface is perturbed from equilibrium in the anteroposterior plane, muscles contract in a distal-to-proximal sequence beginning with the ankle muscle stretched by the perturbation and then radiating proximally to the thigh and then lower trunk muscle on the same dorsal or ventral aspect of the body (fig. 1). This pattern of muscle contraction is termed the 'ankle strategy', because it generates a torque against the support surface which rotates the body about the ankle joints back toward an equilibrium position while approximately compensating for antiphase motions of the knee and the hip joints (fig. 2).

(2) If the subject stands facing perpendicular to the long axis of a narrow beam or if the amplitude of a sway excursion is large compared to the length of the foot, an ankle torque large enough to restore equilibrium cannot be generated about the ankles. Under this condition the same anteroposterior sway perturbation will elicit contractions, in a proximal-to-distal sequence, of the thigh and trunk muscles antagonist to those activated by the ankle strategy (fig. 1). This pattern of muscle contractions is termed the 'hip strategy', because it flexes or extends the hips in the direction of the sway perturbation. The hip strategy generates a shear force against the support surface which moves the center of mass back over the center of foot support (fig. 2). Thus, the hip strategy is effective for stance supported by either a flat or a narrow surface. However, it is ineffective for surfaces with low friction such as ice.

Experiments also suggest that the trunk-leg strategy is selected by a subject in advance of movement. Perturbations imposed immediately following a change from one of the above conditions to the other do not elicit the new strategy immediately; changes frequently require 5–20 trials. During the transition trials, subjects generate hybrids composed of sequential combinations of ankle and hip strategies. Hybrid strategies move the subject back to equilibrium with a combination of ankle and hip motions and support surface torque and shear forces.

Attempting to understand the processes coordinating muscle contractions during postural adjustments using an overly constrained experimental paradigm can lead to inexplicable or inappropriate conclusions. For example, varying the amplitude of sway perturbations will not only modulate the amplitude of postural adjustments but also change the trunk-leg coordination strategy. Physiological and biomechanical measurements limited to a single joint, such as the ankle, would be very difficult to interpret: contractions of the stretching ankle muscles and the strength of torsional resistance at the ankle would at first increase in proportion to perturbation amplitude but then might paradoxically increase in latency and decrease in amplitude as perturbations large compared to the foot length cause a change in the movement strategy.

Trunk-Leg Coordination Strategy Influences the Senses

Because visual and vestibular orientation inputs to posture must be mapped in accordance with the trunk-leg strategy, any assessment of visual or vestibular inputs to posture must take into account the movement strategy selected by the subject. The head rotates and translates in the direction of a postural correction executed using the 'ankle' strategy. In contrast, the head rotates and translates opposite to the direction of correction during hip strategy adjustments (fig. 2). The concept of strategy as I use it here is therefore similar to that suggested by *Berthoz* [*Clément* et al., this volume]: a movement strategy prescribes not only the pattern of muscle contractions but also the mapping of sensory information received as a consequence of the muscular actions.

Head-Trunk Coordination Strategy Influences the Senses

The ability to independently move the head and to redirect gaze while standing and walking implies a neural process for the transformation of orientation information from the head to a body centered orientation reference. The neural mechanisms subserving head-trunk transformations have been the topic of physiological studies [see discussion in *Wilson and Melvill Jones*, 1979]. In a behavioral example, the postural responses of standing subjects to electrical stimulation of the vestibular system were modulated according to position of the head with respect to

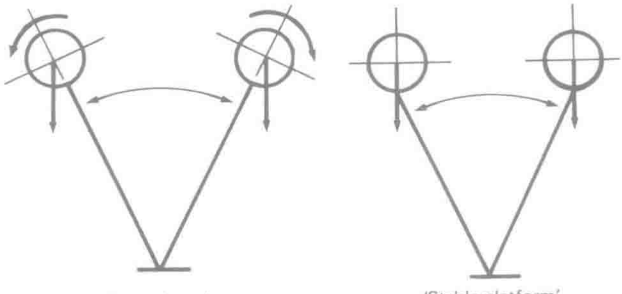

Fig. 3. 'Strap-down' and 'stable-platform' strategies for head-trunk coordination. Note that the head rotates with respect to the gravity vector during 'strap-down' coordination, exciting both the vertical semicircular canals and the retricular otoliths. In contrast, the head does not rotate with respect to gravity during 'stable-platform' coordination. The vertical semicircular canals are excited only by small error movements, while the retricular otoliths are excited only by the linear accelerations of the head.

the trunk [*Nashner and Wolfson,* 1974]. However, strategies for head-trunk coordination actually used by subjects have yet to be described experimentally. Among a number of alternatives the following two strategies, borrowed from principles of inertial guidance, have significantly different effects upon the organization of vestibular and visual inputs to posture:

(1) The strap-down mode of head-trunk coordination fixes the orientation of the head with respect to that of the body, i.e. head and body coordinates are equivalent (fig. 3). With strap-down coordination, the rotational acceleration receptors, the semicircular canals, must accurately transform head rotation input across the entire frequency and amplitude spectrum of body sway motions. While head-trunk coordination is trivial in this strategy, vestibular perception of static head position is complex. As the head rotates with the body, the resultant interactions between gravitational and linear accelerations cannot in general be distinguished [*Nashner,* 1970].

(2) The stable-platform strategy fixes orientation of the head with respect to the gravitational vertical (fig. 3). Now, orientation of the body in space is perceived in relation to the head fixed in space. Head-trunk coordination in this strategy is complex; head orientation is fixed with respect to inertial-gravitational space by feeding back rotational error signals from the semicircular canals to correct small changes in the head

orientation. The semicircular canals need be accurate transducers only in response to small transient head motions, as head stabilization will eliminate the larger sustained rotational motions. Compared to the strap-down strategy the perception of static orientation and linear accelerations will be simpler: with head orientation fixed in space the otoliths are stimulated only by the linear accelerations.

While actual strategies for head-trunk coordination are probably neither strap-down nor stable-platform, the above examples demonstrate the potential importance of head-trunk coordination in understanding the organization of visual, vestibular, and somatosensory orientation inputs to posture. By establishing an invarient relation between head and trunk motions, the organization of sensory information can be simplified and the performance requirements on vestibular receptors minimized. Changes in head-trunk and trunk-leg coordination may be important in adapting to changes in sensory as well as support conditions of the task. Furthermore, the examples suggest ways in which vestibular or CNS disorders affecting head-trunk coordination could have profound indirect affects upon posture and balance.

Strategies for Organization of the Senses

Postural perturbations induce visual, vestibular, and somatosensory orientation stimuli. Each sensory modality signals a change in orientation of the body with respect to a different reference; visual with respect to surrounding objects, vestibular with respect to inertial-gravitational space, and somatosensory with respect to the supporting surface. Under normal sensory conditions, i.e. earth-fixed support and visual surfaces, orientation information from the three modalities is congruent. Evidence from both human and animal studies suggests that under normal conditions all sensory modalities contribute in some way to postural adjustments [*Melvill Jones and Watt*, 1971; *Watt*, 1976; *Nashner and Berthozu*, 1978; *Vidal* et al., 1979]. Hence, attributing a postural reaction generated under normal sensory conditions to a particular sense is in general not possible. Instead, experiments must be devised in which the sensory orientation references are discongruent from one another. Under discongruent sensory conditions, different strategies for organization of the senses can be distinguished by changes in the orientation references of the subject.

Vestibular Role in Organizing Sensory Strategies

Black and Nashner [this volume] review evidence that patients with peripheral vestibular deficits lose their balance under sensory conflict conditions not so much due to lack of a gravitational reference as to a tendency to orient with respect to discongruent visual and support surface references. The group of vestibular patients demonstrating the principles of interaction through organized sensory strategies were those who performed within normal limits with their eyes closed and the support surface orientation reference disrupted by rotations in direct proportion to body sway. Lacking any other appropriate reference, these patients presumably balanced using the vestibular vertical reference. Paradoxically, these same patients became highly unstable and motion sick within 5 s of exposure to a visual surround rotating indirect proportion to anteroposterior sway. In other words, these patients lost their balance by orienting to the functionally inappropriate visual reference, even though vestibular and support surface references were both functionally appropriate alternatives.

Conclusions

We are only beginning to evolve concepts for understanding the organization of functions which constitute integrative behaviors of the posture control system. Yet, the need for an overall organizational concept is essential: whenever the internal workings of a complex system are investigated experimentally, a concept for the organization of that system, though not always stated explicitly, is nevertheless always implicit within the experimental design. When the experimental assumptions are inappropriate to the system under study, the accuracy and repeatability of the experimental observations per se may not be reduced. However, inappropriate assumptions can jeopardize attempts to generalize the observations beyond the narrow confines of the experimental paradigm.

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Lewis M. Nashner, ScD, Neurological Sciences Institute,
Good Samaritan Hospital and Medical Center,
1120 N.W. 20th Avenue, Portland, OR 97209 (USA)