A Control Systems Framework for Understanding Normal and Abnormal Posture

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This paper presents a brief overview of a control systems framework for understanding normal and abnormal posture, with a special emphasis on postural control during arm movements. The need for meaningful and valid definitions of postural output is discussed. A distinction is drawn between the joint posture and balance outputs of the system. The roles of commands and perturbing inputs in controlling and disturbing joint posture and balance are described. The effects of initial conditions on command inputs and postural outputs are considered. Mechanisms for correcting postural errors are described, with a major focus on active closed-loop and open-loop control processes. The method of objectively describing system behavior by the gains, time delays, and thresholds of input–output functions is presented. All concepts are developed in relation to their clinical implications.

Voluntary arm movements that are used in activities of daily living require the stabilization of more proximal segments (trunk, legs) and the maintenance of seated or standing balance. In recent years, much basic and clinical research on human subjects has adopted a control systems approach to understanding the complex processes of postural control. The insights gained from that research are relevant to the evaluation and rehabilitation of persons whose ability to perform voluntary movements is limited by deficits in postural control. This paper provides a brief and selective overview of how this classical control systems framework (Bayliss, 1966) can be used to analyze normal and abnormal postural control, with a special emphasis on the integration of balance control and voluntary arm movements. To help ground the rather abstract description of basic principles and terms, this paper will refer repeatedly to free arm movements (e.g., reaching, lifting, catching, and throwing), which are important components of activities of daily living that can be impaired by postural dysfunctions.

Control Systems Terminology

What Is the Postural Control System?

A system is a device or set of elements that transforms inputs into desired outputs. A complete understanding of a system involves a description of its inputs, outputs, and elements (or internal variables) and the relationships between its inputs and outputs (input–output functions). Structurally, the postural control system has both neural elements (reflexive and voluntary) and mechanical elements (bones, muscles, ligaments, and tendons). Many of the neural elements are themselves systems (e.g., vestibulospinal, visuospinal, and proprioceptive reflexes). A control systems framework must explicitly describe system outputs, inputs, and input–output relationships. This framework can be used to analyze how the system operates at a given time or how it adapts to changed conditions due to development, disease, trauma, and recovery.

Control and Regulation

Two other terms, control and regulation, are needed to understand posture from the systems framework. Control means that the system can achieve the desired value of the output variable. A patient is able to control trunk movement if she or he can lean forward at the hips to reach for a door handle without toppling over, and if she or he can adjust trunk angle appropriately for the location of the door. Regulation is a special case of control in which feedback maintains an output variable at a relatively constant value despite internal or external disturbances. As an example, con-
Consider what might happen when a person raises her or his arms while holding a 5-lb weight (see Figure 1A). The weight of the loaded arms could cause the body's center of mass (CM) to shift forward. In this case, the CM is not regulated. The CM could be said to be regulated if it were kept in the same position by a backward movement of the trunk and hips (see Figure 1B). Thus, abnormal postural control is defined as the reduced ability of a person to control or regulate specific postural outputs.

System Output
Definition of Postural Output
An unambiguous definition of system output is a prerequisite to an analysis of how outputs are controlled. Unfortunately, the term posture has been defined in many ways: It often refers to upright stance, but it also has been used more restrictively (e.g., in reference to a particular arm or head angle). To be useful in a systems analysis, the construct posture needs to be decomposed into distinct components. This paper will focus on two components, balance and joint posture. The general term posture will be used as a shorthand reference to system behavior.

Joint posture is defined as a static or dynamic configuration of one or more joint angles; it can be measured by variables such as joint angle and velocity. Balance refers to the static or dynamic equilibrium of the body relative to the support base. As long as the CM remains over the base of support, balance is maintained. This concept of balance applies when the support base is fixed, as in quiet standing, and when the support base is changed, as in walking or standing up from a chair. Operationally, balance is defined by the location or trajectory of the body's CM relative to the edges of the current or anticipated base of support.

Balance and joint posture may be controlled concurrently (Gordon, Zajac, & Hoy, 1986). Recent experiments have supported this hypothesis by showing that people have some choice of (a) which variable to control and (b) how closely to regulate each variable during different actions. The first point is exemplified by a comparison of how the CM changes during arm flexion and trunk bending. During fast bilateral arm flexions, standing subjects keep the hip joint angle relatively fixed while the CM shifts forward (Lee & Tang, 1988). In contrast, when standing subjects bend the trunk forward or backward, the hip joint angle changes but the location of the CM is closely regulated (Crenna, Frigo, Massion, & Pedotti, 1987; Hasselkus & Shames, 1975). A person's capacity to concurrently control joint posture and balance has been shown in a study in which standing subjects abruptly pulled on a fixed handle (Lee & Rogers, 1987). When subjects were told to pull as hard as possible while maintaining their balance, they executed the pulls with about 15° hip flexion. When told to keep the body straight (regulate the hip position), the subjects reduced hip flexion to 5° or less. This ability to cognitively control hip angle was evident even when the subjects stood on a very small beam to increase balance demands. Neurologists have observed that patients can have selective deficits in controlling joint posture, balance, or both (Dichgans & Mauritz, 1983).

In summary, postural dysfunction is a catchall phrase for substantially different kinds of postural control problems. Joint posture and balance control should not be assumed to be synonymous, either behaviorally or in terms of underlying neural control. A patient with postural dysfunction might be unable to control joint posture, balance, or some other variable (e.g., the vertical orientation of the trunk or head). The therapist must observe behavior carefully to determine each patient's specific postural problems.

Measurement of Postural Output
Mechanical variables. The outputs of the postural control system are probably best described by mechanical variables related to behavioral goals. This approach contrasts with the descriptions of postural system output that use clinical scales or patterns of electromyographic (EMG) activity in the neck, trunk, or leg muscles. Mechanical variables have the advantage of being measurable on interval or ratio scales.
Furthermore, mechanical variables measure events that are physically similar to those sensed by the vestibular, proprioceptive, and visual receptors, which has enabled researchers to quantify the relationships between those sensory inputs and postural outputs. Mechanical measures are not restricted to single variables or joints, but can be complex and dynamic (e.g., the hip and ankle movement patterns observed in the postural reactions of standing persons, Horak & Nashner, 1986).

Mechanical measures do have some limitations. One limitation is purely technical: expensive instrumentation and computer analyses are required to measure relevant kinematic (e.g., joint angle, velocity, acceleration) and kinetic (force, torque) variables. Another limitation involves the validity of the variables used to describe balance or joint posture. For example, balance can be defined as the projected location of the CM over the feet. To compute the location of the body's CM, the mass and location of each segment's (e.g., forearm, thigh) CM must be known. Clinical studies, however, rarely use this procedure. More commonly, the CM is estimated by the motion of the center of pressure (CP), which is the point of application of the net ground reaction force under the feet of a standing subject. The CP is a valid estimate of the location of the CM in quasistatic conditions like quiet standing, but not during rapid body motions such as standing up, raising the arms quickly, or being disturbed by a sudden, rapid push (Murray, Seireg, & Scholz, 1967). Nonetheless, the CP is still sometimes used incorrectly to measure sway or balance under dynamic conditions.

Clinical variables. Clinical scales (Fugl-Meyer, Jaasko, Leyman, Olsson, & Steglin, 1975) provide valuable assessments of patients' functional capacities. Such scales are easily administered but often cannot pinpoint specific postural problems because they combine subscale scores from several aspects of performance. Other variables that are used clinically, such as timed tests of balance, are easily measured but do not directly measure balance or joint posture outputs. For these reasons, there has been an increasing shift toward measuring joint posture or balance directly under systematically varied sensory, cognitive, or mechanical conditions (Nashner, Black, & Wall, 1982; Wolfson, Whipple, Amerman, & Kleinberg, 1986). Research is needed to compare standard clinical measures and more quantitative measures of postural control in (a) predicting patient outcome, (b) identifying specific postural disorders, and (c) guiding patient-specific treatment.

EMG variables. Variables that describe patterns of EMG activity (e.g., muscle recruitment order and onset latencies, EMG amplitudes) also have been used to describe normal and abnormal postural control (Allum & Keshner, 1986; Horak & Nashner, 1986). EMG activity directly reflects neural activity. Nonetheless, mechanical variables probably are preferable in clinical applications for two reasons. First, biomechanical variables such as the location of the CM or joint angles are conceptually closer to the patient's goal of keeping stable while performing activities of daily living. Second, the empirical and theoretical relationships between EMG activity and biomechanical variables are still not completely understood, especially for dynamic multijoint actions such as those involved in standing balance control. This limitation even applies to the prominent hypothesis that discrete postural synergies (stereotyped multimuscle EMG patterns) are used to maintain upright stance (Horak & Nashner, 1986). The natural variability of EMG patterns during standing is only beginning to be probed by studies of how leg and trunk muscle EMG patterns are influenced by factors such as practice, initial weight bearing, behavioral conditions, and the dynamics of the perturbation (Bouisset & Zattara, 1981; Brown & Frank, 1987; Horak, Esselman, Anderson, & Lynch, 1984; Lee, 1980; Lee, Buchanan, & Rogers, 1987; Lee & Tang, 1985). The therapist should not draw inferences about a patient's joint posture or balance control solely from EMG measures, especially if the patient has abnormal weight bearing, joint posture, force-EMG relationships, or speed of movement.

Command Inputs

Command inputs are the least understood aspect of the postural control system. Command inputs, or commands, determine (a) which postural variable to control and (b) the target value of the variable. Postural commands define the goal or reference output of the system. An analogy can be drawn with the homeowner who (a) turns on the heating or air-conditioning system, and (b) sets the thermostat to the desired temperature. Even standing and sitting require some degree of intentional control. An awake, unfatigued, and neurologically normal person clearly chooses to sit, stand, or lie down. Hence, cognitive (not necessarily conscious) processes are likely to play a role in the generation of postural commands.

Initial Conditions

To be effective, commands should be tailored to initial conditions. The act of raising the arms exemplifies this point: When a person raises the arms with the CM in a neutral position (see Figure 2A), the trunk and hips move slightly back before and during the arm movement, and the hip angle does not change. Postural commands at least partly cause these backward body movements (Bouisset & Zattara, 1981). Despite these postural adjustments, the body's CM still shifts...
forward (Lee & Tang, 1988). If the person’s CM is very far forward before the arm movement occurs (see Figure 2B, dashed lines), the same postural command will result in the CM moving beyond the base of support, which will cause the person to fall. A different postural command (to thrust the hips back) could keep the CM fixed so that the person remains balanced (see Figure 2B, solid lines). Similar adaptations in postural reactions have been noted when the size of the support base changes (Horak & Nashner, 1986; Lee & Rogers, 1987). Commands also must be modified if a person’s physical characteristics (e.g., body weight, muscle strength, joint range of motion) are altered substantially by changes in activity level, age, physical or neurological trauma, or disease. Major physical changes could result in unexpected relationships between commands and output, causing previously appropriate commands to result in a fall or joint instability. Consider the example of a person with trunk-muscle weakness due to an incomplete upper thoracic spinal cord injury who reaches out to pick up an object. A command to the trunk muscles that would have been effective before the injury would now generate too little force to stabilize the trunk.

Figure 2. Adaptations of postural adjustments that maintain balance for arm movements made from a neutral posture (A) and a forward-leaning posture (B) (CM = center of mass).

Adjustments to Changes in the Environment or the System

Sensory modalities and cognitive processes normally provide the information needed to (a) initially specify postural commands to meet the demands of current conditions or (b) learn new postural commands when the system changes. Lost or distorted information will impair a person’s ability to adjust postural commands to current conditions. The correct commands to maintain posture or balance cannot be selected if a person does not know where his or her body is or what is happening in the environment. Information about the intended outcome of postural commands and the actual postural output also is crucial for a person to learn to adapt to changes in the system’s musculoskeletal or neurological elements. For example, the spinal cord-injured patient described in the previous paragraph would need to compare actual and intended postural outputs to learn the new commands that could stabilize the trunk during arm movements (Schmidt, 1988). This need to compare intended and actual outputs underlies the fact that a person must make an active effort to learn to adjust postural commands to altered sensory or motor conditions (Gonsbor & Melvill Jones, 1980).

The inability to generate correct postural commands is one reason a patient may be unable to control balance or joint posture. Postural commands must be based on a person’s movement goals and on current conditions. If a patient lacks intrinsic information about initial conditions and actual postural output, the therapist can try to provide the relevant information through alternative sensory channels. However, even active practice and augmented information about initial conditions and final outcome may be insufficient for some patients to learn to generate adequate postural commands (Nashner & Grimm, 1978). When a patient cannot generate adequate postural commands, the therapist must provide an alternative external means for controlling balance or joint posture, such as braces.

Perturbing Inputs

Types of Perturbation

Even persons with normal neuromuscular, cognitive, sensory, or musculoskeletal function can lose balance or fail to achieve a desired joint posture. In the control systems framework, errors can be introduced by (a) an incorrect input command, (b) changes in the system, or (c) perturbing inputs, or perturbations, that cause undesired changes in the output (see Figure 3).

Mechanical perturbations. Mechanical forces that disturb joint posture or balance can be either static or dynamic. External forces, such as gravity, originate outside the person. Being bumped into, tripping over something, or picking up a heavy object are other examples of external perturbations. Self-generated forces include voluntary movements such as lifting the arms, reaching for an object on a table, or pushing open a door. In addition, simple head move-
mments and even respiration can perturb balance and posture.

Sensory perturbations. Sensory inputs, especially unexpected ones, also can perturb posture. For example, a sudden, unexpected looming of the visual field implies that a person is falling forward. The person responds automatically to such visual input with backward body movements, whether or not a fall is actually occurring. Children and adults sway backward when they are presented with a looming visual field induced by moving the artificial walls of the room in which they stand (Lee & Lishman, 1975). The backward sway causes children to lose their standing balance. Normal adults also may lose their balance if they stand on a narrow beam. These effects may be magnified if other sensory cues are distorted (e.g., if subjects stand on a spongy surface). Driving a car, standing by an elevator door that opens, or catching a thrown object are daily life situations in which visual input might disturb balance in some patients with neurological dysfunction.

Important Qualities of Perturbations
The effects of mechanical and sensory perturbations depend on their physical (magnitude, location), temporal (speed, duration, frequency), and cognitive (predictability) qualities. The absolute qualities of perturbations are important. Larger forces (e.g., a 20-lb load vs. a 1-lb load applied to the arms) generally induce greater disturbances of joint posture or balance than do smaller forces. This principle is also generally applicable to sensory inputs, but must be qualified because responses to inputs can reach a point of saturation. For example, posterior sway increases with the velocity of a looming visual field, up to about walking speed. Above that speed, higher velocities elicit less posterior sway (Liston, Soechting, & Berthoz, 1977). Thus, more input does not always imply more output. The temporal qualities of a perturbation also determine how strongly it will disturb postural output. Slow disturbances may be detected and corrected before their effects are too great, whereas very fast disturbances could occur too quickly to be corrected. For example, a slow arm movement might not disturb balance, but a rapid movement might cause instability. Likewise, the effects of a perturbation depend upon its duration and frequency. Low loads may be held indefinitely, for example, but large loads can rapidly induce fatigue and a loss of control. Similarly, a person might be able to control balance against occasional disturbances but not against rapidly repeated ones. Finally, the predictability of a perturbation is crucial; expected disturbances are easier to counteract than unexpected ones.

The physical qualities of a perturbation relative to those of the system also must be considered. For example, holding a 15-lb bag of groceries will perturb balance more for a person who weighs 100 lb than for a person who weighs 250 lb. Recent tests of standing balance have taken such mechanical relativities into account by perturbing balance with loads that are proportional to the subject's weight (Lee, Deming, & Sahgal, 1988: Wolfson et al., 1986). Another example is the maximal static load that a person can resist while standing. A person can maintain balance against static forces of the same magnitude that push the person in the right, left, or forward direction, but a force of only half that magnitude can be resisted if the force pushes the person backward. This effect has been documented in neurologically normal persons of all ages and in persons with hemiparesis due to a cerebrovascular accident (Lee et al., 1988). These relative effects imply that when therapists manually test a patient's balance, they should apply twice as great a load in the forward direction. If the same load were used in both directions, the therapist might conclude erroneously that balance was impaired only in the backward direction. Similarly, reaching back to pick something up could disturb a person's balance more than reaching forward to pick up the same item.

Effects of Initial Conditions
Initial conditions influence how strongly a perturbation will disturb postural output. Therefore, the same perturbation will not always cause the same output error. For example, a person's initial weight bearing will influence whether a given force will lead to a loss of balance. Consider the case of elderly women who, as a population, are more at risk for falls than elderly men or younger persons. Elderly women often have unusually posterior weight bearing (Murray, Seireg, & Sepic, 1975), restricted ankle joint range of motion, or a reduced support base (Lee & Deming, 1988). An action such as turning to reach back and pull shut a door might perturb balance more for a woman with these characteristics than for a person with more normal weight bearing, ankle range of motion, and support base. Thus, abnormal initial physical conditions can impair balance even when neural control pro-
cesses are normal. This means that the therapist must document or control initial conditions to obtain valid evaluations of postural function. Moreover, the therapist may be able to enhance patients' stability by helping them to adopt better initial positions and by alerting them to sensory cues that, if unexpected, could disturb balance.

System Corrective Processes

Mechanical and Neural Corrective Processes

Mechanical corrections. Mechanical processes are reactive and essentially passive. Sufficiently large or rapid external disturbances of joint posture will stretch or deform muscle and other soft tissue about the joints. Reaction forces due to the mechanical impedance of those structures will tend to restore the initial position, especially if the disturbances are small. For example, the stiffness of activated muscles about the ankle joint apparently controls balance against the small changes in ankle joint angle that occur during quiet stance (Gürfinkel, Lipshits, & Popov, 1974).

Neural corrections. Passive mechanical reactions cannot correct all disturbances to joint posture and balance. It is well known that phasic EMG bursts in leg, trunk, and neck muscles occur when upright stance is perturbed by rapid support surface or voluntary arm movements. Those changes are governed by the system's two neural modes of controlling postural output, closed-loop control and open-loop control. Closed-loop control uses feedback processes to correct errors during the movement. Open-loop control either does not correct disturbances or uses predictive feedforward processes to correct expected errors. An understanding of how much feedback and feedforward processes can compensate for disturbances requires knowledge about the properties of the system's input–output (I/O) functions.

Properties of I/O functions. The I/O functions of many subsystems that control and regulate postural variables can be quantitatively described by two properties: gain and time delays (Carpenter, 1977). The gain of a system is simply the ratio of output to input. The time delay of an I/O function is the interval between the onset of the input and the resulting change in output. To determine the gains and time delays of normal and abnormal I/O functions, the system is perturbed with known inputs (under constant initial conditions) and the amount of, or time to, the change in postural output is measured. This method should be familiar to the therapist who routinely evaluates the effects of sensory inputs on motor output, for example, the effects of head position on elbow angle (Coryell, Henderson, & Liederman, 1982). Therapists typically use only one input amplitude (e.g., maximal head rotation). However, gains and time delays can vary with the size and speed of the input. A thorough systems analysis therefore requires that the input be presented repeatedly while its amplitude and frequency are varied. The threshold, defined as the amplitude above which input starts to influence output, is a third important property of I/O functions.

I/O functions provide a more complete and objective description of error-correction processes than clinical tests generally do. I/O gains, loop delays, and thresholds provide an objective basis for comparison of normal and abnormal postural control and for the tracking of changes that occur with recovery and treatment. Knowing these properties for a particular patient enables the therapist to predict how different inputs will disturb that patient's joint posture or balance. The two disadvantages of this approach are that methods for measuring I/O characteristics are technically demanding and that normative values of I/O functions are unavailable for some postural control subsystems.

Feedback Control

Definition of feedback. The first active mode of controlling postural errors involves feedback processes. Feedback processes have three essential characteristics: (a) the output variable must be sensed, (b) an error signal representing the difference between actual and desired output values must be computed, and (c) the error signal must modify the output. When the error signal reduces the output error, the process is called negative feedback. Such systems tend to regulate the output variable at the commanded value and can operate automatically, just as a thermostat regulates room temperature. This definition differs from the common clinical meaning of feedback, which refers to any information about motor performance that is available to the patient (Schmidt, 1988).

Figure 4A diagrams a negative feedback system for regulating shoulder angle during a lifting task. The output variable is shoulder flexion angle. There are two inputs: (a) a command input indicating the desired flexion angle, and (b) a perturbing input in the form of an external load added to the outstretched arms. Proprioceptive or visual receptors detect shoulder angle. That information is fed back to central structures that compare the actual and commanded shoulder angle. The resulting error signal (E) then reduces the discrepancy between the intended and the actual shoulder angle. There are two types of feedback mechanisms. Proprioceptive, vestibulospinal, and visuospinal reflexes are all automatic low-level feedback mechanisms that control joint posture and balance. The other type of feedback mechanism includes more cognitively based processes such as reaction time responses.
Feedback loop delays. Two limitations in feedback loop characteristics typically preclude perfect correction of postural errors by feedback processes. The first limitation is the time delay between an error and its correction. Closed-loop control is ineffective when loop delays are long relative to the perturbation. If the load in Figure 4B is applied very rapidly, the arms might be completely pushed down before feedback processes began to correct the disturbance. If the load were a filled pot, its contents would be spilled. In general, proprioceptive and dynamic vestibulospinal feedback loops are shorter than are visuospinal feedback loops. Time delays of cognitively based feedback tend to be longer, ranging upward from about a tenth of a second and varying with the amount and type of information that must be processed (Schmidt, 1988; Stelmach & Worringham, 1985). Feedback loop delays are lengthened and less effective in patients with peripheral or central processing deficits (e.g., increased nerve conduction velocity or central processing time).

Feedback gains. The second limitation to feedback control involves feedback loop gains. A gain of 1.0 will completely correct errors if the time delay is 0. For example, if picking up a pot (as shown in Figure 4B) perturbed the shoulder angle from 90° to 60°, a feedback loop with a gain of 1.0 would correct the 30° error, returning the shoulder to 90°. If the feedback loop gain were only 0.1, then the correction would be only 3°, resulting in a final angle of 63°. Reflex feedback loops rarely compensate perfectly for errors in joint posture or balance. For example, although stretch reflexes were once thought to regulate joint posture against imposed loads, measurements of elbow joint angle after load perturbations showed that stretch reflexes correct less than 30% of the errors (Allum, 1975). Longer latency, cognitively based responses provide the major correction.

Thresholds of feedback loops. In many patients, the thresholds of sensory feedback loops are abnormal. If the threshold is abnormally low, then the patient will be hypersensitive to that input and a response will be elicited by perturbations to which normal subjects would not respond. If the threshold is abnormally high, the feedback system will neither detect nor correct the error. For example, nearsighted persons cannot visually detect sway during quiet standing and, hence, sway more than persons with normal visual acuity (Paulus, Straube, & Brandt, 1984). Feedback loops can have normal gains and delay times even when their thresholds are abnormal. This type of abnormality differs from one in which the threshold is normal but loop gains or time delays are abnormal. This distinction is important clinically: A feedback loop with only a threshold abnormality can correct errors adequately once the system is above the threshold, whereas a feedback loop with abnormal gains or delays will never provide normal error correction.

Multiple feedback pathways. The visual, vestibular, and proprioceptive feedback subsystems respond to slightly different disturbances of posture or bal-
In contrast to feedback control, feedforward processes do not detect errors during the movement. Rather, corrections are based on past experience, knowledge about one's body and the physical world, and predictions about the upcoming disturbance. For example, a woman may realize that the child she is holding is about to move. This realization allows her to make anticipatory corrections to keep from falling or dropping the child. Sensory inputs also can be predictive. Head acceleration, for example, can be used to predict and correct an upcoming fall because acceleration precedes any substantial change in head position. Feedforward corrections can be matched closely to the timing and size of the expected disturbance, and the gain and time delay problems of feedback control can thus be avoided. The disadvantage is that if the prediction is wrong, the error may be greater than if the feedforward correction had not been made. The act of lifting up a suitcase illustrates this point. The shoulder girdle, trunk, and leg muscles are activated before the lift and the expected balance disturbance. If the suitcase is as heavy as expected, the lift will be made smoothly. If the suitcase is unexpectedly light, then balance could be lost.

Probably the most studied example of cognitively based feedforward postural control involves fast shoulder flexion movements made by standing subjects. (Illustrated in Figure 2A; diagrammed in Figure 5). Belen'kii, Gurfinkel, and Pal'tsev (1967) reported that leg and trunk muscles are activated not only before the shoulder flexes, but even before the anterior deltoid muscle is activated. These results have been replicated many times, although it is now known that the leg muscles are not always activated before the arm muscles (Lee, 1980; Lee et al., 1987; Rogers, Kulka, & Soderberg, 1987). Pre-arm-movement EMG activity in the leg muscles is not due to feedback because it precedes movement-related sensory input. This EMG activity is generally assumed to represent

**Open-Loop and Feedforward Control**

The postural control system does not have to rely solely on feedback to correct errors. Open-loop control processes also are available. In the simplest form of open-loop control, the command signal is directly transformed to the desired output without any correction of errors that arise during the movement. Open-loop control is especially effective when conditions are predictable and perturbations are fast. Feedforward is a type of open-loop control that can correct errors due to expected perturbations, whether they are self-generated or externally imposed. The corrective feedforward command is generally separate from the command input.
feedforward control of balance against disturbances during the arm movement.

Behavioral conditions and instructional set alter EMG or movement patterns of premovement postural adjustments associated with voluntary arm movements (Belen'kii et al., 1967; Horak, et al., 1984; Lee & Rogers, 1987). For example, leg muscles are often recruited before shoulder muscles when the arm movement is self-paced, but leg and shoulder muscles tend to be recruited simultaneously for visually triggered movements (Brown & Frank, 1987; Lee et al., 1987). Such effects are relevant to therapists because some patients may have selective deficits in feedforward control (Pal'tsev & El'ner, 1967), possibly associated with more global deficits in anticipation, planning, or other cognitive processes.

Therapists can use several feedforward mechanisms to minimize a patient's postural errors during functional tasks. First, instructions can help the patient to generate feedforward commands that activate specific leg or trunk muscles against a given perturbation. Second, the patient can be encouraged to increase the stiffness of a joint by coactivating antagonist muscles, especially during fast or unpredictable disturbances. Third, the patient can be taught to assume advantageous initial positions that minimize the effect of upcoming perturbations. Finally, feedforward instructions about the upcoming disturbance and how to respond (e.g., resist, relax) can modify the thresholds, delays, or gains of feedback loops and enhance the feedback corrections of disturbance.

Hybrid Open-Loop/Closed-Loop System to Control Posture

Because both open-loop and closed-loop processes are used to control and regulate postural output, joint posture and balance are controlled by a hybrid control system. The hybrid control system achieves desired postural outputs with a combination of direct commands and neural processes that correct expected and unexpected errors. In persons with normal balance or joint posture control, both processes help to minimize output errors due to predictable disturbances. Patients with abnormal balance or joint posture control, in contrast, may show selective deficits in either feedback or feedforward control or in both (Dichgans & Mauritz, 1983). The therapist should seek to identify which error correction processes are impaired. The patient with impaired feedback control will have the most difficulty in controlling joint posture or balance after unexpected disturbances, but will have normal balance control when disturbances are predictable (e.g., during voluntary arm movements or expected external perturbations). The patient with impaired feedforward control, in contrast, will have normal responses to unexpected perturbations, but will be unable to benefit from advance information about upcoming perturbations.

Improved Postural Control to Enhance Functional Arm Movements

Identification of which aspect of the system is disordered is the first step toward improving arm movements that are impaired by the postural or balance dysfunction. If a person lacks adequate muscle strength or range of motion in the trunk or legs, then increased strength or flexibility may improve the ability to stabilize. Persons with impaired feedback control but normal feedforward control may be helped by cues about what disturbance to expect during voluntary movements. Feedback control of posture and balance often can be enhanced with augmented sensory feedback about body position. Patients also should be taught the optimal initial positions from which to start arm movements. A person who has suffered a sensory or perceptual loss may be able to achieve a long-term, functional adaptation of remaining I/O functions. In general, practice on postural control tasks both in isolation and during functional arm movements should follow principles for enhancing motor performance and motor learning (Schmidt, 1988). If a patient lacks the cognitive and sensory-motor capacity to relearn posture and balance control, the therapist should provide external support with braces or other assistive devices. These devices may, however, improve short-term performance without necessarily generalizing to daily-life situations in which augmented feedback is impossible or attention must be focused on other aspects of the environment. For long-term improvement in the postural control system to occur, the patient must try to actively control joint posture or balance while receiving knowledge of performance and results from therapists or through natural sensory systems, preferably under variable conditions that are graded in their complexity (Carr & Shepherd, 1987). If full functional stabilization cannot be achieved, the patient may need to adapt arm movements (e.g., keep them closer to the trunk or perform them more slowly) to retain balance and posture.

Conclusions

Patients with postural disorders may (a) be unable to select the right postural output to control in a given situation, (b) be unable to choose the correct command to achieve a desired postural goal in a particular situation, (c) have deficits in one or more feedback loops, or (d) lack the capacity to correct expected perturbations through feedforward processes. The
References


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Cordelia Myers Writer's Award

The American Occupational Therapy Association is pleased to announce that Jane Case-Smith has been chosen to receive the Cordelia Myers Writer’s Award of the American Journal of Occupational Therapy for the 1988 volume year. Her paper, “An Efficacy Study of Occupational Therapy With High-Risk Neonates,” published in the August issue, was considered by the journal’s Editorial Board members to be the best piece of professional writing by a first-time contributor to the journal in that year.

The journal’s Editorial Board members and the staff extend their congratulations to Jane Case-Smith.