Coordination of Posture and Movement

Movement is performed against a background of subtle postural adjustments that counteract destabilizing forces imposed by the movement. Despite the importance of these postural adjustments to the safe and efficient performance of movement, little is known about the properties of these postural accompaniments. The purpose of this article is twofold. First, it provides a review of properties of postural adjustments that accompany a variety of limb and trunk movements. Second, a schema for the coordination of posture and movement is proposed. This schema suggests that a central nervous system model of body dynamics is essential to anticipatory control of posture during movement. [Frank JS, Earl M. Coordination of posture and movement. Phys Ther. 1990;70:855–863.]

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Movement is performed against a background of subtle postural adjustments that often go unnoticed by the performer. Movement perturbs posture by imposing forces on adjoining body segments; these forces arise from the inertia and momentum of the body segment moved and from the object being moved. For example, when pulling on a heavy door, the body would fall toward the door if the posterior muscles of the legs and trunk did not stabilize upright stance. Postural adjustments that accompany movement serve to prevent or minimize the displacement of the center of gravity and thereby allow safe and efficient performance of movement. Such postural accompaniments to movements were reported many years ago by Babinski. He noted that healthy individuals flex their knees when arching the head and trunk backward. Flexion of the knees ensures that the center of gravity remains over the feet. Patients with cerebellar disorders, however, failed to initiate this knee flexion and fell backward. Babinski’s observation revealed the importance of coordinating posture and movement control and suggested that this coordination is regulated by the nervous system (rather than being controlled by the passive reactions among adjoining body segments).

Coordination refers to an optimal relationship among events. Research is just beginning to reveal how the central nervous system (CNS) optimizes the regulation of upright stance during movement. Postural control research has focused primarily on the regulation of upright stance when perturbed by external disturbances, such as movement of the base of support. However, the regulation of upright stance is fundamental to the safe and efficient performance of many of our voluntary movements. Damage to the CNS can interfere with the coordination of posture and movement control, placing an individual in fear of his or her own movements. The purposes of this article are to examine characteristics of the regulation of upright posture during voluntary movement of the limbs and trunk and to propose a schema for coordination of posture and movement.

Strategies for the Control of Upright Stance During Voluntary Movement

Several strategies can be adopted to maintain upright stance during voluntary movement of the limbs and trunk. These strategies vary with respect to the degree of safety provided and the energy expended (ie, efficiency). First, postural disturbances imposed by movement can be counteracted by sensory-based feedback strategies. The general mechanism of feedback strategies consists of excitation of sensory receptors (visual, vestibular, cutaneous, and proprioceptive) that trigger automatic postural adjustments. Feedback strategies are the primary defense against unexpected, external perturbations, such as those experienced while standing.

James S Frank
Marie Earl

J Frank, PhD, is Assistant Professor, Department of Kinesiology, University of Waterloo, Waterloo, Ontario, Canada N2L 3G1. Address all correspondence to Dr Frank.

M Earl, MSc, is a doctoral degree candidate, Department of Kinesiology, University of Waterloo.
on a moving vehicle. Feedback-triggered postural adjustments act quickly, within 100 milliseconds; however, they still manage the regulation of posture on a crisis basis. A second strategy for preserving upright stance involves postural preparations engaged well before movement. Such postural preparations include setting a more stable posture by increasing the base of support and stiffening the joints through muscle co-contraction. These strategies are seen frequently in athletes, as well as among persons with postural instability. For example, an elderly person may seek the additional support of a handrail before starting to climb a flight of stairs. Finally, perturbations to upright posture can be counteracted by postural adjustments that occur simultaneously with, or just before, the initiation of voluntary movement. The general mechanism of postural accompaniments involves anticipating the effect of the movement on posture and coordinating the activation of postural adjustments and the intended (focal) movement to minimize the postural disturbance. This mechanism of control has been termed "feedforward control" by Cordo and Nashner.

Gahery has classified these three postural control strategies as postural reactions, postural preparations, and postural accompaniments, respectively. An individual may select one or another of these strategies, depending on the perceived need for safe regulation of the body's center of mass and motor efficiency. Figure 1 displays these strategies on a time scale relative to movement initiation and the relative relationship of each strategy to safe regulation of upright posture and motor efficiency. Postural preparations establish a large margin of safety but are inefficient means of regulating posture. Provided that the conditions of the task are known, postural accompaniments provide a safe and efficient method of regulating posture. Finally, postural reactions provide efficient, but not necessarily safe, control of upright posture. Postural reactions may act too late or be of insufficient magnitude to recover upright posture.

The functional consequence of this pattern of postural muscle activity accompanying arm elevation is not entirely clear. Bouisset and Zattara reported a backward acceleration of the shanks, thighs, and hips of subjects during bilateral arm elevation in addition to a forward acceleration of the shoulders, occurring approximately 50 milliseconds prior to arm acceleration. In a subsequent study, they reported a forward and upward acceleration of the center of mass prior to arm acceleration. Initial upward and forward acceleration of the arm would cause a resultant downward and backward reaction force at the shoulders. Based on these kinematic data, Bouisset and Zattara argued that early postural muscle activity does not consist of a simple rigidification of some joints; rather, it displaces body segments and center of gravity in a direction that opposes reaction forces arising from the focal movement. It is not clear, however, how early activation of hip extensors causes a backward acceleration of the hips and forward acceleration of the center of gravity. Bouisset and Zattara did not address this issue in either of their articles.

![Figure 1. Safety and efficiency of three postural strategies for regulating upright stance during voluntary movement. Postural strategies are displayed along a continuum of time with postural preparations arriving well before movement initiation, postural accompaniments arriving within 100 milliseconds of movement initiation, and postural reactions arriving 100 milliseconds or more after movement initiation.](image)
We also have been examining the relationship between postural accompaniments and their functional consequences. We have chosen a task that perturbs upright posture only in the sagittal plane. Subjects (N=9) were asked to rapidly pull on a stiff handle (20-N resistance), following the onset of a reaction light. Using surface electromyographic (EMG) recordings, we examined the relationship between the onsets of activity in selected arm, trunk, and leg muscles. The EMG recordings were ensemble-averaged across eight trials, relative to the onset of handle acceleration, prior to analysis. Activation of the biceps brachii muscle was preceded by activation of the posterior leg and trunk muscles in a predominantly distal-to-proximal order. The mean onset times of the subjects' lateral gastrocnemius, biceps femoris, and erector spinae muscles, relative to the activation of the biceps brachii muscle, were 120±16 (SEM), 72±15, and 44±12 milliseconds, respectively. We also calculated center-of-pressure displacement from force-plate data and center-of-mass displacement from film data. A shuttered video camera was used to record the trajectories of reflective markers positioned on the foot, ankle, knee, hip, shoulder, and ear. The x and y coordinates of each marker and anthropometric data were used to calculate the position of the whole-body center of mass. Prior to backward acceleration of the handle, center of pressure was displaced forward and center of mass was displaced backward. Hence, postural muscle activity appears to displace the center of mass in a direction that opposes reactive forces imparted to the trunk by the inertia of the handle. This pattern of postural and focal muscle activity and the displacements of the center of pressure and the center of mass are shown in Figures 2 and 3, respectively.

Several other examples of the regulation of posture during voluntary movements of the limbs and trunk are reported in the literature. All studies used surface EMG recording of selected focal and postural muscles. Force-plate data and film analysis were often used to examine the kinematic and kinetic patterns produced by these patterns of muscle activation. These examples are summarized as follows.

**Elbow Flexion-Extension**

Rapidly flexing the elbows to raise a bar through 90 degrees of motion is accompanied by activation of the biceps brachii and erector spinae muscles (hip and trunk extensors), occurring 30 to 50 milliseconds prior to activation of the biceps brachii.12 Kinetic and kinematic analysis has revealed a hip flexor moment, in addition to a slight forward displacement of the trunk, during the early phase of elbow flexion. The trunk returns to a position slightly posterior to its original posture at the completion of movement.13 Hence, it appears that postural accompaniments serve to constrain displacement of the body's center of mass. Elbow extension is accompanied by early activation of the quadriceps femoris and rectus abdominis muscles (hip and trunk flexors). Kinematic and kinetic patterns are the reverse of those observed for elbow flexion.

**Trunk Flexion-Extension**

Rapid trunk flexion, displacing the head 30 cm forward, is accompanied by decreased tonic activation of the soleus muscle and by activation of the tibialis anterior and vastus medialis muscles, occurring 20 to 120 milliseconds prior to activation of the trunk flexors (rectus abdominis muscles).14 Kinematic analysis has revealed a backward translation of the hips simultaneous with forward flexion of the trunk. Although the counteracting motions of the trunk and hip (action-reaction) maintain the body's center of mass over the feet, postural accompaniments likely serve to constrain displacement of the hips. Soleus muscle inactivity and activation of the tibialis anterior muscle would resist backward displacement of the shanks. The vastus medialis muscle would serve to maintain knee extension. Backward trunk extension is accompanied by activation of the soleus and semimembranosus muscles, occurring simultaneously with activation of the trunk extensors (erector spinae muscles). Trunk extension is coupled with knee flexion, which serves to maintain the body's center of mass over the feet. The semimembranosus muscle could contribute to the compensatory flexion of the knees, whereas soleus muscle activation might function to restrain forward displacement of the shank.

**Rise to Toes**

Rising to the toes is preceded by decreased tonic activation of the soleus muscle, in addition to frequent activation of the tibialis anterior muscle, occurring 60 milliseconds prior to phasic activation of the soleus and medial gastrocnemius muscles.15 Silencing of the soleus muscle, coupled with activation of the tibialis anterior muscle, displaces the body's center of mass forward over the toes; subsequent rising of the toes moves the body's center of mass upward over the new base of support.

These examples of postural regulation during voluntary movement demonstrate that postural accompaniments can serve several purposes: (1) to constrain displacement of the body's center of mass, (2) to generate an opposing displacement of the center of mass, and (3) to position the center of mass over a new base of support. The act of rising to the toes affords the therapist an easy opportunity for viewing the importance of postural accompaniments. The body can be observed to sway forward prior to rising to the toes. In the absence of this postural adjustment, the subject stumbles backward as the body's center of mass is pushed up and backward.

**Timing and Gain Properties of Postural Accompaniments**

Most research on postural control during voluntary movement has focused on identifying patterns of postural muscle activity for different movement tasks. However, timing and gain of the postural control system...
Figure 2. Pattern of postural muscle activity that accompanies a voluntary pull on a stiff handle. The vertical broken line marks the onset of backward handle acceleration. Posterior leg and trunk muscles were activated in a distal-to-proximal order prior to handle acceleration. (LG = lateral gastrocnemius muscle, BF = biceps femoris muscle, ES = erector spinae muscle, TA = tibialis anterior muscle, RF = rectus femoris muscle, RA = rectus abdominis muscle.)
Figure 3. Body center-of-pressure (CP) and center-of-mass (CM) excursions that accompany a voluntary pull on a stiff handle. The vertical broken line marks the onset of backward handle acceleration. As CP moves forward (upward displacement), CM moves backward (downward displacement). These events precede movement initiation and serve to counteract reactive forces attributable to inertia of the handle.

also are important properties to examine if we wish to understand how the CNS uses these advance postural adjustments to optimally control upright stance. It seems intuitive that the timing and gain of postural accompaniments must be matched to the magnitude of destabilizing forces imposed by the movement. Postural adjustments that arrive too early or are too large can be destabilizing in themselves (ie. they will fail to match the destabilizing forces of movement). Hence, the CNS requires information about the movement task and internal knowledge about the interaction between body parts (posture and movement) in order to specify the appropriate direction, timing, and gain of postural adjustments accompanying movement. The importance of an internal CNS model of body dynamics to the coordination of posture and movement will be discussed in the next section.

Lengthening the interval between early postural and focal responses will allow the stabilizing forces of postural adjustments to act over a longer period, and increasing the gain of the postural response will increase the magnitude of stabilizing forces. Both timing and gain can be scaled together to produce more optimal stabilization of posture; however, this is not always the case. Increasing the mass of the moving limb increases both the latency between postural and focal responses and the gain of the postural response. Horak et al9 observed a 25-millisecond increase in postural-focal latency (90-115 milliseconds) and increased muscle activation after adding a 1-kg load to the wrist prior to arm elevation. Friedli et al10 observed similar changes when the load was introduced during the movement. Subjects flexed the elbows through 90 degrees, and an additional 1-kg load was added to the forearms when the elbow reached 60 degrees of flexion. Although feedback postural strategies could compensate for loads added after movement initiation, it is interesting that the CNS optimized postural control by modifying the early postural accompaniments. Movement acceleration also influences the magnitude of destabilizing forces imparted to the trunk (force=massx acceleration). Lee et al11 observed a linear increase in the amount of postural muscle activity when subjects raised their arms at velocities ranging from 40 to 320°/s. Acceleration had a very limited effect on the timing of postural and focal responses. At low velocities (<90°/s), the postural response followed the focal response, whereas at higher velocities, postural and focal responses were initiated in synchrony.

Symmetry of movement also affects the timing of postural and focal responses. Bouisset and Zattara12 observed that the latency between postural and focal responses was longer when subjects rapidly raised a single arm versus both arms (51 versus 25 milliseconds, respectively). This finding might be explained by the level of complexity of postural adjustments required in the two tasks. Elevation of a single arm causes anterior-posterior, as well as vertical-axis, rotational destabilization of upright posture. These forces are opposed by activation of the contralateral hip flexors, followed by activation of the ipsilateral hip extensors. During bilateral arm elevation, destabilizing forces are restricted to the anterior-posterior plane. Postural adjustments in this task involve only activation of the hip extensors, which can be affected over a shorter interval prior to the initiation of the focal response.7-8

The temporal coupling of postural and focal responses is not entirely controlled by the physical demands of a task. The "instructional set" given to a subject also can influence the postural-focal onset latency. When
movement is initiated under self-paced conditions, postural responses usually precede initiation of the focal response by 50 to 90 milliseconds.9 However, when the subject is instructed to react as quickly as possible to an external cue (eg, a tone or a light), the postural-focal onset latency is shortened and the postural response often occurs simultaneously with the focal response.5,11 This difference cannot be accounted for by differences in movement acceleration under the two instructional sets.11 Therefore, we might assume that the CNS trades off optimal stability for speed of movement initiation under reaction-time conditions; unfortunately, biomechanical data are not available to verify this assumption.

This last finding on the effects of instructional set on the timing of postural and focal actions begins to shed some light on the neural processes underlying the organization of posture and movement control. Babinski’s1 early observations of patients with cerebellar disorders suggest that posture and movement are controlled independently by the nervous system. When those patients attempted to lean backward by extending their hips, they failed to flex their knees in order to maintain an upright stance. Although the movement control system was intact, the postural control system failed. The finding that the temporal coupling between postural and focal actions is not rigidly regulated by the physical demands of the movement task, but also can be influenced by the behavioral conditions of the task (ie, triggered versus self-paced initiation), further argues that posture and movement are controlled by independent processes.

Brown and Frank17 used a precued reaction-time task to examine this same issue. The question was whether prior information about the direction of movement influences the timing of postural and focal responses. Subjects were required to push or pull on a stiff handle following the onset of a reaction signal. A precue on each trial informed subjects of the most probable (80% probability) direction of responding. Reaction latency to the onset of postural (gastrocnemius) and focal (posterior deltoid) muscles was shortest when the direction of responding agreed with the precue. This finding suggests that subjects used the precue information to bias the CNS toward one direction of responding. Despite this shortening of reaction time, the latency between postural and focal responses was the same as that occurring when no precue was given (equal probability of pull and push responses). A different finding occurred on trials in which the direction of responding was opposite to that of the precue (eg, pull-push). The reaction latency of postural muscles was equivalent to that occurring when no precue was given; however, the onset of the focal muscles was delayed further, resulting in a lengthening of the postural-focal latency. On these trials, it was necessary for subjects to reprogram the direction of postural and focal responses. The fact that this reprogramming is accomplished more quickly for the postural response than for the focal response argues for these responses’ independent control.

**Simplifying the Control of Upright Stance**

When considering the postural as well as the focal requirements of a movement task, it is evident that even simple movements require complex control. An act as simple as raising the arms requires control over numerous joints and muscles of the trunk and legs in order to stabilize posture, as well as control over the shoulder joint and muscles. How does the CNS simplify this control? One mechanism for simplifying the control of posture is to use the same set of prestructured postural synergies that subserve feedback-triggered postural reactions. Postural accompaniments and postural reactions share the goal of maintaining upright posture. Hence, it is possible that they share motor output patterns. Brown and Frank’s17 observation that the reprogramming of a postural response requires less time than that of a focal response suggests that postural accompaniments may be controlled by prestructured postural synergies.

Characteristics of feedback-triggered postural reactions have been studied extensively over the past 15 years.18–21 Based on postural reactions evoked by displacement of the support surface, Nashner and McCollum2 have suggested that upright stance is regulated by a limited set of prestructured postural synergies. For displacements in the anterior-posterior plane, upright stance is controlled by an ankle synergy, a hip synergy, or some combination of these synergies. The ankle synergy is characterized by activation of anterior or posterior muscles in a distal-to-proximal sequence; upright stance is restored by torque generated about the ankles. The hip synergy is characterized by activation of anterior or posterior muscles, but in a proximal-to-distal order. Early activation of trunk and hip muscles moves the body’s center of mass back over the base of support in order to maintain upright stance.

Cordo and Nashner4 provided evidence that postural adjustments accompanying voluntary movement and postural reactions may have common postural synergies. They reported a common pattern of postural muscle activation for three conditions that induced forward body sway: (1) backward translation of the support surface, (2) forward translation of a handle held by the subject, and (3) voluntary pulls on a handle held by the subject. Upright stance was maintained under all conditions by activation of the gastrocnemius and hamstring muscles in a distal-to-proximal order. Furthermore, the timing and relative magnitude of hamstring-to-gastrocnemius muscle activation remained constant under all three conditions.

We recently repeated Cordo and Nashner’s4 experiment, but we also recorded the postural reactions of the trunk muscles, in addition to the postural reactions of the muscles of the legs. For perturbations delivered to the trunk, the trunk muscles may play an important role. Postural reactions
were evoked by forward or backward displacement of a handle held by the subject. Subjects were instructed to maintain handle position against a 20-N preload; at random intervals, an increase in handle force (80 N, 200 milliseconds) was generated by a stepping motor. Postural adjustments accompanying voluntary movement were examined by instructing subjects to voluntarily push or pull on a handle against a 20-N preload. The latency of activation of six postural muscles is shown in Figure 4. Latencies are expressed as time after handle acceleration for postural reactions and time before handle acceleration for postural accompaniments.

Postural reactions and postural accompaniments in our experiment displayed very similar patterns of postural muscle activation. Forward sway was controlled by greater activation of posterior muscles (medial gastrocnemius, biceps femoris, and erector spinae muscles) than anterior muscles (tibialis anterior and rectus femoris muscles; the rectus abdominis muscle was not active consistently). The medial gastrocnemius muscle was the first muscle activated, followed by activation of the biceps femoris and erector spinae muscles, respectively. For backward sway, the anterior muscles (tibialis anterior and rectus femoris muscles) showed the greatest activity and were the earliest muscles activated. The order of activation again occurred in a distal-to-proximal order. These findings suggest that postural reactions and postural accompaniments may have common postural synergies to maintain upright stance. The findings presented, however, are based on data averaged across subjects (N=9). Individual subject analysis would provide a better test of this hypothesis.

**Organization of Posture and Movement Control**

Our current knowledge about the control of upright stance during voluntary movement is limited. We have a number of observations on the pattern and timing of postural adjustments during various movement tasks and some speculation on the organization of postural synergies. What is lacking is a general schema of the organization of CNS processes that control posture and movement. Figure 5 attempts to synthesize what we

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**Figure 4.** Pattern of postural muscle activity that accompanies voluntary (left) and externally perturbed (right) displacements of a handle held by the subject. Forward destabilization was caused by voluntarily pulling or resisting forward displacement of the handle. Backward destabilization was caused by voluntarily pushing or resisting backward displacement of the handle. Missing values infer that the muscle was not activated. Time 0 milliseconds represents the onset of handle acceleration in each graph. Subjects' (N=9) means and standard errors are presented. (RA = rectus abdominis muscle, ES = erector spinae muscle, RF = rectus femoris muscle, BF = biceps femoris muscle, TA = tibialis anterior muscle, MG = medial gastrocnemius muscle.)
Figure 5. A schema for the coordination of posture and movement. The central theme of the model is that a central nervous system (CNS) model of body dynamics translates cognitive motor plans into physical parameters for the regulation of posture and movement.

know about control of upright stance during voluntary movement and what we speculate about the underlying central control processes.

A central feature of the schema presented in Figure 5 is a CNS model of body dynamics (i.e., a model of how body segments interact during movement). This model is developed through repeated movement experiences that provide feedback regarding interactions between body segments. For example, healthy adults can experience difficulty with rising to the toes and maintaining this position for several seconds. This is not a well-practiced movement for many adults, and their initial attempts push them backward off balance. However, the individual soon learns to initially shift the body's center of mass forward over the toes prior to rising up on the toes. This very subtle postural adjustment at the onset of movement is essential to successful completion of the task. In addition, this model of body dynamics must be very state-dependent. Interactions between body parts will change, depending on how the body is supported (e.g., one versus four limbs) and the orientation of the body (e.g., forward or backward leaning). Nardone and Schieppati provide a good example of this state-dependence for the task of rising to the toes. When subjects were permitted to hold on to a stable support in front of them, the early silencing of the soleus muscle and activation of the tibialis anterior muscle disappeared. Presumably, postural control was transferred from the legs to the arms when arm support was provided.

The schema presented in Figure 5 suggests that cognitive motor plans are translated into physical parameters for movement by an internal model of body dynamics. The movement parameters include specification of the direction and gain of the focal movement (focal set) and the accompanying postural adjustments (postural set) and of the timing of these events. If this model of body dynamics is poorly developed, as with novel movement tasks, or disrupted by damage to the nervous system, postural accompaniments may be absent, inappropriate, or poorly timed. Babinski reported an absence of postural adjustments during backward leaning among patients with cerebellar disorders. An absence or change in postural accompaniments also has been reported among patients with Parkinson's disease. Rogers et al reported less-frequent postural adjustments prior to rapidly raising the arms in patients with Parkinson's disease. Kano et al reported a prolonged silencing of the soleus and gastrocnemius muscles prior to rising up on
the toes in patients with Parkinson's disease.

This clinical evidence suggests that the basal ganglia and the cerebellum may be involved in the translation of motor plans into movement parameters by way of a model of body dynamics. This role is supported further by the input-output connections of the basal ganglia and the cerebellum. Both of these structures receive and integrate input from all regions of the cerebral cortex. Thus, both structures are able to integrate motor intentions with feedback about postural stability and movement success. Outputs of the basal ganglia and the cerebellum are directed via the thalamus to the secondary and supplementary motor regions of the cerebral cortex. These cortical regions possess a diffuse somatotopic arrangement and may serve to set the direction and gain of the postural and focal responses without targeting specific muscles for activation.

Postural and focal sets lead to the selection of specific motor patterns that will regulate muscle contraction and joint displacement. Earlier, we argued that upright stance is regulated by a limited set of prestructured postural synergies. This has been a strong theme in the study of postural reactions. Postural control could be simplified by drawing upon a common set of postural synergies to regulate upright stance during voluntary movement and in response to external perturbations. Focal motor patterns, especially of the arms, are likely less stereotyped because they require greater flexibility in interacting with the environment. The selection of postural synergies and focal motor patterns probably involves the motor cortex, brain-stem motor regions, and the spinal cord.

Selected postural synergies and focal motor patterns are ultimately responsible for excitation or inhibition of muscles, which, in turn, stabilizes upright stance and guides movement. Proprioceptive vestibular and visual feedback are compared with an internal model of sensory dynamics to evaluate the success of the movement. Within the present schema for the control of posture and movement, we have suggested that the CNS model of body dynamics generates a model of sensory dynamics for the current movement task. Discrepancies between actual and expected consequences of movement on posture are used to modify the CNS model of body dynamics. It is this final process that contributes to the learning of novel movement tasks and that is important to the relearning of motor skills following injury to the CNS.

References