The Organization of Anticipatory Postural Adjustments

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Abstract — Central control of posture is expressed through anticipatory and compensatory postural adjustments. Anticipatory postural adjustments (APAs) precede planned postural perturbations and minimize them with anticipatory corrections, while compensatory postural adjustments deal with actual perturbations of balance that occur as a result of suboptimal efficiency of anticipatory corrections. The process of generation of APAs is affected by three major factors: expected magnitude and direction of the perturbation, voluntary action associated with the perturbation, and postural task. The results of studies investigating the effect of each of these three major factors on APAs while standing, as well as differences in organization of APAs in individuals with pathology, are discussed.

Index Terms — vertical posture, anticipatory postural adjustments, human.

I. INTRODUCTION

The existence of postural adjustments related to voluntary movement has been known since Babinski’s publication [1], and many studies have reported changes in the activity of postural muscles associated with simple or complex voluntary movements.

Central control of movement involves multiple parallel commands coordinated to fulfill a certain goal [2]. In particular, control of a voluntary movement requires maintaining a frame of reference in conditions of possible external and internal perturbations [3, 4]. This reference frame may refer to the position of a segment, of an extremity, or of the whole body. It may also refer to a more general notion of equilibrium, i.e., keeping the projection of the body center of gravity (CG) within the support area. Any voluntary movement, especially a fast one, induces a postural perturbation because of dynamic, inter-segmental forces, and also shifts of the center of gravity. Therefore, voluntary movements may be considered self-inflicted postural perturbations that may be predicted, to a certain degree, by the central nervous system (CNS), which adjusts the activity of postural muscles both prior to the actual perturbation and in response to it.

There are clear differences in the function and mode of control of these two groups of associated changes in activity of postural muscles. Anticipatory reactions are initiated by the subject, while later, compensatory reactions are initiated by sensory feedback triggering signals. The CNS tries to predict postural perturbations associated with a planned movement and minimize them with anticipatory corrections, while compensatory reactions deal with actual perturbations of balance that occur because of the suboptimal efficacy of the anticipatory components.

Russian scientists Belenkii, Gurfinkel and Paltzev [5] were the first to show that changes in the electromyographic activity of postural muscles in standing humans appear prior to (and during) voluntary movement of an upper limb and are specific to this movement. Since this pioneering study, anticipatory postural adjustments have been studied during leg movements [6, 7, 8], trunk movements [9, 10], arm movements in standing subjects [11, 12, 13, 14, 15], and during load release from extended arms [16, 17, 18], as well as in tasks restricted to upper extremities that did not involve maintenance of the vertical posture [19, 20, 21, 22, 23].

II. FACTORS AFFECTING ANTICIPATORY POSTURAL ADJUSTMENTS

The assumed role of the anticipatory activity of postural muscles is to counteract the expected mechanical effects of the perturbation in a feedforward manner [3]. A number of factors characterizing the forthcoming perturbation may affect anticipatory postural adjustment. As was suggested recently [18], the process of generation of APAs is affected by three major factors: expected magnitude and direction of the perturbation, voluntary action associated with the perturbation, and postural task.

A. The Effect of a Motor Action

The relation between the magnitude of a motor action triggering a postural perturbation and the magnitude of anticipatory postural adjustments was investigated in experiments which involved an unloading triggered by motor actions of different apparent magnitude (bilateral shoulder abduction vs. small finger flexion movement) while the magnitude of the unloading remained constant.
Standing subjects were required to hold a 2.2 kg load in extended hands, and then release it by a low-amplitude, fast, bilateral shoulder abduction movement; or to hold and release in a similar fashion an inflated balloon with this same load suspended on a short cord; or to pop a balloon with the same load suspended on a short cord, using a tack taped to the middle finger. Alternatively, the subjects held the balloon with the load, but the experimenter popped it at an unexpected time. Anticipatory postural adjustments were seen during all self-initiated unloadings as changes in the level of activation of the trunk and leg muscles and in displacements of the center of pressure (Fig. 1).

![Graph](image)

**Fig. 1.** Normalized integrals of anticipatory changes in the activity of biceps femoris, averaged across 7 subjects, with standard error bars. Standing subjects were required to hold a 2.2 kg load in extended hands, and then release it by a low-amplitude fast bilateral shoulder abduction movement (1); or to hold and release in a similar fashion an inflated balloon with the same load suspended on a short cord (2); or to pop the balloon with the same load suspended on a short cord, using a tack taped to the middle finger (3); or to hold the balloon with the load while the experimenter popped it at an unexpected time (4).

However, absolute values of these changes were significantly smaller in the series with balloon popping as compared to the series with shoulder abductions. Such reactions were absent when the unloading was triggered by the experimenter. The experiment demonstrated that a self-triggered perturbation is always associated with anticipatory postural adjustments, and that the magnitude of the adjustments may be scaled with respect to the magnitude of a motor action used to induce the perturbation.

The effect of the direction of perturbation on APAs was studied in experiments where the subjects were instructed to perform bilateral shoulder movements in different directions, from forward to backwards with increments of 30 deg [15]. Bilateral shoulder movements gradually changed the magnitude of postural perturbations in the sagittal plane.

Anticipatory postural adjustments were seen as changes in the electrical activity of postural muscles, and as displacements of the center of pressure and center of gravity. Proximal postural muscles demonstrated the largest anticipatory increase in background activity during movements in one of the two opposite directions (forward or backwards). These changes progressively decreased when movements deviated from the preferred direction, and frequently disappeared during movements in the opposite direction. The patterns in distal muscles generally demonstrated larger anticipatory changes during movements forward and backwards as compared to movements in intermediate directions. The results demonstrated that a change in the direction of voluntary bilateral shoulder movements leads to changes in anticipatory EMG activity of both proximal and distal muscles of the dorsal and frontal parts of the trunk and legs.

In experiments where a load was added to the arm to be raised, it has been shown that the intensity of anticipatory postural adjustments is graded as a function of the postural disturbance expected from the movement [24, 25, 26, 15]. An increase in movement velocity leads to earlier and more pronounced changes in the activity of postural muscles [24, 27], while a decrease in movement velocity leads to smaller anticipatory postural adjustments, or even to their disappearance [28].

**B. The Effect of Magnitude of Perturbation**

It has been shown in experiments with voluntary arm movements that the mass of a moving segment is commonly large enough to displace the projection of the center of gravity outside the area of support, which is rather small for common bipedal standing. When arm raising was performed with and without a load, the onset of postural adjustments was fixed with respect to the “go” signal [29]; however, the duration of anticipatory postural adjustments increased when a load was raised by the arm [30]. Quantitatively, a modest increase of anticipatory postural adjustments with inertial load was observed in some postural muscles [15].

We studied the effect of the magnitude of perturbation on APAs in an experiment in which subjects were required to apply vertical force to a horizontal bar connected to a force transducer by a cord, hold it, and then release the bar by a fast, low-amplitude, bilateral shoulder abduction movement. The subjects were instructed to apply forces of different magnitude varying from “maximal” to “small”, in a subject-selected, random order. Each subject performed 40 “unloadings”. Anticipatory postural adjustments were seen as changes in the level and/or timing of the background activation of postural muscles (Fig. 2). Muscles of the frontal part of the legs and the trunk demonstrated an anticipatory increase in activity, of which the timing and amplitude correlated positively with the magnitude of the perturbation. The experiment demonstrated that anticipatory postural adjustments could be scaled with respect to the magnitude of a self-triggered perturbation [31].

**C. The Effects of Posture**

The majority of studies of the effect of the postural task on APAs while standing were performed by modulating the stability of the body, using unstable surfaces or reducing the plantar support [32, 33, 34]. Additional evidence related to the effect of postural task on APAs was obtained when lower extremities were involved in a perturbation. In
particular, APAs were studied during leg flexion [35], lateral leg raising task [8, 36], while rising on tiptoe [37, 38]. APAs were also studied in subjects standing on one leg [34, 35] and during standing inclined forward. In the latter case, inclination was induced in the ankle joints, and a perturbation was induced by a load release from extended hands [34].

![Figure 2](image1.png)

**Fig. 2.** EMG patterns of rectus femoris (RF) and biceps femoris (BF) for a representative subject performing unloadings of highest, medium, and lowest magnitudes. Note typical changes in anticipatory EMG activity with magnitude of unloadings. BF traces are inverted for better visualization and their scale is on the right.

It has been reported that anticipatory postural adjustments are absent when the posture is unstable [39] as well as when it is stable [38]. The requirements in a series of experiments with backward bending were maximal speed, the same excursion in both tests, and return to the initial position after bending. The anticipatory EMG burst typically observed in the calf muscles was reduced when the subjects performed the same task while standing on a small plate placed on a narrow support [10].

The effect of instability on APAs was studied in an experiment where the subjects held a standard load in extended arms and then released it by a standard motor action. The stability of the vertical posture was manipulated: the subjects stood on a wooden board (0.45m square) resting on a beam providing contact with the platform. The beam was 0.45m long and either 0.04m or 0.08m wide. Anticipatory changes in the activity of postural muscles were seen in all series as a decrease in the activity of erector spinae, biceps femoris, and soleus and an increase in the activity of rectus abdominis, rectus femoris, and tibialis anterior approximately 100 ms prior to the load release (Fig.3). Anticipatory postural adjustments were smaller when the posture was unstable. Instability in the sagittal plane had larger effects on anticipatory postural adjustments than instability in the frontal plane. Standing on a board with the smaller area of support produced greater effects on the magnitude of anticipatory postural adjustments [34].

This study demonstrated that the magnitude of anticipatory postural adjustments, in conditions of a standard perturbation induced by a standard motor action by the subject, depends on two factors related to the postural task: the plane of postural instability and the area of support. This last factor may be considered an inverse measure of the degree of instability. Note that the purpose of anticipatory postural adjustments is to generate joint torques whose effects on the position of the center of gravity should be opposite to the expected effects of a perturbation. As such, anticipatory postural adjustments lead to shifts of the center of gravity and may, by themselves, be sources of postural perturbations. It would seem that in conditions of postural instability the central nervous system may be "unwilling" to generate strong anticipatory postural adjustments in order to avoid subjecting the fragile equilibrium to another source of perturbations. The study showed that anticipatory postural

![Figure 3](image2.png)

**Fig. 3.** EMG patterns of rectus abdominis (RA) and erector spinae (ES) for a representative subject during regular (stable) standing (thick lines) and while standing on a board that was unstable, with instability in the sagittal plane (thin lines).
adjustments could indeed be graded with respect to the degree of postural instability.

In a recent experiment, the effect of changes in the configuration of the body was investigated. The subjects performed fast bilateral shoulder extension movements while standing. Body configuration was modified by instructions to the subjects to stand vertically or with a forward bend [40]. The electrical activity of postural muscles and displacements of the center of pressure were recorded. Results indicated that APAs were modified with changes in the angular position of the upper body (Fig. 4). Decreased anticipatory activation was seen in rectus abdominis and rectus femoris. The results suggest that the CNS uses reorganization of the anticipatory activity of postural muscles to accommodate diminished stability of the body due to forward bend.

Fig. 4. Normalized integrals of anticipatory changes in the activity of rectus femoris, averaged across 8 subjects, with standard error bars. Reg: regular standing, 30°: standing with bend of 15°, and 45°: standing with bend of 45°. Note the decrease of anticipatory activity with changes of the angle of bend.

The results of studies of anticipatory postural adjustments in conditions of postural instability taken together allow us to formulate the hypothesis [34] that anticipatory postural adjustments themselves may be perturbations to balance, and that the lack of anticipatory postural adjustments in conditions of postural instability represents a defensive strategy of the CNS.

III. ANTICIPATORY POSTURAL ADJUSTMENTS AND PATHOLOGY

The task of generating anticipatory postural adjustments may be trivial for the CNS of a healthy person; but it can be challenging for a person whose ability to perform voluntary movements is impaired by natural processes (e.g., aging), or for someone with a neurological disorder, an inborn deficiency, or a lower limb amputation.

A. Anticipatory Postural Adjustments in Parkinson’s Disease.

Postural instability is a common problem in patients with Parkinson’s disease (PD). The basal ganglia play a particularly important role in regulation of posture, and postural deficit involving changes in both anticipatory and compensatory groups of postural reactions is a recognized clinical problem in many patients with Parkinson’s disease [41, 42, 43].

There is substantial variability among the studies of anticipatory postural adjustments in Parkinson’s disease. The reports vary from minor changes in the anticipatory reactions [44, 45, 46]; to no differences in the timing of early EMG bursts in postural muscles but decrease in the amplitude of the bursts [25]; to smaller EMG changes in muscles involved in a postural component of a bi-manual task and, often, a lack of anticipatory EMG changes [41]; to a lack of anticipatory postural adjustments in 95% of patients with Parkinson’s disease [28]. It was suggested that the deficit in anticipatory postural adjustments in individuals with PD are likely to be of a quantitative nature, rather than an actual deficit in the ability to use mechanisms of feedforward postural corrections [46].

B. Motor Patterns in Down Syndrome.

Motor disorders in Down syndrome (DS) are commonly addressed as “clumsiness.” Two major components of clumsiness in DS include the slowness of movements and the inability to respond rapidly to a changing environment [47, 48]. In a number of postural and movement tasks, persons with DS frequently use atypical coactivation patterns of muscle activity [49]. Such patterns are seen, in particular, in preprogrammed reactions, both anticipatory and corrective [50, 51]. Cocontraction might be the consequence of an altered (impaired) mechanism of preprogramming or it could represent a “safety-catch” imposed by the CNS to allow movement to be controlled within the constraints of its impaired operating capacity. Such anticipatory cocontraction was observed in individuals with DS performing fast arm movements [51].

Novices in the early stages of acquiring a motor skill frequently demonstrate greater than optimal levels of cocontraction that appear to increase stability and reduce the likelihood of error [52]. This cocontraction commonly disappears after the skill is well learned. Thus, we think, anticipatory muscle coactivation seen in individuals with DS is likely to reflect active intervention by the CNS in an attempt to optimize motor performance.

C. Motor Reorganization After a Lower Limb Amputation.

The obvious shortening of one leg and the necessity to learn how to use a prosthesis are not the only factors that contribute to the hardships encountered by amputees. Other potentially important factors include unavoidable prolonged disease during convalescence, leading to weakening and loss of endurance in the residual (proximal) leg muscles [53, 54, 55]; changed biomechanics of the lower limb, necessitating modification of the control strategies previously used for locomotion and postural control; loss of neural input from proprioceptive afferents, leading to changes in the spinal reflex circuitry; and secondary adaptive changes in the
distribution of cortical projections to segmental structures [56, 57]. Following below-the-knee amputation, patients demonstrated a general pattern of larger anticipatory changes in the activity of muscles on the intact side of the body, compared to corresponding muscles on the side of the amputation, which may reflect central adaptive changes secondary to the amputation [58, 59].

D. Motor Reorganization After a Stroke. Studies have shown that both anticipatory and compensatory mechanisms are impaired in individuals with stroke [60, 61]. In particular, APAs have been shown to be decreased and/or delayed with respect to those seen in healthy individuals [61, 24]. Individuals with hemiparesis due to a stroke also show impaired acquisition of APAs associated with a newly learned task [62]. In a recent study [63] we found that APAs were reduced in individuals with hemiparesis, especially on the paretic side.

IV. THE MODE OF ORGANIZATION OF ANTICIPATORY POSTURAL ADJUSTMENTS

Two major views exist concerning the relation between anticipatory postural adjustments and voluntary motor action (Fig. 5). The first view considers anticipatory postural adjustments to be reflections of a separate control process, one which may depend on the type and magnitude of the motor action but which has a degree of autonomy [3]. According to this view, changes in the relative timing of APAs and focal movement can occur with changes in instructions from the controller. The second view considers anticipatory postural adjustments a distinct peripheral pattern of a single control process directed at both apparently "focal" and apparently "postural" joints [16]. In this view, a common controller for the focal and postural commands exists. This hypothetical controller produces a command that is later transformed (processed), giving rise to commands to individual joints. The process of this transformation is assumed to reflect, in particular, prior experience of the subject with the task or with similar tasks. According to this scheme, one may expect commands to apparently postural joints to be closely tied to commands to apparently focal joints. Thus, anticipatory postural adjustments are not an addition to a "voluntary motor command" but an inherent component of this command. This scheme suggests the possibility of a close relation between the magnitude of anticipatory postural adjustments and the magnitude of a motor action that triggers a postural perturbation, if the same transformation process is used.

There are data supporting both views. For example, it has been shown that the interval between the onset of a postural adjustment and the onset of voluntary action varies as a function of the mode of control. Anticipatory postural adjustments mostly occur simultaneously with the onset of motion in a reaction time paradigm, and they precede it during self-paced arm movement [64, 65]. In the locomotor cycle, the onset of anticipatory postural adjustments may be time-locked with certain events within the locomotor cycle rather than with the onset of the prime mover [66]. However, in bimanual load-lifting tasks the onset of the movement and that of anticipatory postural adjustments are time-locked [21, 4]. In experiments with self-initiated standard perturbations, anticipatory postural adjustments scaled with respect to the magnitude of the motor action used to induce the perturbation [16], with the magnitude of the perturbation [31], or with the degree of instability [34]. These results support the single control process scheme. On the other hand, changes in the relative timing of APAs with instructions, in experiments where arm movements were performed in self-paced and reaction time conditions, corroborated the parallel control scheme [17].

V. CONCLUDING COMMENTS

The results of studies of the anticipatory postural adjustments suggest that there are three major components that influence anticipatory postural adjustments: motor action, perturbation, and postural task. The experimental results that could be used to support such an organization of the APAs demonstrated in particular that: 1) anticipatory postural adjustments change with the magnitude of the motor action even when the magnitude of a perturbation is standard; 2) anticipatory postural adjustments are modified with the expected magnitude of a perturbation when the motor action is standard; 3) anticipatory postural adjustments change with the postural task when both the motor action and the perturbation are standard. Additionally, the experiments demonstrated that anticipatory postural adjustments are attenuated and even disappear if postural stability is compromised. It is quite likely that in such cases anticipatory postural adjustments themselves are regarded as a perturbation to postural balance and the central nervous system may be "unwilling" to generate strong anticipatory postural adjustments in order to avoid subjecting a fragile equilibrium to another source of perturbations. Adaptive changes in anticipatory postural adjustments seen in patients with postural instability, and in healthy subjects while posture is unstable, support this conclusion.
REFERENCES


