Motor Control, 2003, **7**, 264-277

The Effect of Changes in the Body Configuration on Anticipatory Postural Adjustments

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A number of factors are likely to play a major role in the process of generation of anticipatory postural adjustments (APAs). Among them are the magnitude and direction of an expected perturbation, properties of a voluntary action associated with the perturbation, and features of the postural task such as a body's configuration prior to the action. The aim of this study was to analyze the effect of body configuration on APAs. Experiments were performed on 8 healthy subjects performing fast bilateral shoulder extension movements while standing. Body configuration was modified by instructions to the subjects to stand vertically or with a forward upper body bend varying from 15 to 60°. 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. Decreased anticipatory activation was seen in rectus abdominis and rectus femoris, while increased anticipatory inhibition was observed in erecteor spinae and biceps femoris across conditions with forward bend. As a result, the total anticipatory activity of muscles in a muscle pair in series with a forward bend showed only slight modulation as compared to vertical posture. These results suggest that the CNS uses reorganization of the anticipatory activity of postural muscles by compensating for the changes in APAs of individual muscles in a muscle pair in such a way that the overall anticipatory activity of the muscle pair stays unchanged. Such compensation in counteracting the expected mechanical effects of the perturbation is used to accommodate both changes in the length of postural muscles and diminished stability of the body due to forward bend.

Key Words: posture, anticipatory postural adjustments, EMG, human

1. Introduction

Many motor actions performed by a standing individual may induce perturbation of vertical posture. The central nervous system (CNS) uses a number of mechanisms to maintain equilibrium. Among them are changes in the background activ-

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ity of postural muscles seen prior to the perturbation, commonly referred to as anticipatory postural adjustments (Belenkiy et al., 1967; Cordo & Nashner, 1982; Hugon et al., 1982; Massion, 1992). Anticipatory postural adjustments (APAs) are believed to be generated in a feed-forward fashion based on predictions of an upcoming perturbation. Their purpose is to counteract the effects of the perturbation on vertical posture. A number of factors are likely to play a major role in the process of APA generation. Among them are the magnitude and direction of an expected perturbation, properties of a voluntary action associated with the perturbation, and features of the postural task, in particular, body configuration (Aruin & Latash, 1995b, 1996; Aruin et al., 1998; Dufosse et al., 1985; Gantchev & Dimitrova, 1996; Lee et al., 1987; Massion, 1992).

Reports of the dependence of APAs on the stability demands of the postural task or on the configuration of the body have been somewhat fragmented, suggesting that the dependence may be non-monotonic. In particular, APAs associated with voluntary movements were attenuated or absent when the posture was unstable (Aruin et al., 1998; Gantchev & Dimitrova, 1996; Nouillot et al., 1992; Pedotti et al., 1989; Slijper & Latash, 2000). On the other hand, when the posture was very stable—for example, during standing while grasping two handles (Nardone & Schieppati, 1988)—APAs were also attenuated. In a recent study involving load releases during vertical and inclined standing, it was shown that APAs are attenuated in conditions of unstable posture and that APAs are scaled with the degree and direction of instability (Aruin et al., 1998).

In all these studies, however, the upper body was aligned with the lower body. It was also stated that orientation and stabilization of the trunk axis, the largest axis of any body segment, is critical for balance maintenance (Massion, 1992). Thus, changes in the trunk position and associated changes in length of the muscles around the hip joint could be an important factor that affects the organization of anticipatory postural adjustments.

The main purpose of the present study was to investigate whether anticipatory postural adjustments are modified with changes in body configuration. To test this, we used an earlier paradigm (Aruin & Latash, 1995a), which includes fast bilateral shoulder extension movements while standing. Within this paradigm, changes in body configuration were manipulated by having the subjects stand with different angles of the upper body forward bend.

2. Methods

2.1. Subjects

Eight subjects, 6 males and 2 females, 42.6 ± 11.7 years old, mean weight 75.8 ± 2.7 kg, and mean height 1.7 ± 0.1 m, participated in the experiment. All subjects were free of any known neurological or motor disorders. The subjects gave informed consent according to the procedures approved by the Institutional Review Board.

2.2 Apparatus

The subjects stood comfortably and quietly on a biomechanical platform (AMTI, OR-6). The signals from the platform were amplified and used to measure reaction forces in three orthogonal directions (along the direction of gravity F_z, parallel to the ground in the sagittal plane F_x, and parallel to the ground in the frontal plane F_y) and moments of force in three directions (in the sagittal plane, M_y, in the frontal plane, M_x, and around the vertical axis of the body, M_z).

Disposable pediatric electrocardiographic electrodes were used to record the surface electromyographic (EMG) activity of the following postural muscles from the right side of the body: rectus abdominis (RA), erector spinae (ES), rectus femoris (RF), biceps femoris (BF), soleus (SOL), and tibialis anterior (TA), using standard skin-preparation procedures (Basmajian, 1978). The electrodes were taped over the muscle bellies. The distance between the two electrodes of a pair was about 4 cm. The EMG signals were amplified by means of differential amplifiers (×3000), and digitized with a 16-bit resolution at 1000 Hz.

A miniature unidirectional accelerometer (Sensotec) was taped to the wrist of the subject, with the axis of its maximal sensitivity oriented in the plane of expected perturbation. The sensitivity of the accelerometer was 50 mV/g at 50 Hz, its mass was 0.005 kg, and its range was ± 100 g.

A PC with customized software based on the LabView-4 package was used to control the experiment, collect data, and perform most of the analyses.

2.3. Procedure

The experimental procedure involved five series in which the subjects were instructed to stand comfortably on the force platform and perform bilateral shoulder extension movements (backwards) over the nominal amplitude of 45°. The bilateral shoulder extension movements were chosen because they create forward angular momentum of the body leading to postural destabilization. Before each movement, the subjects were asked to stand quietly, their feet 0.3 m apart, their arms hanging loosely at their sides, and their palms oriented towards the body. Within the first series (regular standing), the subjects performed arm movements while standing using a regular bipedal stance. In the following four series, the subjects were instructed to bend the upper trunk slowly to 15, 30, 45, or 60° from the initial vertical position. The angle of bend of such a quasi-static, “freezing” position was measured with a goniometer; special attention was paid to achieve bending with no ankle and knee extension or flexion movements, and the subjects made adjustments to the selected position of the body based on verbal feedback provided by the experimenter. The angle of bend was used as a measure of the instability based on the assumption that the projection of the center of mass of the body in the bending postures is located closer to the front border of the base of support than in the erect posture. After the desired posture was adjusted, the subjects were instructed to perform, upon hearing a computer-generated tone, the required extension movement with both arms “as fast as possible,” stop at the final position, wait for the second computer-generated tone (which came after a 3-s interval), return to the initial position, and wait for the next signal. The acceleration of the arm was measured in order to estimate the magnitude of perturbation to the body induced by the arm extension movements. Each series consisted of 6 movements of a nominal amplitude of 45° that was recommended to the subjects, but they were free to select comfortable actual movement amplitude as long as all the movements were similar to each other. The subjects were requested to keep the position of their lower extremities vertical, and the experimenter checked that the lower body was kept straight prior to performing required shoulder extension movements in all the trials; no lifting of the heels or bending of the knees was allowed. Trials in which either the knee, ankle, or hip angle differed from the initial posture were rejected during data processing; this happened in 0 to 1 trials per series. Two to three practice trials were performed in each condition before data collection. The subjects were told that they had up to 3 s to start performing the task in a self-paced manner upon hearing a computer-generated tone. They started with 0° of bend; the order of series with 15, 30, 45, and 60° was randomized. The subjects were always able to take a step to avoid falling if they lost their equilibrium. In such rare cases, the trial was excluded from analysis.

2.4. Data Processing

The trials were viewed off-line on a monitor screen and aligned according to the first visible deflection of a signal from the accelerometer. This time was considered “time zero” (t_0) in all subsequent analyses.

EMG signals were rectified and low-pass filtered at 100 Hz. The area under the rectified EMG curve (EMG integral) was calculated from –100 ms to +50 ms with respect to t_0 ($\int EMG_{APA}$) and used to characterize the anticipatory $\int$EMG changes in the activity of the postural muscles. These intervals of integration were chosen based on previous studies that described APAs as typically starting about 100 to 150 ms prior to the focal movement (Aruin & Latash, 1995a). These values were

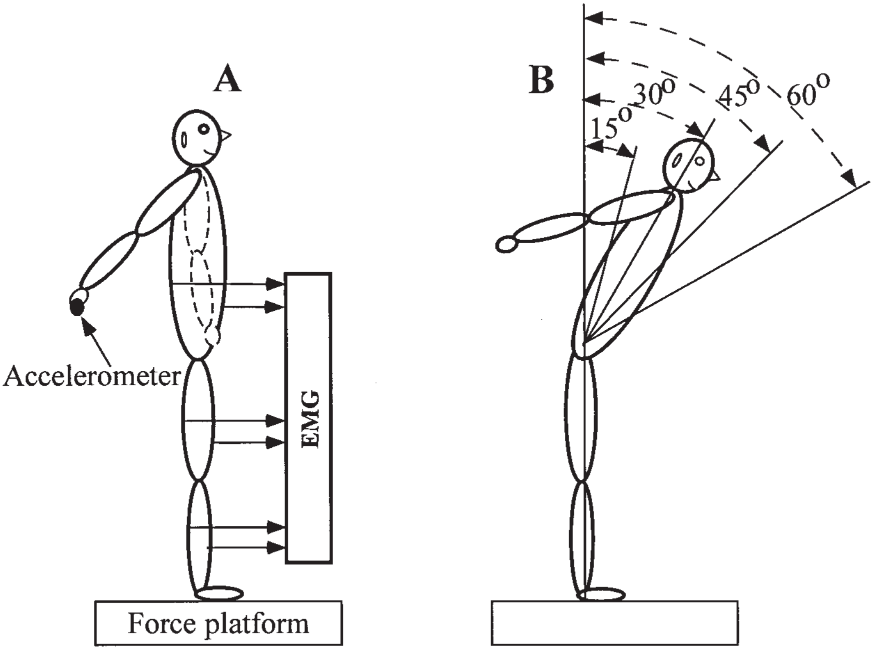

Figure 1 — A schematic illustration of the experimental procedures. A: The experimental setup. B: The scheme of the experiments with different angles of bend. The subject performed rapid bilateral shoulder extension movements in the standing position with various anteriory inclined angles.

corrected for the background EMG integrated over a time period from –500 ms to –450 ms prior to t_0 ($\int EMG_{bg}$); this background activity recorded during 50 ms was multiplied by 3 to match with the APAs integrated over a period of 150 ms:

$$\int EMG = \int EMG_{APA} - 3 \int EMG_{bg}$$

The integral values for each muscle and each subject were normalized by the maximal magnitude of the integral seen in all the series in the experiment. In addition, the differences (R) and sums (C) between normalized $\int$EMG values for muscle pairs were calculated (Slijper & Latash, 2000) as:

$$R_{RA/ES} = \int EMG_{RA} - \int EMG_{ES} \qquad C_{RA/ES} = \int EMG_{RA} + \int EMG_{ES}$$

$$R_{RF/BF} = \int EMG_{RF} - \int EMG_{BF} \qquad C_{RF/BF} = \int EMG_{RF} + \int EMG_{BF}$$

$$R_{TA/SOL} = \int EMG_{TA} - \int EMG_{SOL} \qquad C_{TA/SOL} = \int EMG_{TA} + \int EMG_{SOL}$$

Horizontal displacements of the center of pressure in the anterior-posterior (CP_y) and medio-lateral (CP_x) directions were calculated using equations described previously (Slijper et al., 2002). Displacements of the center of pressure were quantified at t_0.

Statistical methods included repeated measures ANOVAs, with the main factor being bend angle (5 levels: 0, 15, 30, 45, 60°). Post hoc comparisons between individual levels were made using a Student *t* test. For all statistical tests, significance was set at $p < .005$.

3. Results

No significant differences were found for the acceleration of the arm across the five conditions. Therefore, the magnitudes of perturbations to the body across the five conditions were assumed to be similar.

APA patterns in a vertical posture included an anticipatory burst of activity of rectus abdominis and rectus femoris, and an anticipatory inhibition in the background activity of erector spinae and soleus muscles, starting from about 100 to 150 ms prior to the start of the arm movement. The EMG patterns of the proximoaxial (rectus abdominis and erector spinae) and intermediate (recurs femoris and biceps femoris) agonist-antagonist pairs controlling posture demonstrated the commonly observed triphasic pattern similar to what was observed earlier (Aruin & Latash, 1995a). During bend standing, however, there were considerable changes in EMG patterns during APAs. Figure 2 illustrates such differences in APAs during regular standing and standing with bend for one of the subjects. When the subject performed arm movements while standing with 15° of forward bend, the anticipatory bursts of activity of rectus femoris muscle disappeared. Note also an increased background activity in erector spinae and biceps femoris muscles due to maintenance of posture while bending and anticipatory inhibition of the activity of the erector spinae and biceps femoris muscles; such an inhibition remained in the experimental series with bends of 30, 45, and 60°. There was also a small anticipatory increase of the EMG activity in tibialis anterior, with increase in the angle of bending. Different subjects could demonstrate somewhat different patterns of anticipatory changes in the background activity, with different relative involvement of individual muscles.

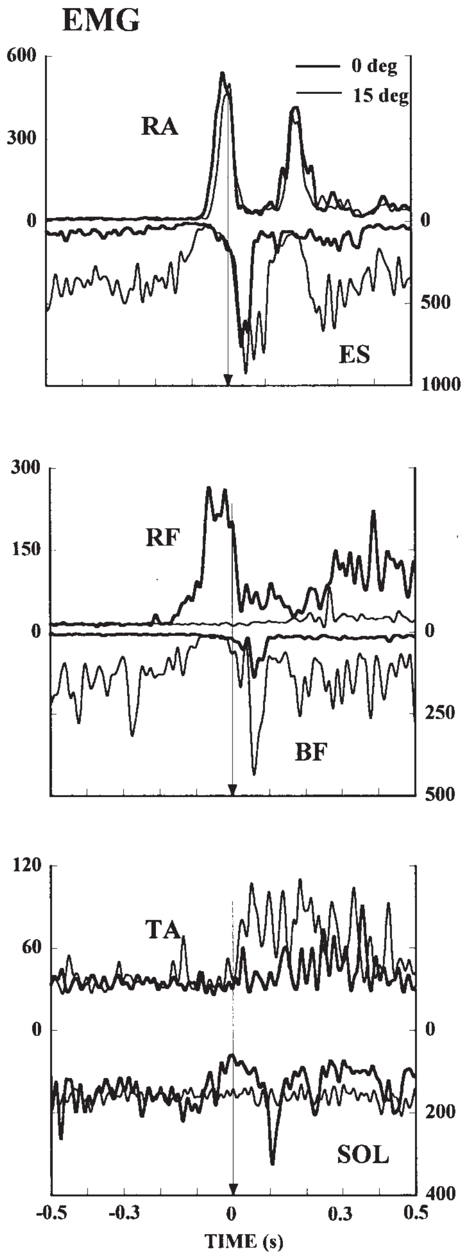

Figure 2 — EMG pattern (averages of 6 trials for one of the subjects) during regular standing and with a bend of 15°. Time scale is in seconds; EMG scales are in arbitrary units. EMGs of the muscles of the dorsal part of the body are inverted for better visualization. The arrows show the time of alignment (see Methods). Increased background activity in erector spinae (ES) and biceps femoris (BF) muscles prior to a perturbation are the result of the forward bend.

EMG patterns in the rectus abdominis and erector spinae agonist-antagonist pairs in the series with bending were characterized by four alternating phasic bursts. The increase of activity of erector spinae was seen approximately 250 ms after the start of the arm movements.

EMG integrals during APAs were measured in averaged trials, for each series and each subject separately, and normalized (see the Methods). Figure 3 presents ∫EMG indices averaged across subjects. Note similarities in patterns of the changes in the ∫EMG of two muscle pair: RA-ES and RF-BF.

One-factor ANOVAs were run for each muscle and demonstrated significant effects of the angle of bending for rectus abdominis ($F_{4,7} = 3.08$, $p < .05$), erector spinae ($F_{4,7} = 10.58$, $p < .01$), rectus femoris ($F_{4,7} = 15.20$, $p < .001$), and biceps femoris ($F_{4,7} = 8.73$, $p < .001$). Within individual muscles, the difference between ∫EMG for regular standing and 15° of bend reached the level of statistical significance (two-tailed Student's *t* test, $p < .05$) for RA ($t = 4.85$), ES ($t = 6.61$), RF ($t = 9.22$), and BF ($t = 4.61$). The differences between ∫EMG for regular standing and 15° of bend for TA and SOL were insignificant. The differences in ∫EMG between 15 and 30, 30 and 45, and 45 and 60° for each of RA, ES, RF, BF, TA, and Sol muscles were also not significant (two-tailed Student's *t* test, $p < .05$).

To characterize the overall effect of muscle pairs at the joint level, the differences and sums between normalized ∫EMG were calculated. Changes in R-indices and C-indices for all three muscle pairs are shown in Figure 4. Significant main effects of the angle of bend were seen in R-indices only for RA-ES muscle pair ($F_{4,7} = 7.62$, $p < .001$), while no significant effects were seen for RF-BF and TA-Sol muscle pairs. For C-indexes, significant effect was seen for RA-ES muscle pair ($F_{4,7} = 6.73$, $p < .001$) and RF-BF ($F_{4,7} = 12.70$, $p < .001$).

The displacements of the center of pressure in the lateral direction were very small due to symmetry of arm movements and will not be discussed. Figure 5 presents the relationship between the displacement of the center of pressure in the anterior-posterior direction and the angle of bending for all subjects. An apparent anticipatory component in the displacement of the center of pressure in a backward direction was seen in all the series except 60° bending. Displacements of the center of pressure in an anterior-posterior direction were largest for vertical posture (–0.0055 ± 0.002 m) and gradually decreased for greater angles of bending. One factor ANOVA demonstrated statistical significance for these changes ($F_{4,7} = 3.41$, $p < .05$).

4. Discussion

The majority of studies of the effect on APAs of a postural task while standing was done by having the subjects stand on unstable surfaces or with reduced plantar support (Aruin et al., 1998; Do & Gilles, 1992; Gantchev & Dimitrova, 1996; Kaminski & Simpkins, 2001). An additional body of evidence related to the effect of instability on APAs was obtained when lower extremities were involved in a perturbation. In particular, APAs were studied during leg flexion (Nouillot et al., 2000), in a lateral leg raising task (Mille & Mouchnino, 1998; Mouchnino et al., 1992), and while rising on tiptoe (Lipshits et al., 1981; Nardone & Schiepatti, 1988). Very few studies were performed when configuration of the entire body was manipulated prior to a perturbation. Thus APAs were studied while standing on one leg (Aruin et al., 1998; Nouillot et al., 2000) or while standing inclined forward. In the latter case, inclination was induced in the ankle joints, and a

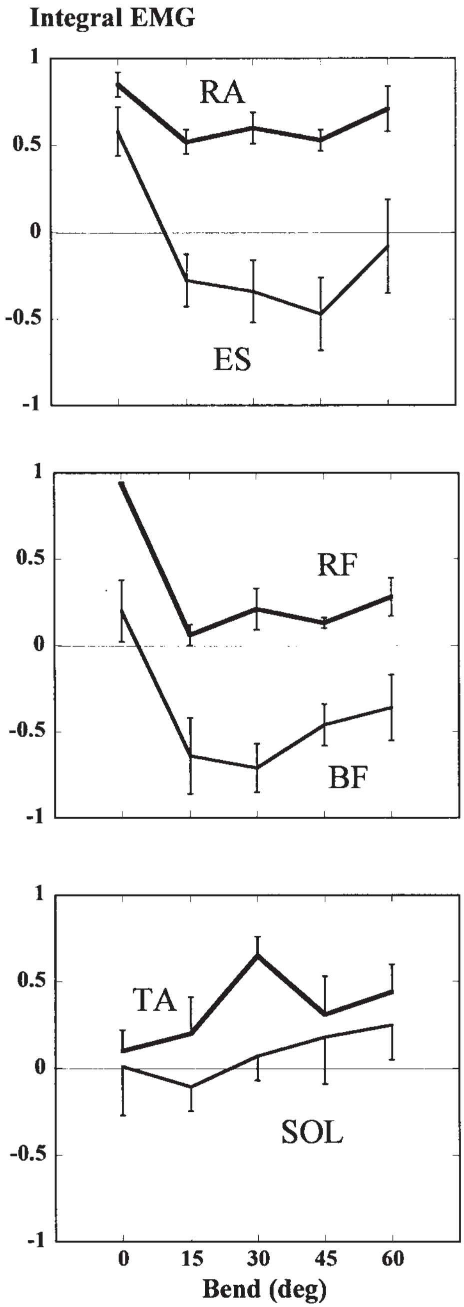

Figure 3 — **Normalized integrals of anticipatory changes in the activity of postural muscles, averaged across 8 subjects, with standard error bars. Note the differences in the behavior of postural muscles of the frontal part of the body (rectus abdominis, RA; rectus femoris, RF; and tibialis anterior, TA) and of the dorsal part (erector spinae, ES; biceps femoris, BF; and soleus, SOL).**

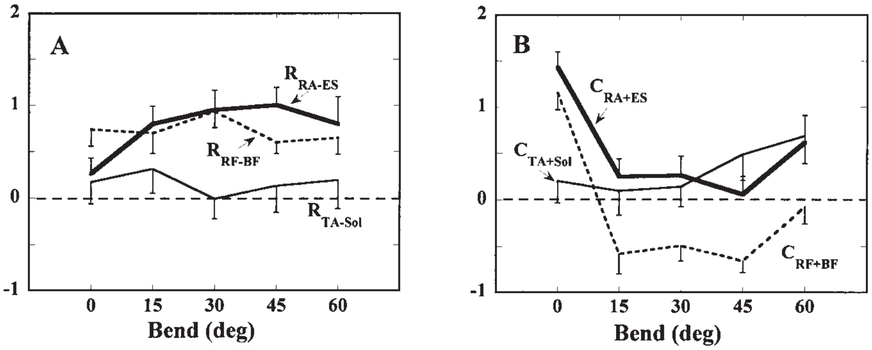

Figure 4 — Changes in the R-indices (A) and C-indices (B) for postural muscle pairs. Data averaged across 8 subjects, with standard error bars.

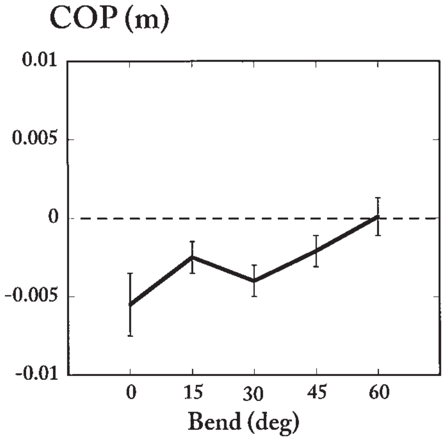

Figure 5 — Displacements of the center of pressure in the anterior-posterior directions for the five different postures averaged across 8 subjects, with standard error bars. The displacement was measured at the time of alignment (t_0) with respect to time –500 ms. Negative values correspond to displacements backwards.

perturbation was induced by a load release from extended hands (Aruin et al., 1998). However, in all these studies, the position of the upper body was vertical and/or aligned with the position of the lower body.

The current experiments were designed to study the effect of configuration of the body induced by forward bend accomplished without rotation of the lower limbs backwards about the ankle joints. This was achieved by having the subjects bend their trunk while keeping the verticality of the lower legs that was controlled by the experimenter (see Methods). As a result, a subject could stand with different hip angles producing self-initiated perturbations, confined mostly to perturbations in the anterior-posterior direction, using similar motor actions. This is important for making comparisons among APA characteristics in different conditions, since APAs have been shown to depend on properties of motor actions associated with a postural perturbation (Aruin & Latash, 1995b; Dufosse et al., 1985). We assumed that the magnitudes of perturbations to the body were comparable in different experimental series, as no significant differences were found in the arm acceleration across the five conditions. While additional experiments would be needed to evaluate the effect of possible variability of the position of the center of mass of the body due to different forward bend, the measurement of acceleration of the arm commonly used in postural studies (see, e.g., Bouisset & Zattara, 1987; Bouisset et al., 2000; Gantchev & Dimitroova, 1996) could be considered as an estimate of the magnitude of perturbation.

4.1. Specificity of Proximal Muscles

Anticipatory postural adjustments observed while the subjects performed fast bilateral shoulder extension movements in standing with forward bend were modified compared with the APAs recorded in conditions of upright standing. A significant dependence on the angle of bend has been seen for proximoaxial (RA-ES) and intermediate (RF-BF) postural muscle pairs (cf. the classification by Moore et al., 1988; Aruin & Latash, 1995a). This modification of the anticipatory activity of the postural muscles with changes in the angular position of the upper body was different for muscles of the ventral and dorsal parts of the body. Consequently, the anticipatory increase in activity in RF muscle was suppressed in trials when the position of the upper body was not vertical. It is possible that the activation of RF in conditions of forward bend (that is used to support the initiation of the arm movement when the body is vertical) is not required as the hip is flexed. The changes in the activity of ES and BF (Figure 3) were even more noticeable as the anticipatory increase of their activity seen in vertical posture was replaced by the inhibition of the background activity. Such a distinct attenuation or inhibition of proximoaxial and intermediate postural muscles seen for 15° bends remained for all other angular positions of the upper body.

An interesting finding related to changes in the initial position of the upper body refers to observation of the fourth burst of electrical activity in the rectus abdominis–erector spinae muscle pair. Typically, EMG patterns of the postural muscles have been described as triphasic patterns and have commonly been seen in the leg and trunk muscles of individuals performing voluntary arm movements while standing. Triphasic patterns have been described in healthy individuals (Aruin & Latash, 1995a; Crenna et al., 1987; Friedli et al., 1984), in individuals with Down syndrome (Aruin & Almeida, 1997), in patients with Parkinson disease (Latash et al., 1995), and in individuals with lower leg amputation (Aruin et al., 1996).

The emergence of the fourth burst of activation in the rectus abdominis–erector spinae muscle pair approximately 250 ms after the start of a perturbation may be attributed to differences in the initial position of the upper body prior to a perturbation. Due to the fact that the mass of the upper body represents approximately 50% of the entire body mass (Zatsiorsky et al., 1984), its deviation from the vertical line shifts the projection of the center of mass closer to the border of a base of support, resulting in a less stable posture. While the direction of the perturbation (fast bilateral arm movements performed in the sagittal plane) coincides with the direction of instability of the body (induced by forward bend), additional compensatory adjustments in the activity of postural muscles directed at stabilization of the body may be needed. An alternative explanation could be associated with returning activity of the ES to its initial level of background activity needed to counteract the gravity torque at the hip joint due to the bent trunk position. While an additional burst of activity was observed in a proximal muscle pair, there was no indication of such a compensatory activity seen in the distal muscles.

4.2. Specificity of Distal Muscles

The distal muscles controlling the ankle joint show less reproducible, subject-specific dependence, and a lack of significant effects. Similar behavior of distal muscles was seen in experiments with multidirectional movements while standing (Aruin & Latash, 1995a). Contrariwise, significant contributions of TA-SOL to APAs were reported during unilateral shoulder movements performed by standing subjects (Zattara & Bouisset, 1988) and during load releases while standing inclined forward (Aruin et al., 1998). In addition, substantial involvement of the TA-SOL pair in APAs has been demonstrated during asymmetrical perturbations (Aruin et al., 2001) and under unusual postural conditions involving standing on roller skates (Shiratori & Latash, 2000). The contrast between significant effects in proximoaxial and intermediate muscles and the lack of effects in distal muscle pairs in the current experiment could be due to a different role those muscle groups play in the control of limb dynamics and posture. Additionally, as suggested by Winter et al. (1996), the dynamic balance of the upper body (including the head, arms, and trunk) is controlled by the hip muscles, with almost no involvement of the ankle muscles. These results taken together suggest that the role of the distal muscles controlling the ankle joint in experiments with forward bend is relatively minor and might involve fine tuning the general APA pattern provided mostly by the proximal muscles.

4.3. Activity of Muscles in Postural Pairs

Two major factors may affect the organization of anticipatory postural adjustments in conditions of forward bend. The first relates to changes in the length of the muscles around the hip joint with modulation of the angular position of the upper body. Such a length change is associated with additional muscular excitation and may result in changes of the muscle force production (Hay, 1992; Lunnen et al., 1981; Zatsiorsky, 1995). Thus we might expect to observe changes in muscular excitation as a function of muscle length or joint configuration as was demonstrated, for example, for knee extensors with changes in hip joint angles (Hasler et al., 1994). Indeed, increase of the background activity in ES and BF was seen in conditions of leaned-forward standing.

Second, changes in the initial configuration of the body induced by flexion in the hip joint could be associated with lesser stability of the body due to shift of projection of the center of mass closer to a border of the base of support (Crennna & Frigo, 1991). This suggests that we might expect attenuation of anticipatory activity of postural muscles as a premeditated, protective act that the CNS uses in conditions of postural instability (Aruin et al., 1998). In fact, our findings suggest that there were suppressions of APA activity of individual muscles with changes in the angle of bend. Such attenuation of the anticipatory bursts of activity of RA and RF seen in the current experiments is consistent with previously reported suppression of anticipatory activity of postural muscles in conditions of instability of the body (Aruin et al., 1998; Gantchev & Dimitrova, 1996; Noulillot et al., 2000).

The question arises whether the CNS uses an activation strategy to accommodate changes in the lengths of muscles around the hip, or whether it uses a protective strategy of suppressing the APA due to instability of posture. It would seem that the CNS uses a combination of both strategies by compensating for the changes in APAs of individual muscles in a muscle pair in such a way that the overall APA activity of the muscle pair remains unchanged.

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Acknowledgments

This study was supported by NIH grant HD-37141.