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Anticipatory activation of postural muscles associated with bilateral arm flexion in subjects with different quiet standing positions

Katsuo Fujiwara [a,*], Hiroshi Toyama [a], Kenji Kunita [b]

[a] *Department of Human Movement and Health, Graduate School of Medical Science, Kanazawa University, 13-1 Takara-machi, Kanazawa 920-8640, Japan*

[b] *Institute of Health Science and Physical Education, Osaka City University, 3-3-138 Sugimoto, Sumiyoshi-ku, Osaka 558-8585, Japan*

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Abstract

We investigated changes in activation timing and magnitude of the postural muscles according to initial standing positions. The subjects were divided into three groups depending on the position of the center of foot pressure (CFP) during quiet standing, namely backward, middle, and forward. Subjects maintained standing postures at various CFP positions in the anteroposterior direction, and then started bilateral arm movement at their own pace. The activation magnitude of the biceps femoris (BF) and erector spinae (ES) did not differ among any of the initial CFP positions. In only the BF, the preceding action to the anterior deltoid (AD) was clearly observed at more forward CFP positions in the order of the forward, middle and backward groups. Between initial CFP positions adjacent to quiet standing posture, the smallest change was observed in the preceding activation time of the BF. Significant correlation was observed between the background activity and activation time in both the BF and ES.

Keywords: Anticipatory postural control; Arm movement; Electromyogram; Muscle action sequence; Center of foot pressure

1. Introduction

Many previous studies have shown that the activation onset in the postural muscles of the legs and trunk that control standing postures precedes that in the focal muscles that rapidly move the arm [1,2]. The preceding activations of the postural muscles are adjusted by a preprogram selected in advance in order to moderate the effect of disturbances of posture and equilibrium caused by the arm movement [3–12]. When both arms are rapidly flexed to the front, body balance is disturbed by the increase in rotational momentum of the body in the anterior direction. The postural muscles in the rear of the body begin activating before the focal muscles to moderate the effect of disturbance, and this preceding activation leads to the enhancement of preparatory muscle tension in the postural muscles [6,8] and/or the postural movement to compensate the forward transition of the center of gravity [13,14]. The target muscles in this scenario are the biceps femoris (BF) and erector spinae (ES) [5,7,9,15]. The effect on postural movement is that activation of the bicep femoris produces hip extension and/or knee flexion, and the ES produces trunk extension [16].

Many studies have found that the muscle action sequence of focal and postural muscles significantly differs according to behavioral condition, and particularly in self-paced arm movement, the postural muscles show a large preceding activation [5,7,17–19]. Cord and Nashner [20] proposed a functional model of postural control in which the postural muscle activity associated with rapid arm movement was adjusted on the basis of an anticipatory postural set. Many studies have suggested that the two main factors affecting the postural set are the state of equilibrium [7,13,20] and the initial standing position just before arm movement [9,21–23]. The steadiness of the standing posture varies according to the center of foot pressure (CFP) in the anteroposterior direction [24], and thus, the equilibrium presumably has strong correlation with initial standing position. Benvenuti et al. [18] have reported that the

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* Corresponding author. Fax: +81-76-234-4219

E-mail address: fujikatu@med.kanazawa-u.ac.jp (K. Fujiwara).

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muscle activation of the postural muscles begins earlier in a forward leaning posture with the CFP at the metatarsal head than in a quiet standing posture. We previously reported that when subjects performed arm flexion movement with the initial CFP maintained at 30% of foot length from the heel, the CFP moved nearer to the quiet standing position, and preceding action in the postural muscles was not observed [25]. Therefore, we presume that the activation timing of postural muscle changes according to the initial CFP position.

The afore-mentioned studies focused on the activation timing of the postural muscles from the viewpoint of anticipatory postural adjustment. Vernazza et al. [26] have proposed a functional model that includes the activation timing and magnitude of the postural muscle. The time factor of postural muscle action is relatively fixed when the disturbing event is triggered in animals in response to cortical stimulation [27] and when the arm movement is performed by human subjects in a reaction time task [28]. In automatic postural control associated with rapid floor translation when the length of the support base was alternated, the activation magnitude of the postural muscles changed gradually, while the activation timing changed abruptly following a period of constancy [13]. If the preceding action of the postural muscles is equally required to maintain body balance irrespective of the initial CFP position, it is possible that the preceding action occurs at a fixed time and that only amplitude changes according to the initial CFP position [29].

Aruin and Latash [12,15] analyzed the EMG integration from -100 to $+50$ ms with respect to the activation onset of the focal muscle, within which range both the factors of activation timing and magnitude were contained. In the present study, we separately analyzed the activation timing and magnitude of the postural muscles, in order to investigate the programmed content in the postural adjustment. The magnitude was evaluated using the integrated EMG for the first 50 ms after the onset of each postural muscle, during which time the feedback information from the peripheral nerve was not used [9,11,30].

Studies have shown that a remarkable individual difference exists in anteroposterior CFP position during quiet standing [31,32]. We also reported that the CFP position is distributed in the range of 30–60% of foot length for healthy adults [33]. The standing position is thought to be perceived through the perceptual reference system including the body schema built up during motor experiences [34,35]. The body schema is most likely built up based on the quiet standing posture frequently maintained in daily life. If this presumption is found to be valid, the changing pattern of postural muscle action according to the initial CFP position when both arms are rapidly flexed differs greatly among individuals.

We reported that the anteroposterior CFP position of quiet standing varied in the range of 15% of foot length when subjects repeatedly carried out standing with seated rest between trials [24]. In addition, the perceptibility of the standing position was examined on the basis of the reproducibility of the anteroposterior CFP position in the forward and backward leaning postures [36]. The results clearly demonstrated that the perception of the standing position when the CFP was located in the range of 30–60% was less accurate than that when it deviated beyond this range. One possible factor causing this inaccuracy is that the steadiness of standing is high in the CFP range of 30–60% [24] and standing posture is automatically controlled in that range, therefore, the necessity to perceive the position may be reduced. We presume that the marked difference in preceding activation of the postural muscles in conjunction to the initial standing position is not found in the anteroposterior CFP positions which are near to that of quiet standing.

In the present study, in subjects with various quiet standing positions, we investigated changes in anticipatory activation of the postural muscles associated with the initial standing position when the subjects flexed their bilateral arms at their own pace. The working hypotheses were as follows. (1) The time factor and/or the magnitude of the activity of the postural muscles are regulated according to the initial CFP position. (2) The changing pattern in activation of the postural muscles according to initial CFP positions will differ among subjects with various quiet standing positions. (3) No differences in activation of the postural muscles will be found between initial CFP positions located near quiet standing. (4) The background activity in the postural muscles changes according to the initial CFP position, and this change affects the activation pattern of the postural muscles.

2. Methods

2.1. Subjects

The CFP position in the anteroposterior direction during quiet standing was measured in 109 adults, all of whom appeared to be free of any neurological or orthopedic impairment. The CFP position was defined as the distance of CFP from the heel relative to total foot length. The subjects were selected from the original group and divided into three groups of ten, namely the backward, middle, and forward groups, in which the CFP position during quiet standing was less than 38%, from 38 to 48%, and more than 48%, respectively. Informed consent was obtained from all subjects following an explanation of the experimental protocol. Table 1 shows the subject number and the range, means

Table 1
Subject number and range, means, and S.D. of age, height, weight, foot length, and CFP position during quiet standing posture

	Forward group			Middle group			Backward group		
	($n = 6$ men, 4 women)			($n = 5$ men, 5 women)			($n = 3$ men, 7 women)		
	Mean	S.D.	Range	Mean	S.D.	Range	Mean	S.D.	Range
Age (year)	22.4	3.4	19–28	21.3	1.5	19–23	21.2	2.0	19–25
Height (cm)	168.7	9.0	156–183	165.2	7.8	155–176	163.2	5.6	156–174
Weight (kg)	59.1	7.7	44.5–73.0	58.8	12.2	42.5–79.0	52.7	6.8	42.0–61.0
Foot length (cm)	25.3	1.6	22.9–28.0	24.3	1.6	22.3–27.1	23.9	2.7	21.2–26.6
CFP_{QSP} (%)	51.6	3.5	48.6–58.4	42.9	1.4	40.9–44.7	33.1	3.3	26.5–35.9

CFP_{QSP}, CFP position during quiet standing posture.

and standard deviations (S.D.) of age, height, weight, foot length, and CFP position during quiet standing. No significant differences among subject-groups were found for any of the mean values, except for the CFP position.

2.2. Apparatus

All measurements were performed while subjects were standing on a force platform (WAMI, WA1001) composed of three load-cells. The platform was used to record CFP position in the anteroposterior direction. A light-emitting diode (diameter 5 mm) was set 1.5 m in front of the force platform at eye level and used as the ON–OFF signal indicating the beginning and end of each trial, as well as to function as a visual target.

The electronic CFP signal was sent to a computer (NEC, PC9801BX2) via an A/D converter (I/O-DATA, PIO9045) at 1000 Hz with 12-bit resolution to indicate the initial standing position to the subjects. The computer generated a buzzing sound when the CFP was located within ±1 cm of each target CFP position.

Electromyograms were recorded using bipolar surface electrodes (spaced 3 cm apart) placed over the following muscles: the soleus (Sol), tibialis anterior (TA), BF, rectus femoris (RF), ES at the level of the iliac crest, rectus abdominis (RA) at the level of the navel, and anterior deltoid (AD) on the left side. The electrode input impedance was reduced to below 10 kΩ. The signals from the electrodes were amplified (× 5000) and band-pass filtered (1.6 Hz to 1.5 kHz) with an EMG amplifier (NEC-Sanei, 6R12).

For subsequent analysis, the signals from the force platform and electrodes were recorded on a digital tape recorder (TEAC, RD-130TE).

2.3. Procedure

The subjects performed the following tasks while standing with their bare feet touching slightly, their hands clasping the grip bar (40 cm in length and 68 g in weight) and positioned close to the trochanter majors, and their elbows fully extended. In all trials, the subjects were told to direct their gaze to the light-emitting diode placed in front of them.

In the beginning, the CFP position was measured for 10 s while subjects maintained quiet standing. Five trials were carried out with a 30 s period of seated rest between trials. Next, the CFP positions were measured while maintaining extreme backward or forward leaning postures with the ankles as a pivotal axis for 3 s. The measurement was performed twice with a 30 s rest between measurements. Thereafter, the arm movement trial was performed. The subjects maintained the CFP within a range of ±1 cm of the target position while hearing the buzzing sound. Next, they started at their own pace to move their arms within 3 s after the examiner stopped the buzzing sound at the same time as a light ON-signal appeared, and then stopped their arms at a frontal horizontal level position. The subjects were told to move their arms at maximum speed and to maintain the horizontal position of their arms for 3 s until a light OFF-signal appeared. Eight target CFP positions at 10% increments from 20 to 80% and at quiet standing was randomly set for the initial standing position. One and two subjects in the forward and backward groups, respectively, could not maintain the CFP position at 80%. They maintained their extreme forward leaning postures, which translated as CFP positions of 78.8, 75.5, and 77.0%, respectively. A total of 80 trials (eight positions × a set of ten trials each) were performed with 3 min of seated rest between sets.

2.4. Data analysis

For each subject, the CFP signal during quiet standing was sent to a computer (NEC, PC9801BX2) via an A/D converter (I/O-DATA PIO9045) at 20 Hz with 12-bit resolution, and the mean CFP position for 10 s was calculated. The mean value for five trials was calculated and adopted as the representative CFP position during quiet standing. The mean CFP positions while maintaining extreme backward and forward leaning postures were computed using the same system. The more forward position of two measurement values was adopted as the extreme forward positions of the subject, and the more backward position the extreme backward position.

The first three trials in each set of the arm movements were designated as trials of practice and the data of the latter seven trials were used for the analysis. The data on muscle activity was sent to a separate computer (NEC, PC-9821V233) via an A/D converter (Canopus, ADJ-98) at 1000 Hz with 12-bit resolution. The time course of muscle action in each trial was analyzed by visual inspection on a computer screen and the mean EMG amplitudes were analyzed as follows. Electromyograms of the postural muscles were high pass filtered (40 Hz) using the Butterworth method in order to exclude ECG and then were full-wave rectified. Muscle activity lasting at least 50 ms in a period of −150 to +100 ms with respect to the action onset of the deltoid (D0) was identified as an increase in postural muscle activity (the first EMG burst), and the time difference between burst onset and D0 was measured as the start time of the first EMG burst. The postural muscle showing the earliest EMG burst was specified. The integrated EMG was computed for a period of −300 to −150 ms with respect to D0 and that value was adopted as background activity. In cases where the start time of the first EMG burst for postural muscles could not be measured due to large background activity, the start time was defined as when the rectified EMG deviated more than the Mean+2S.D. of background activity within a period of −150 to +100 ms with respect to D0. The integrated EMG of the postural muscle was computed during the first 50 ms after burst onset, and from which the integrated EMG corresponding to 50 ms of background activity was subtracted. This value was adopted as the activation magnitude of the postural muscle. Analyses were performed using Bimutas-E version E2.20 software (Kissei Comtec Co. Ltd.).

The data from each trial was used for statistical analysis related to the following items in each postural muscle: the background activity, the presence or absence of the first EMG burst, and the postural muscle showing the earliest EMG burst. Mean values of start time and activation magnitude were calculated for each initial standing position of each subject, and which were adopted as the representative values. Two-way analysis of variance (ANOVA) was used to study the effect of the initial standing position in each parameter of EMG. One-way ANOVA was used to study the differences in those parameters among subject-groups. Multiple comparison analysis in Fisher's Protected Least Significant Difference was performed to examine the differences suggested by the ANOVA. A t-test was used to assess the difference in the start times between a certain initial standing position and during quiet standing, and to determine whether the start time differed from zero. The χ^2-test was used to assess differences in the number parameters of subjects. Pearson correlation and linear regression were applied to estimate the relationship between the background activity and the start time of the first EMG burst in the postural muscle. The difference in two correlation coefficients (r_{xy} and r_{xz}) was assessed according to t value:

$$t \text{ value} = \frac{[(r_{xy} - r_{xz})\sqrt{(n-3)(1+r_{yz})}]}{\sqrt{2(1 - r_{xy}^2 - r_{xz}^2 - r_{yz}^2 + 2r_{xy}r_{xz}r_{yz})}}$$

The alpha level was set at $P < 0.05$. All statistics were calculated using Excel version 98 (Microsoft Corp.) with STATCEL (OMS Co. Ltd.).

3. Results

3.1. CFP positions in extreme forward or backward leaning postures

No significant difference among subject-groups was found in the CFP position while maintaining extreme forward leaning posture, and mean value across all subjects was 82.3% (S.D. = 2.8). The CFP position while maintaining extreme backward leaning posture was significantly affected by the subject-group (16.8±1.7% for the forward group, 15.9±2.5% for the middle group, 14.2±1.9% for the backward group, $F_{2,29} = 4.02$, $P = 0.030$), and the CFP position was located significantly further back in the backward group than in the forward group ($P = 0.009$).

3.2. Background activity of postural muscles

The changing pattern of background activity accompanying the initial CFP position was different among subject-groups in the RF and BF (Fig. 1). As shown in Fig. 1, the CFP position generating the alternation in the background activity between those muscles was located more forward in the following order: backward group < middle group < forward group. No significant effect of the subject-group was found in the minimum value of each muscle. The CFP position where the background activity significantly increased ($P < 0.05$) against its minimum value shifted to a more forward position in the following order: backward group < middle group < forward group. The CFP positions were only 20% in the backward group, 30% or less in the middle group, and 40% or less in the forward group in the RF, and 50% or more, 60% or more, 70% or more, respectively, in the BF. A significant effect of the subject-group was found in the background activity only in the RF at the 20–40% positions ($F_{2,29} > 3.89$, $P < 0.05$), and the background activity in the forward group was highest.

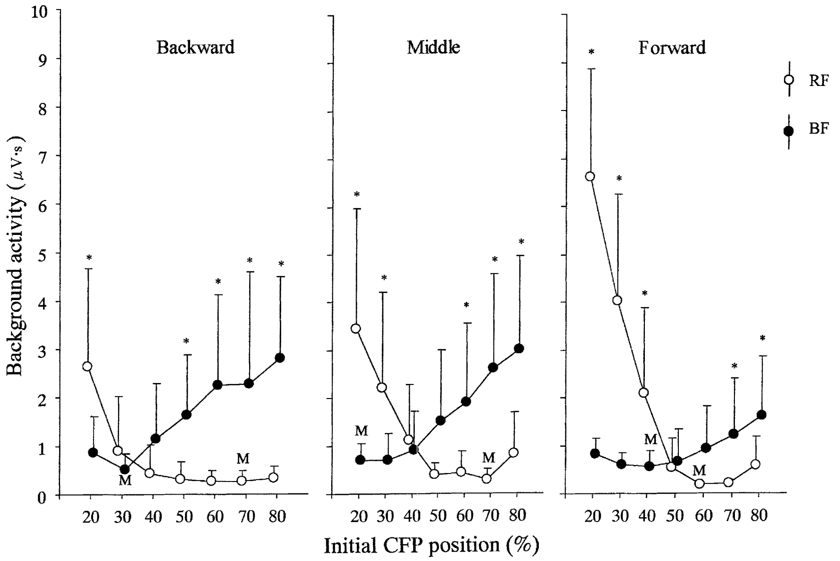

Fig. 1. Changing patterns of background activity in the RF and BF accompanying the initial CFP position. Data represent mean (+S.D.) for each subject-group. An asterisk indicates a significant difference ($P < 0.05$) relative to minimum activity (M).

In the trunk, the changing patterns of background activity of the RA and ES showed no significant difference among subject-groups. The CFP position generating the alternation in background activity between those muscles was judged to be almost the same in all subject-groups. For both trunk muscles, no significant difference among subject-groups was found in either the minimum value of the background activity or the CFP position where the background activity significantly increased against its minimum value (only 20% in the RA, 50% or more in the ES). In the crus, the changing pattern of background activity in the TA and Sol was similar to that in the trunk muscles.

3.3. *Frequency of the first EMG burst of postural muscles*

The relative frequency (%) of the trial in which the first EMG burst was observed was 100% in the ES in all subject-groups. That in the BF was 97% (mean) in all subject-groups and no significant effect of the initial CFP position was found. The relative frequency in the Sol was in the range of 56–64% in all subject-groups. In the RA, RF, and TA, the relative frequency was less than 20% in all subject-groups. The postural muscle showing the earliest EMG burst was the ES or BF in almost all trials in each subject group (95–97%).

3.4. *Activation timing of postural muscles*

Fig. 2 shows the start time in the BF and ES. The BF did not begin activating prior to D0 when the initial CFP position was located backward. This phenomenon was observed in all subject-groups at the 20 and 30% positions, and in the forward group at the 40% position. The start time at the 20% position was the latest of all subject-groups, and became earlier when the position was located more forward ($F_{6,69} > 13.39$, $P < 0.001$). The initial CFP position where the first EMG burst was significantly earlier ($P < 0.01$) than that at 20% showed a systematic tendency according to subject-group and was located more forward in the following order: backward group < middle group < forward group (30% or more, 40% or more, and 50% or more, respectively). In the middle and forward groups, the differences in start times between CFP positions adjacent to quiet standing position (connected by a heavy line) were negligible (0.7 and 3.3 ms, respectively). However, that in the backward group was considerably large (13.1 ms). The initial CFP positions, where the start time showed no significant difference against that during quiet standing, were 30–60% in the backward group, 40 and 50% in the middle group, and 50–80% in the forward group. In the backward group, the difference in start time between the positions at 70 and 80% did not differ significantly from zero.

The start time in the ES at all initial CFP positions was significantly earlier ($P < 0.05$) than D0 except for that at 20% in the middle group. The start time at the 20% position was the latest of all subject-groups, and became earlier when the position was located more forward ($F_{6,69} > 12.99$, $P < 0.001$). The initial CFP position, of which the start time was significantly earlier ($P < 0.01$) than the start time at the 20% position, was 40% or more in the backward and forward groups and 50% or more in the middle group. However, the systematic tendency according to subject-group in this position, such as shown in the BF, was not observed. The difference in start time between CFP positions

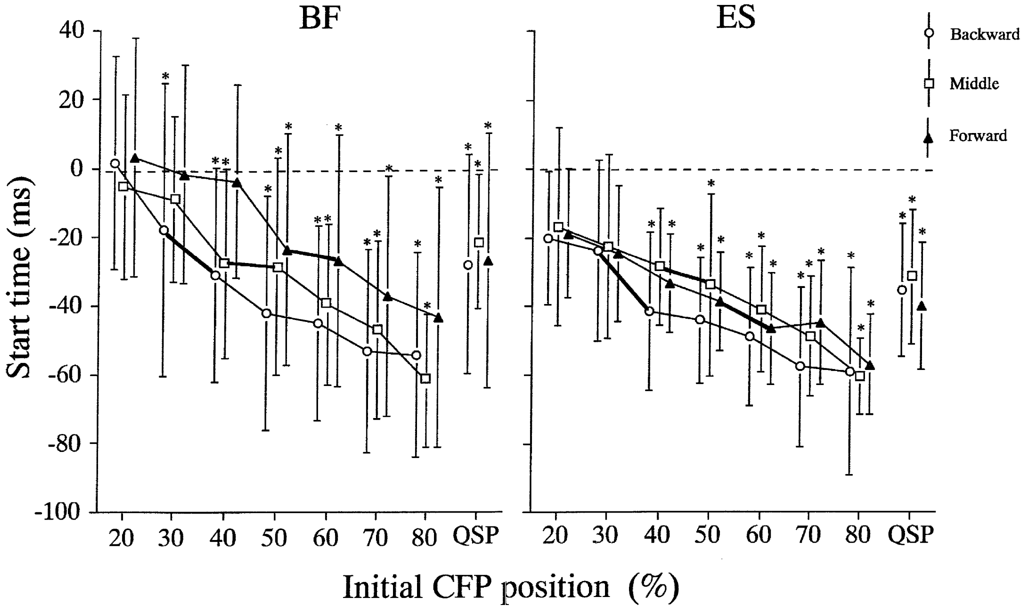

Fig. 2. Start times of the first EMG burst in the BF and ES with respect to burst onset of the AD. Data represent mean (±S.D.) for each subject-group. An asterisk indicates a significant difference relative to the mean value at the initial CFP position of 20% ($P < 0.05$). QSP, quiet standing

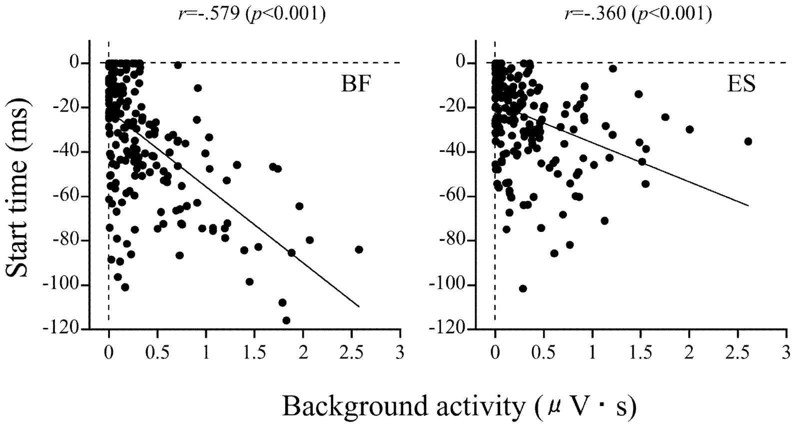

Fig. 3. Correlation between background activity and activation timing in the BF and ES across all subjects under all initial CFP positions ($N = 210$). Data were calculated by subtracting the minimum value in background activity and the maximum value in start time for each subject.

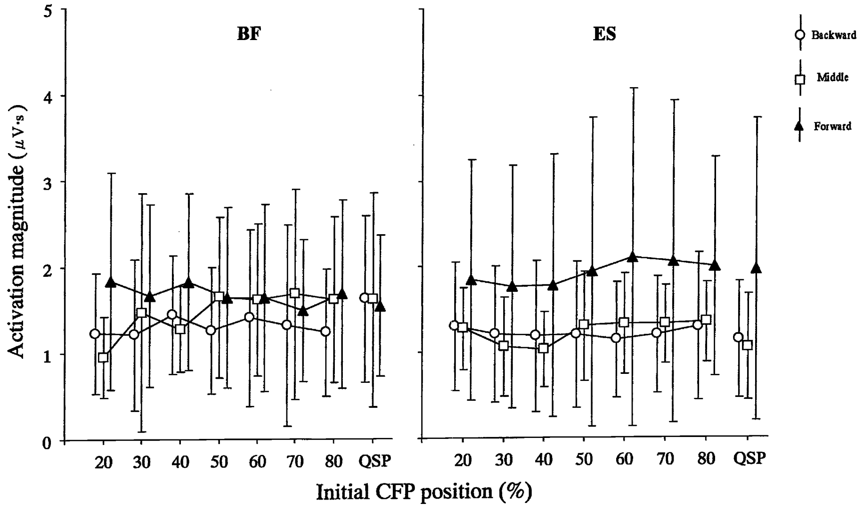

Fig. 4. Changing patterns of activation magnitude in the BF and ES accompanying initial CFP position. Data represent mean (S.D.) for each subject-group. QSP, quiet standing posture.

adjacent to quiet standing position (connected by a heavy line) in each subject-group was relatively large (17.7 ms in the backward group, 5.3 ms in the middle group, 7.7 ms in the forward group). Although the difference in the start time between the adjacent two positions located forward in the backward group (70 and 80%) and forward group (60 and 70%) was negligible, no relationship to the CFP position during quiet standing was observed. The initial CFP positions, where the start time showed no significant difference against that during quiet standing, were 30 and 40% in the backward group, 40 and 50% in the middle group, and 30–70% in the forward group.

3.5. *Relationship between background activity and activation timing of postural muscles*

Fig. 3 shows the relationship between the background activity and activation timing in the BF and ES across all subjects under all initial CFP positions. Data were calculated by subtracting the minimum value in the background activity and the maximum value in the start time for each subject. The larger the background activity in the BF, the earlier its start time, and relatively strong negative correlation was found ($r = -0.58$, $P < 0.001$). The start time in the ES also showed negative correlation with background activity ($r = -0.36$, $P < 0.001$). However, the correlation coefficient in the ES was significantly lower than that in the BF ($t = 3.305$, $P < 0.001$).

3.6. *Activation magnitude of postural muscles*

The activation magnitude of the BF and ES was not significantly affected by the initial CFP position in each subject-group (Fig. 4). No data regarding the activation magnitude while performing the arm movement during quiet standing was of sufficient importance to be reported.

4. Discussion

The frequency of first burst activation in the postural muscles was extremely small in the crus compared with the trunk and femur. For the BF and ES, the first burst activation was observed at most trials, and one or the other of these muscles began activating earliest. Many studies have reported that in arm flexion movement, the postural muscles in the rear begin activating before the focal muscle [7,9,15,37]. The present study confirmed that such postural muscle action was commonly recognized in trials at any of the initial CFP positions. Cord and Nashner [20] suggested that the command from the central nervous system for anticipatory postural adjustment was sent to the muscles identified to be functionally useful for equilibrium maintenance. Studies have shown that the activity level of muscles that control hip joint movement changes corresponding to the change in load according to the direction of the arm movement, while the activity level of the distal muscles that control ankle joint movement do not change according to load [7,15]. The postural demand in this case is believed to emphasize the movement in which the hip joint performed as a pivotal axis, while that of the ankle joint is supplementary. The target of postural control is likely to influence our present study. The focus of this discussion will now turn to the BF and ES, and the discussion is done according to the order in which the hypotheses were presented in the Section 1.

The activation magnitudes of the BF and ES did not differ depending upon initial CFP positions before arm movement. For patients with a specific lesion in the brain, the basal ganglia and the cerebellum participate in postural adjustment when a bar is pulled towards the body, and the influence of the lesion appears more clearly in the amplitude than the timing of postural muscle activation [38]. Viallet et al. [39] reported that the other brain region concerned with anticipatory postural control is the supplementary motor cortex. Many researchers have reported that the magnitude of postural muscle activation is influenced by postural demand, which changes according to the size of the support base or the magnitude of postural disturbance by arm movement [9,15,20,26,28,40]. The results of the present study showed that the initial net activation level of the postural muscles is nearly equal at any of the initial CFP positions. This suggests that the magnitude of postural disturbance by arm movement and that of postural demand do not differ in every CFP position before arm movement. That is, the goal of postural adjustment may not be the return to the quiet standing position but the prevention of extreme shift from the set position.

The timing of postural muscle activation was not fixed and changed distinctly according to initial CFP position in the present study. This means that the spending energy is constant and that the timing to produce this energy varies with initial CFP position. The overall result appears to be enhancement of energy efficiency and simplification of postural adjustment. Belen'kii et al. [1] pointed out that energy efficiency increases by anticipatory postural control. Horak and Nashner [13] reported that the automatic postural control in some kinds of the tasks is executed with the simple strategy combined. We believe that the change in only the activation timing of postural muscle activation with the amplitude fixed is one of the simplifications of postural control. Hay and Redon [29] compared the CFP movement in the anteroposterior direction when an unloading on the upper extremity was initiated by a subject or externally imposed. A significant difference was not observed in the time factors but was in the amplitude of postural muscle activation. Therefore, we believe that the modality of the adjustment in the time factor and the amplitude differs according to the motor task. Further research will be required to investigate the modalities involved.

The change pattern in activation timing according to initial standing position varied among subject-groups whose CFP position in a quiet standing posture differed. The CFP position in which the BF showed the preceding activation was located at the more forward position in the order of forward, middle and backward groups. The preceding activation of the postural muscles is not observed when a subject's body is attached with restrainers to a wall [1,7,20]. As an explanation of this phenomenon, no disturbance of equilibrium associated with arm movement was anticipated. Horak et al. [5] clarified that equilibrium is never disturbed in slow speed arm movements, and in such cases the necessity for preceding activation of the postural muscles decreased. Aruin and Latash [15] suggested that the preceding activation of the BF and ES for postural control functioned to resist the forward transition of the center of gravity and to maintain it within the support base in the foot. Steadiness in a quiet standing posture has been clearly established to be higher than other standing positions [24]. The theoretical movement distance of the CFP when only the arm was flexed at 90° from the body was about 13% of the foot length [14]. We presume the following concerning CFP movement if arm movement is undertaken without postural control. CFP in the backward posture shifts to a position where steadiness is high. In a posture that is near in position to quiet standing it shifts to a low steadiness position, and in a forward posture it shifts to an extremely low steadiness position. This leads to the supposition that the displacement of CFP associated with the arm movement is anticipated in relation to the CFP position in a quiet standing posture where steadiness is high, when the activation timing of the postural muscles is regulated.

In the ES, the earlier activation accompanying the forward shift in the initial CFP position before arm movement was also observed. However, no significant difference in the change in activation timing was observed among subject-groups, unlike in the case of the BF. Judging from the background activity of the postural muscles before arm movement, CFP positions generating the alternation in muscle activity between the RF and BF were located at the more forward in the order of forward, middle, and backward groups. This was consistent with the order in the activation timing of the BF. Furthermore, no significant difference among subject-groups was observed in the CFP position generating the alternation in muscle activity between antagonists in the trunk. This may be related to the fact that no difference among subject-groups in the change in activation timing of the ES was observed. Reports on vibration stimulation to the postural muscles have revealed that muscle sensation plays an important role in the perception of standing position [41–43]. Sensory data according to muscle activity in the femur is thought to be the essential information source for perception in the relative positional change from quiet standing. Muscle sensory information from the trunk perhaps correlates with sensory information from the neck muscles and the vestibular organs, and may then participate in the perception of the gravity direction [44]. Massion [11] divided postural adjustment into balance control over the entire body and positional control of specific body parts in order to provide a reference axis for action. Our present result most likely reflects the same kind of functional difference in the sensory-motor system between the trunk and leg.

The difference in activation timing of postural muscles was not detected at CFP positions near quiet standing for the forward and middle groups. This position was 40 and 50% in the middle group, and 50 and 60% in the forward group. The third hypothesis is confirmed for the BF in the middle and forward groups. We previously reported that the perceptibility of standing position was very low in positions located near quiet standing [36,45]. The steadiness at those positions remained high, and consequently the sensitivity of the standing position was low. Thus, postural adjustment associated with arm movement in the initial CFP positions located near quiet standing is likely to be similar to that in quiet standing.

In the backward group, the difference in activation time of the BF between the initial CFP positions of 30 and 40% was extremely large. This may have occurred because the backward leaning posture at 30% position had similar biomechanical characteristics for all subject-groups. As mentioned above, when the subjects performed the arm flexion movement while maintaining the backward leaning posture at the 30% position, the CFP was theoretically shifted near the CFP position during quiet standing. Therefore, at an initial CFP position of 30%, earlier activation for postural muscles to prevent an extreme CFP shift in the forward direction should be unnecessary. In contrast, unlike the middle and forward groups, the initial CFP position of 40% position in the backward group is located anterior to the quiet standing position and thus earlier activation of the postural muscles is necessary. As a result of this, the activation timing of the BF in the backward group was significantly different between the initial CFP positions of 30 and 40%. However, no significant difference in the activation time of the BF between the initial CFP position at 40% and that in quiet standing was observed in the backward group. This result also supports the third hypothesis.

Moreover, in the backward group, the BF began to activate much earlier at the initial CFP position of 50% and the differences in activation timing among the initial CFP positions of more forward than 50% were small. The effectiveness of anticipatory postural control has been shown to decrease as the tolerance limit to unbalance increases with growth [29,46], while an increase in the safety limit of balance was estimated to be lower in the elderly [47]. In the backward group, these standing positions would deviate largely from the standing position in daily life, and the muscle postural demand to maintain body balance would increase greatly. Thus, the above-mentioned result is plausible.

In contrast, the activation time of the ES showed a distinct change between initial CFP positions adjacent to quiet standing. It is likely that the muscle activity of the ES is sensitively regulated even in positions located near quiet standing in order to provide the reference axis for action, as proposed by Massion [11].

Relatively high correlation between the background activity and activation timing was found in the BF. That correlation in the ES was significantly lower than that in the BF, suggesting that background activity is one of the factors that influences activation timing of the postural muscles. The above mentioned other factors, sensory information from the neck muscles and the vestibular organs, would strongly influence the activation timing in the ES. In addition, the amount of muscle sensory information increases according to the strength of the isometric muscle contraction. Therefore, the muscle sensory data from the BF is thought to be the essential information source for perception in the standing position. We believe that disturbance of body balance caused by arm movement is anticipated in relation to the sensory information from the BF in an initial standing position, and based on this anticipation the activation timing of the postural muscles is adjusted.

Further research will be required to elucidate the influences of the size of support base, the degree of equilibrium disturbance, and the initial CFP position on the activation timing and magnitude of the postural muscles.

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