Brief report

Attenuation of the anticipatory postural adjustments in the frontal plane with the increase of the forward propulsive velocity of step initiation in humans

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Abstract

Step initiation involves anticipatory postural adjustments (APA) that propel the center of body mass (CM) forward and laterally before onset of heel off of the swing leg for the first step. It is recognized that the APA in the mediolateral direction (ML-APA) associated with step initiation can counteract lateral instability in a single support of the stance foot before onset of the primary movement. The purpose of this study is to elucidate whether and how the ML-APA, i.e. the EMG activity of postural synergists, the center foot of pressure (CP) towards the swing leg, lateral shear force on the CM for propelling the CM towards the support leg, is modulated with the lateral instability related to the forward propulsive velocity in volitional step initiation. Seven healthy subjects instructed to land on the regular swing-foot placement performed the initiation of a single step forward at two speeds (as fast as possible, FST; normal speed, NML). The anticipatory peak amplitudes of the velocity and displacement of the CM towards the stance leg at FST were significantly lower than those at NML. The present results indicate that the central nervous system may attenuate the ML-APA according to decreasing degree of the lateral instability with the increase of the forward step velocity.

Key words　Anticipatory postural adjustments, Step initiation, Frontal plane, Postural instability, Propulsive velocity

1. Introduction

In volitional step or gait initiation from a bipedal stance, a stepping movement cannot be executed until the position of the center of body mass (CM) has reached a given point. Electromyographic (EMG) activities in the tibialis anteriors of both swing and stance legs in step (Ito et al., 2003; Yamashita et al., 1995) or in gait initiation (Crenna and Frigo, 1991), and the gluteus medius and the tensor fasciae latae of the swing and stance legs in step (Yamashita et al., 1995) or gait initiation (Patchay and Gahéry, 2003) were observed prior to the first heel-off, i.e., the onset of a step movement. Consequently, the center of

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foot pressure (CP) was displaced backwards and towards the swing leg while the CM was transferred forwards and towards the stance leg before the first heel-off. These phenomena, anticipatory postural adjustments (APA) associated with step or gait initiation, are generally known to be decided by descending commands from the central nervous system (CNS) whose intensities are determined centrally according to voluntary movement parameters prior to the execution of the intended movement (Massion, 1992). The APA has two functions: creation of the necessary conditions for achieving the propulsive velocity of the CM, and transfer of the CM onto or over the narrow base of support (i.e. stance foot) to allow lifting the swing foot. In relation to the former function, it has been established by numerous experimental results that the larger APAs in the sagittal plane can assist the forward step velocity (Crenna and Frigo, 1991, Ito et al., 2003, Yamashita et al., 1995). The latter function has not been satisfactorily clear. However, if the mediolateral APA (ML-APA) (e.g., EMG activities of the gluteus medius, displacement in the CP towards the swing leg and CM towards the stance leg prior to the first heel-off) do not emerge before the swing heel-off, it has been suggested that lateral instability, in which the body becomes unstable and begins to topple, pivoting about the ankle and falling downwards and sideways away during a single support of the stance foot, will be caused in the step initiation (Lyon and Day, 1997) and the compensatory stepping reactions evoked by unpredictable antero-posterior perturbation (Burleigh and Horak, 1996; McIlroy and Maki, 1999). Though it was reported that the quantity factors (i.e. amplitude and duration) of the ML-APA depend on the initial stance width or step direction (Lyon and Day, 1997), it was left many problems to be elucidated in the relationship between the ML-APA and step velocity. In earlier studies, it was indicated that the anticipatory duration of the ML-APA decreases with increases in the velocity of perturbation, namely, passive step velocity, in the compensatory stepping reactions (Burleigh and Horak, 1996). In volitional step initiation, it has been suggested that it is not clear whether the ML-APA is dependent on the forward progressive velocity. The aim of the present study was to elucidate whether and how the ML-APA will be modulated with the forward propulsive velocity in the volitional step initiation.

2. Methods

Seven male volunteers (mean age 23.3 ± 4.0 years, height 171.4 ± 4.7 cm, body weight 66.9 ± 8.4 kg and foot length 26.6 ± 0.5 cm) participated in this experiment. None of the subjects had any history of neurological, musculoskeletal, or orthopedic deficit. In all subjects, the right leg was dominant, as indicated by each subject's stated limb preference for kicking a ball. The motor task in the present experiment was a step initiation forward from a bipedal stance with a right foot departure. We proposed in our previous study (Ito et al., 2003) that it is necessary to set up the experimental conditions by identifying all or most factors, which affect the anticipatory locomotor adjustments (McFadyen et al., 1993), in order to clarify the subtle and proper relations between the APA and step velocity. The forward movement of step initiation, which is governed by the same motor program from the standpoint of the APA as gait initiation (Brunt et al., 1999; Crenna and Frigo, 1991; Dietrich et al., 1994), was performed at two speeds (as fast as possible, FST; normal speed, NML) with constant initial CP position and step length in this experiment. All of the subjects gave their informed consent to this study. Each subject was instructed to stand upright (with the feet 5 cm apart) on a force platform (AMTI OR6-5); to keep their

CP in the normal position at rest (a position 45% foot length from the heel point) by monitoring the X-Y plotter placed 2 m from the eyes at eye level; to initiate the stepping forward volitionally at a time of their own choice; to step in a straight line with constant step length (40% of body height); to land on the target (a horizontal aluminum tape, 10 cm wide × 100 cm long, able to detect the first foot-contact signal) with heel of the swing leg; to walk from the heel-off of the swing to the foot-contact of the stance. In order to acclimate to experimental tasks, all subjects practiced 15-20 trials of a single step forward. Each subject performed 10 trials at FST, and 6 trials at NML. These series were separated by a 3-min rest period. The EMG activities of the lower extremity muscles, a goniogram of the hip joint, foot on-off signals, and ground reaction forces and moments in the antero-posterior (X), mediolateral (Y) and vertical axes were simultaneously recorded during the experiment.

EMG signals from the gluteus medius of the swing leg and bilateral tibialis anteriors were detected by means of bipolar surface electrodes (Nihon Kohden, NM-512G) on the muscle bellies after cleaning the skin with alcohol. EMG signals recorded were amplified, filtered with a bandwidth of 10-500 Hz, rectified, sampled at 1 kHz, and normalized to the isometric maximum voluntary muscle contraction (MVC) for each subject. The onset times of individual muscles were identified by the time points, which correspond to increases of $\geq 1.5 \times$ the background EMG amplitudes.

The CP in the frontal plane was calculated by dividing the moment about the X-axis by the vertical force. The displacement and velocity of the CM in the sagittal and frontal planes were computed by the method of integration of the acceleration data derived from the curve in the shear force to the X- and Y-axes, respectively. The goniogram of the hip joint in the swing leg was detected by a flexible electrogoniometer (Penny & Giles, M110) attached at the great trochanter of the swing leg. These kinematic and kinetic data were sampled at 1 kHz.

Data in which the initial CP position exceeds the reference CP by ± 8 mm or the step length is judged improper by the foot-contact signal were excluded. Data in each trial were divided into two phases by a boundary line at the onset of a focal movement, i.e. the first heel-off (vertical dash lines in Figure 1): the anticipatory and executive phases. The variables measured from the digitized EMG, kinematic and kinetic data were as follows (Figure 1 and Table 1): duration and maximal displacement of the CP towards the swing side in the preparatory phase (YPdur and YPmax, respectively); maximum velocity of the CM towards the stance side of the anticipatory phase (YVmax); maximum displacement of the CM towards the stance side around the time of the first heel-off (YMmax); duration of a single leg stance (SSdur) from the first foot-off to the foot-contact; duration and mean amplitude of EMG activity of the tibialis anteriors of both swing and stance legs, and of the gluteus medius of the swing leg from the onset of individual EMG activity to first heel-off; maximum step-forward velocity of the CM around the first foot-contact in the executive phase; mean angular velocity of the hip flexion of the swing leg from the onset of hip flexion to peak in the executive phase. All data were evaluated statistically by Student's paired t-test for analyzing the difference of variables between two speed conditions. A statistical significance level of $P < 0.05$ was chosen.

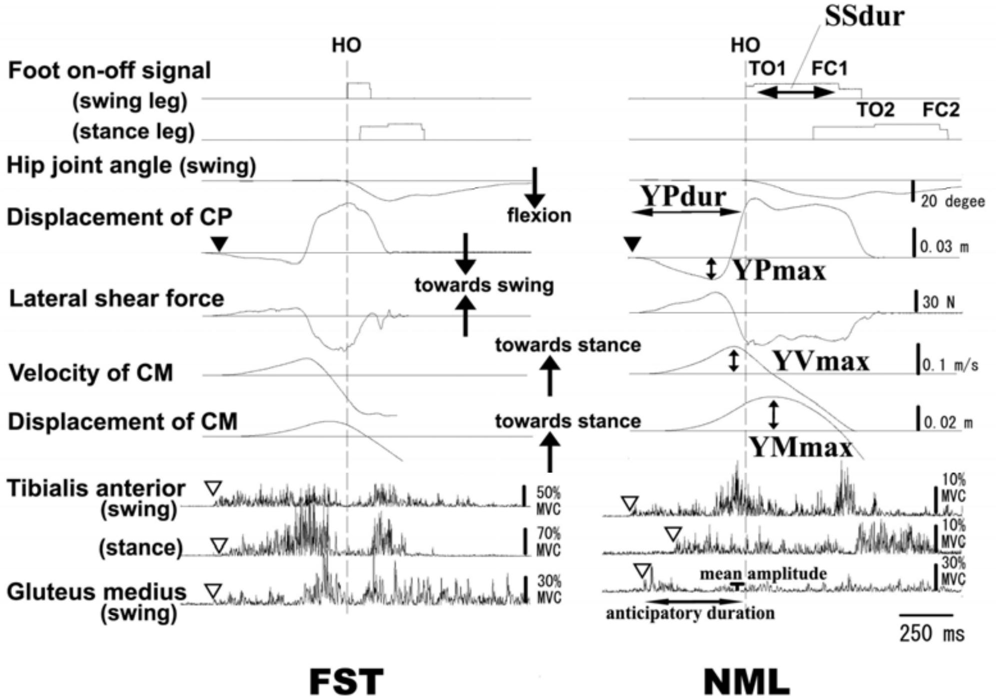

Figure 1 Typical traces of the kinematic and kinetic data for the foot on-off signal, hip joint angle, the center of foot pressure (CP) and the center of body mass (CM) in the frontal plane, and the EMG activities of postural synergists (bilateral tibialis anteriors and gluteus medius) at two speed conditions (left, as fast as possible, FST; right, normal speed, NML) in step initiation. HO (vertical dashed line), TO1, FC1, TO2, and FC2 show the heel-off, toe-off, foot-contact of the swing leg, and the toe-off and foot-contact of the stance leg, respectively. The inverted filled-triangle shows the onset of the anticipatory phase. The vertical arrows with uni-head show the direction of the deflection of the kinetic data curves. The measured kinematic and kinetic variables were as follows: SSdur (horizontal arrows), duration of a single leg stance from the first toe-off to foot-contact; YPdur and YPmax, duration and maximum displacement of the anticipatory phase in the CP towards the swing leg side, respectively; YVmax, maximum velocity of the CM towards the stance leg side of the anticipatory phase; YMmax, maximum displacement of the CM towards the stance leg side at the instant of the HO. The vertical and horizontal arrows with dual-heads show the peak amplitude and the time, respectively, in the kinematic and kinetic data. The inverted open-triangles show the onsets of the anticipatory phase in the individual postural synergists. Anticipatory duration and mean amplitude were measured in the anticipatory phase between the onset of individual EMG activity and the HO.

3. Results

Data discarded by reason of the improper displacement of the CM during stepping were in 15 trials at FST and 5 trials at NML, respectively. The maximum step forward velocity of the CM around the first foot-contact showed 1.287 m/s ± 0.183 (mean ± SD) at FST and 1.059 m/s ± 0.124 at NML ($P < 0.001$), while the SSdur from the first toe-off to foot-contact at FST shortened by a lesser amount than at

NML (P < 0.001) (Table 1). The angular velocity of the hip flexion of the swing leg in the executive phase at FST showed a significantly greater value than that at NML (94.2 degree/s ± 31.6 and 45.7 degree/s ± 12.6, P < 0.01; at FST and NML conditions, respectively). The incidence in which the CM was onto or over a line defining the medial border of the stance foot until the swing toe-off were 47.3% of total trials at FST and 83.8% at NML. No significant differences between the two speeds were found in the YPdur (P = 0.55, not significant, NS) or YPmax (P = 0.11, NS), although mean values of YPmax at FST had a tendency to decrease more than that at NML as shown in Table 1. YVmax and YMmax at FST showed significantly lower values than those at NML (P < 0.05 and P < 0.01, respectively) (Table 1). The mean amplitude of the anticipatory EMG activity in the gluteus medius of swing leg was significantly higher at FST than that at NML (P < 0.05), whereas no difference was seen between the two speeds in the anticipatory durations of the gluteus medius (P = 0.23, NS)　(Table 1).

Differences between the swing and stance sides were observed in the anticipatory EMG activities of the tibialis anterior, which are components related to the antero-posterior APA, at NML. The mean amplitude (26%MVC ± 4 and 17%MVC ± 4; swing and stance leg, respectively; P < 0.05) and duration (569 ms ± 87 and 515 ms ± 114, P < 0.05) of the anticipatory EMG activity in the tibialis anteriors showed significantly greater values in the swing leg than that in the stance leg at NML, whereas these measured values at FST showed no differences between both leg sides (amplitude, 59%MVC ± 9 and 72%MVC ± 36; swing and stance legs, respectively; P = 0.38, NS: duration, 599 ms ± 104 and 581 ms ± 108; P = 0.16, NS). EMG activity of the tibialis anterior in the swing leg showed the earlier onset (inverted open-triangles in Figure 1) and greater mean amplitude than that in the stance leg.

Table 1　Differences of means (±SD) of anticipatory and executive parameters between two speed conditions

Parameters	FST condition (mean ± SD)	NML condition (mean ± SD)	Paired *t*-test (*n* = 7)
SSdur (ms)	259±55	449±54	*P* < 0.001
YPdur (ms)	577±87	599±68	*NS*
YPmax (m)	0.023±0.007	0.029±0.003	*NS*
YVmax (m/s)	0.086±0.015	0.116±0.022	*P* < 0.05
YMmax (m)	0.022±0.007	0.037±0.010	*P* < 0.01
Mean amplitude of gluteus medius (%MVC)	22 ± 13	11 ± 7	*P* < 0.05
Anticipatory duration of gluteus medius (ms)	568 ± 67	610 ± 100	*NS*

SSdur shows the duration of a single leg stance from first toe-off to foot-contact of the swing leg. YPdur and YPmax express the anticipatory duration and maximum displacement, respectively, in displacement of the center of foot pressure (CP) towards the swing side. YVmax represents the maximum velocity of the center of body mass (CM) towards the stance side in the anticipatory phase. YMmax indicates the maximum displacement of the CM towards the stance side.

4. Discussion

In the present results, the SSdur at NML was longer than that at FST. The longer duration required for a single leg stance was more challenging to mediolateral postural control, and therefore, this phase is used as an index of lateral instability (McIlroy and Maki, 1999). In other words, the increases of the time required to reestablish a new base of support with the reduction of the forward step velocity can lead to the lateral instability during a single leg stance. We could ascertain that the amplitude of the ML-APA, YVmax and YMmax, prior to the onset of a single leg stance decreased with the attenuation of the lateral instability associated with the augmentation of the forward propulsive velocity in volitional step initiation. A lower percentage (47.3%) in the incidence of shifting the CM onto or over the stance leg at FST also provides evidence that the mediolateral postural control at FST was less required than that at NML. It is suggested that the ML-APA must be judged the size and direction of the initial throw given to the body-mass in advance of the onset of a single leg stance in step initiation by the CNS (Lyon and Day, 1997). The present findings indicate that larger ML-APA, such as velocity and displacement of the CM towards the stance leg, may be required to counter the greater lateral instability prior to postural adjustments.

In the duration and amplitude of the lateral CP of the ML-APA, we were unable to observe a significant difference between the two speed conditions. This implies that the deflection of the lateral CP directly reflects the global motor profiles in the frontal plane, including the functions of shifting the body mass toward the stance leg and of lifting the swing leg. In the movement of a rapid leg flexion, it is generally known that the anticipatory EMG activities of the hip abductor muscles of the stepping limb, such as the gluteus medius and the tensor fasciae latae, can assist in the control of frontal plane motion (Rogers and Pai, 1993), and can increase the maximum velocity of unilateral hip flexion from a standing position (Nouillot et al., 1992). However, anticipatory EMG amplitudes in the gluteus medius of the swing leg increased with the hip angular velocity, but did not increase with the velocity or displacement in the CM shifts towards the stance leg in the present study. These results showed that the anticipatory EMG amplitude in the gluteus medius of the swing leg was independent of the shift of the CM towards the stance leg, and its amplitude might promote the increase of the hip angular velocity of the swing leg. There was a tendency for the YPmax at NML to increase greater than that at FST ($P = 0.11$). At NML, the tibialis anterior of the swing leg showed earlier onset and greater mean EMG amplitude than were seen in the stance leg. It is speculated that these asymmetric activities of the tibialis anteriors between the swing and stance legs in the anticipatory phase could have contributed to shifting the CP towards swing leg, i.e. events associated with shifting the CM towards the stance leg with step initiation (Rogers and Pai, 1993).

The present results may lead to better the motor function tests for patients in disorder of the CNS. Disorder of the CNS, especially cerebellar lesions, cause deficits in appropriate anticipatory control in response to postural disturbances by forthcoming movement. In repeated stepping in antero-posterior directions, subjects with cerebellar pathology showed symptoms of significantly greater lateral CM instability, which was consistent with increased lateral CP and CM displacement ranges and variability reflecting their excessive and irregular body lateral sways, compared to non-disabled subjects (Hudson and Krebs, 2000). Damage to the cerebellum can produce motor disturbances affecting posture and limb function, such as dysmetria, because of the inaccurate scaling of the spatial-temporal characteristics of volitional movements. In postural responses to platform perturbation, the subjects with cerebellar lesions had much greater postural response magnitudes, such as overshoots of initial sway positions or excessive EMG activities of the postural synergies, than normal subjects, and this hypermetria and these inabilities to use the central set of commands for predictive amplitude determination appear to be sensitive and specific indicators of anterior lobe cerebellar syndrome (Horak and Diener, 1994). Horak and Diener (1994) suggested that the midline cerebellum would play an important role in adjusting the gain of muscle excitability accurately according to predictive scaling, based on a central set of commands built up from prior experience, to forthcoming perturbation amplitudes. In the midline cerebellar white matter, Mori et al. (1999) searched out the cerebellar locomotor region for evoking locomotion by stimulation studies in decerebrate cats. The cerebellar locomotor region is located where a decussation of fastigiofugal fibers occurs, and the fastigial nucleus of the cerebellum projects to the cells of origin of the reticulospinal and vestibulospinal tracts (Mori et al., 1999; 2001). In other words, the fastigial nucleus of the cerebellum is sited at an important strategic point in the CNS for initiating the stereotypic locomotor movements and for counteracting the postural disturbance associated with the initiation of locomotion. The present finding that the intended propulsive velocity of step affected the ML-APA implies that the variables concerning the ML-APA may be a brief, noninvasive and quantitative index for measuring the degree of impaired co-ordination between posture and movement in the CNS.

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