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Coordination of rapid stepping with arm pointing: Anticipatory changes and step adaptation

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Abstract

The present study explored whether rapid stepping is influenced by the coordination of an arm pointing task. Nine participants were instructed to (a) point the index finger of the dominant arm towards a target from the standing posture, (b) initiate a rapid forward step with the contralateral leg, and (c) synchronize stepping and pointing (combined task). Force plate and ankle muscle electromyography (EMG) recordings were contrasted between (b) and (c). In the combined task, the arm acceleration trace most often peaked around foot-off, coinciding with a 15% increase in the forward acceleration of the center of gravity (CoG). Backward displacement of the center of foot pressure at foot-off, duration of anticipatory postural adjustments (APAs) and ankle muscle EMG activity remained unchanged. In contrast, durations of swing phase and whole step were reduced and step length was smaller in the combined task. A reduction in the swing phase was correlated with an increased CoG forward acceleration at foot-off. Changes in the biomechanics of step initiation during the combined task might be ascribed to the postural dynamics elicited by arm pointing, and not to a modulation of the step APAs programming.

PsycINFO classification: 2330

Keywords: Stepping; Pointing; Arm/leg coordination; Anticipatory postural adjustments; Motor control

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1. Introduction

Most human daily activities are characterized by combined simple motor tasks, such as stepping from quiet standing associated with goal-directed upper limb pointing or grasping tasks. Postural adjustments related to each simple task of a motor activity have been extensively examined in the literature, however only when simple tasks were performed in isolation. It is known that postural adjustments can precede the execution of a voluntary movement (they are referred to as "anticipatory postural adjustments" or APAs), but they can also accompany and follow the movement (see Bouisset & Lebozec, 2002; Massion, 1992 for reviews). The extent to which postural adjustments interact when simple tasks are coordinated remains unclear.

When no displacement of the postural basis is required (e.g., during hand pointing to a target or raising the arm during quiet standing) APAs counter the internal postural perturbation induced by the focal voluntary movement (Bouisset & Zattara, 1987; Friedli, Cohen, Hallet, Stanhope, & Simon, 1988) and/or generate an additional force for the execution of the movement (Lee, Michaels, & Pai, 1990). Conversely, when displacement of the postural basis becomes a task on its own, such as stepping from quiet standing, APAs generate the initial propulsive forces required for the forward body progression (Brenière, Do, & Bouisset, 1987; Lepers & Brenière, 1995). APAs contribute also to the transfer of body weight during stance to swing transition (Do, Schneider, & Chong, 1999; Lyon & Day, 1997; Schneider, Do, & Bussel, 1997).

Classically, APAs have been characterized by concomitant displacement of center of foot pressure (CoP) and acceleration of center of gravity (CoG) in opposite direction, mirrored by antagonistic activation of ankle muscles (see Brenière & Do, 1986, 1991; Brenière et al., 1987; Crenna & Frigo, 1991; Herman, Cook, Cozzens, & Freedman, 1973; Jian, Winter, Ishac, & Gilchrist, 1993; Lepers & Brenière, 1995). Brenière et al. (1987) showed that duration of stepping APAs increased with progression velocity. They proposed that the central nervous system (CNS) tuned the APAs duration to generate the initial antero-posterior (A/P) propulsive forces required for reaching the intended speed at the end of the first step. The first swing phase following APAs was described as a ballistic forward fall around the stance ankle (Lepers & Brenière, 1995; Lyon & Day, 1997). Moreover, the duration of the whole stepping initiation, i.e., the time elapsed from the onset of APAs to the end of the swing phase, did not depend on the intended progression velocity (Brenière & Do, 1986, 1991; Brenière et al., 1987; Brunt, Liu, Trimble, Bauer, & Short, 1999; Jian et al., 1993), but was rather related to anthropometrical characteristics (body mass and inertia, distance between the CoG and the ground). It was proposed that this invariance in step duration was due to the pendulum-like motion of the whole body during gait initiation (Brenière & Do, 1986, 1991; Lyon & Day, 1997).

Characteristics of stepping initiation can change following postural perturbation related to the loss of balance or to obstacle clearance during stepping. Moreover, following translation of the postural basis, APAs were shortened prior to volitional step initiation in response to the perturbation (Burleigh & Horak, 1996; Burleigh, Horak, & Malouin, 1994); they even were abolished when stepping helped recover balance (Mc Ilroy & Maki, 1993, 1995). In addition, step length was increased if participants were instructed to clear obstacles presented in front of them (Zettel, Mc Ilroy, & Maki, 2002). These changes were interpreted as adaptation to postural instability generated by the perturbation at foot-off, and were thought to be triggered by afferent information (see Burleigh & Horak, 1996).

According to the laws of mechanics, and first emphasized by André Thomas (1940), the action of moving the upper limb also induces a postural perturbation requiring postural adjustments, especially when performed at maximal velocity. It was proposed from the observation of biomechanics and motor profiles, that those upper limb task-related postural adjustments could share common functional principles with postural adjustments triggered by translation of the postural basis and could even be controlled by the same neural networks (Cordo & Nashner, 1982; Layne & Abraham, 1991; Nashner & Cordo, 1981). Indeed, it would be expected that the duration of stepping APAs and the step length will increase when stepping is combined with an upper limb task performed at maximal velocity. In contrast, it was recently reported that the duration of APAs related to a leg flexion from the upright posture was equivalent when performed in isolation and in combination with a pointing task (Yiou, 2005). A similar result was reported during the coordination of a *lunge* with *touche* in fencing, i.e., the duration of the lunging APAs was equivalent during the combined task and the isolated lunging task (Yiou & Do, 2001). It thus remains unclear whether, and how, spatio-temporal parameters of APAs, associated with a voluntary step initiation, are influenced by the coordination of an upper limb task. Moreover, to our knowledge, nobody ever addressed whether and how other parameters of step initiation (duration of swing phase, total duration of the stepping initiation, progression velocity, step length, etc.) are modulated during the combined task.

The goal of the present study was to investigate the influence of an upper limb pointing task on spatio-temporal parameters of stepping initiation. To this end, recordings from a force plate and ankle muscle EMG activity in young healthy adults were compared in an "isolated stepping" task and a combined "stepping + pointing" task. Our previous studies suggested that the amplitude of stepping APAs (as reflected by CoG acceleration and CoP displacement), however not their duration, should be modulated by pointing-elicited postural dynamics. If so, it is further expected that other biomechanical parameters of stepping should be changed. In the present study, the ankle EMG activity was used to detect whether these changes could be ascribed to a modulation of step programming.

2. Methods

2.1. Participants and outline of the experiments

This study was performed in nine healthy human participants (2 females, 7 males, mean age = 28 ± 5 years, 8 right-handed, 1 left-handed, mean mass = 66 ± 8 kg, mean height = 174 ± 6 cm). All participants gave their written informed consent as to the nature and purpose of the experiment, which was approved by the local ethics committees. Participants stood on a force plate and were instructed to perform 15 trials in three different tasks tested in a random order between participants: (1) pointing the index finger towards a target with the dominant arm (referred to as isolated pointing); (2) stepping forward with the contralateral leg (isolated stepping); (3) synchronizing pointing with the dominant arm and stepping with the contralateral leg, which was referred to as the swing leg (combined task). In this experiment, we chose 'contralateral' upper and lower limbs coordination to mimic the most natural combination of level-walking. However, preliminary results in three participants suggested that coordinating the ipsilateral upper and lower limbs should not change the outcomes of the study. At the onset of each experiment, participants trained for up to 10 trials to familiarize with the instruction, tasks and equipment. An auditory cue (constance, cf. p. 10) served as Go signal. Movements were self-triggered so that participants reacted spontaneously following the Go signal and not as fast as possible. They were instructed, however, to execute each task at maximal velocity and not to anticipate the Go signal. Participants could rest for a few minutes between each series of tasks to avoid the effects of fatigue.

2.2. Data recordings

The EMG activity of the *soleus* and *tibialis anterior* (TA) was recorded bilaterally, using pairs of bipolar pre-amplified surface electrodes (1.5-cm inter-electrode distance and 8-mm square active surface each), strapped over the muscle belly after skin preparation. EMG signals were amplified (*1000), high- and low-pass filtered (15–450 Hz) prior to sampling (1 kHz). Ground reaction forces were recorded by means of a large triangle force plate (see Brenière & Do, 1986 for technical details). Instantaneous coordinates of CoP were calculated from the force plate vertical transducer data. The onset of pointing was detected by means of a mono-axial accelerometer (ENTRAN, ±5 g), firmly fixed to the participant's wrist joint by adhesive rubbers (active axis aligned with the A/P direction). Small oscillations, due to postural movements, might sometimes be observed in the signal delivered by the accelerometer. This may have affected a priori the accurate measuring of the onset of pointing in the combined task. However, compared to pointing, the rising rate of the wrist acceleration trace during stepping was negligible (see Fig. 1, lower panels). This contrast clarified the pointing onset in the combined task. Moreover, in addition to the accelerometer trace, electrogoniometers (Biometrics Ltd, Gwent, UK) fixed at the elbow (arm–forearm) and shoulder (arm–acromion) joints were used as a post-hoc blind test to check the onset of the voluntary arm movement and, thereby, insure an accurate measure of the pointing onset. It is noteworthy that the electrogoniometers signal is only sensitive to arm joint movements and is not affected by postural oscillations. All biomechanics data were digitized at a sampling rate of 500 Hz. EMG and biomechanics signals were stored on a PC hard disk for post-hoc analysis.

2.3. Experimental procedures

All participants stood barefooted on the force plate in a comfortable upright posture, with the feet approximately shoulder-width apart and gaze directed to the center of a target (8-cm diameter), placed at participants' shoulder height and at an out-of-reach distance (approximately 3-m ahead in front of participants). This target served as a visual reference against which the pointing task was directed in all trials and for all participants. The dominant arm (used for pointing) was initially positioned alongside the trunk with the forearm flexed at 90°, the wrist in the neutral position and the index finger extended. The non-dominant arm was relaxed alongside the body. The initial feet positioning was marked on the force plate covering; these marks served as a visual reference for participants (under experimenters' supervision), to reposition after each movement. The initial feet positioning along the A/P axis was adjusted so that each participant could step at maximal velocity without being limited by the size of the force plate. Practice trials were also used to adjust the individual initial position.

In pointing and combined tasks, participants were instructed to extend their dominant arm toward the target and maintain full extension for approximately 2–3 s. Experimenters

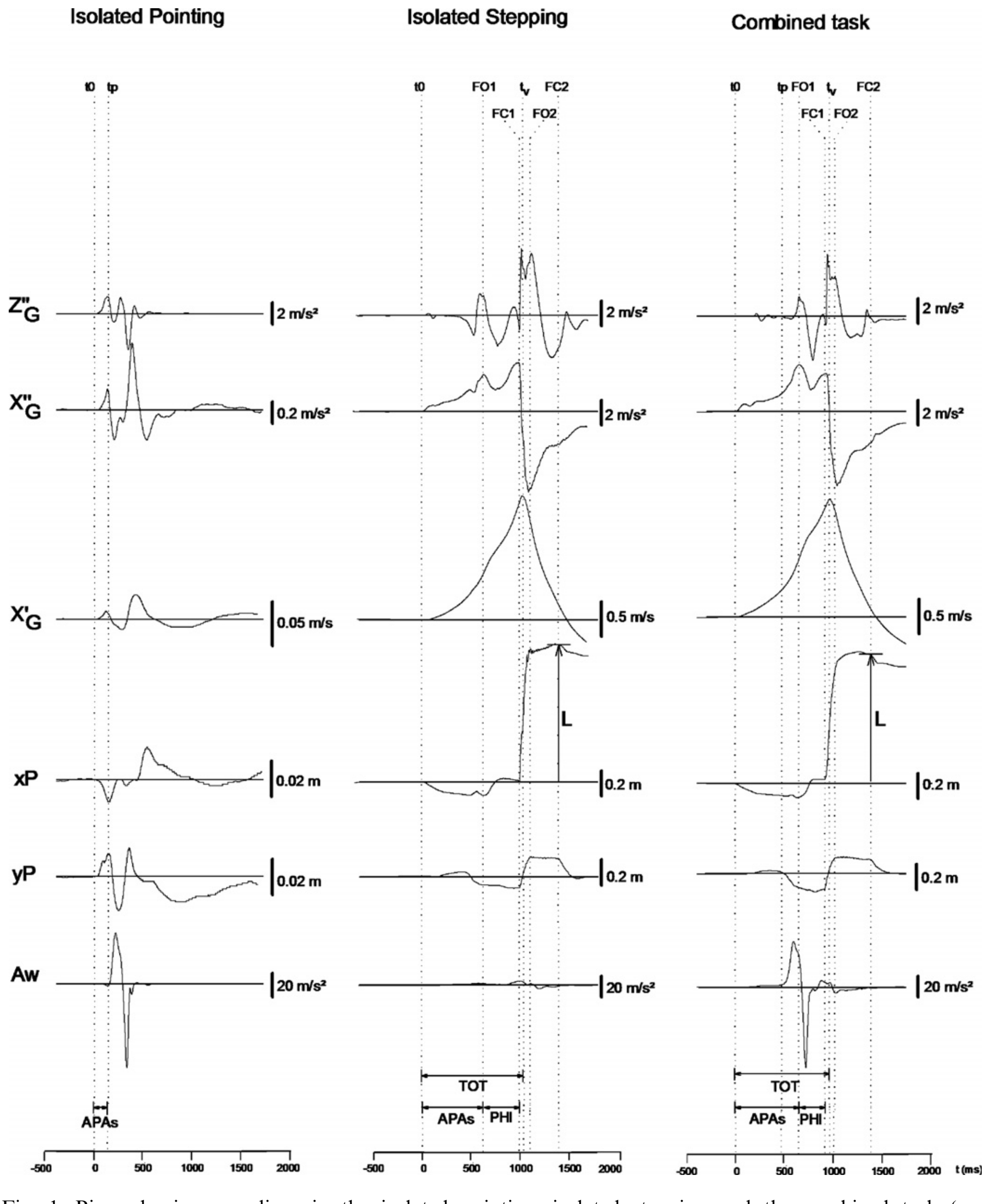

Fig. 1. Biomechanics recordings in the isolated pointing, isolated stepping and the combined task (one participant). x''G, z''G: A/P and vertical CoG acceleration, respectively; x'G: A/P CoG velocity; xP, yP: A/P and M/L CoP displacement, respectively; L: step length; Aw: wrist acceleration. An upward trace variation indicates a forward, upward or leftward acceleration or displacement; t_0: onset of biomechanical trace deviation (onset of APAs); t_p: onset of pointing; FO1, FC1, FO2 and FC2: swing foot-off, swing foot-contact, second foot-off, second foot-contact, respectively; t_V: peak of CoG velocity time; APAs: anticipatory postural adjustments; PHI: swing phase; TOT: whole stepping initiation process.

checked visually – and on electrogoniometric traces – the initial and final positioning of the pointing arm. A single step was required in the isolated stepping task and the combined task. Participants were instructed to remain standing quietly, as in the starting position, for approximately 2–3 s at the end of movement. There was no instruction regarding step length. The delay between the onset of pointing and stepping initiation was not imposed and participants were instructed to synchronize the arm pointing with stepping. The term "synchronize" was preferred to "coordinate" for instructions to be univocally understood by participants. Data acquisition was triggered 200-ms prior to the Go signal, which allowed the post-hoc calculation of CoP position in the initial posture. Trials, where the onset of movement occurred within 100-ms after the auditory cue, were considered anticipations. In addition, precise onset of APAs was generally difficult to establish in these trials because of slow and progressive increase in the CoG acceleration trace. Such trials, therefore, were discarded from further analysis (<5% of all trials).

2.4. Data reduction and analysis

2.4.1. EMG variables in both stepping tasks

Bilateral TA EMG signals were Kalman-filtered at 80 Hz, rectified and integrated during the time-interval elapsed from the onset of TA EMG bursts to the end of APAs at foot-off (anticipatory TA EMGi burst). The TA background EMG activity was also integrated in each trial for a 100-ms interval prior to the Go signal and this baseline was systematically removed from the anticipatory TA EMGi burst. For both stance and swing legs in each participant, anticipatory TA EMGi bursts were normalized with respect to the maximal value obtained among all trials and averaged among all participants in each task. We also measured the duration of anticipatory TA EMGi bursts and the time elapsed from the *soleus* deactivation to the onset of TA activation, since this time-interval was doomed to be pre-planned (Crenna & Frigo, 1991).

2.4.2. Biomechanical variables in both stepping tasks

We focused on phenomena occurring along the A/P axis (progression axis). The instantaneous acceleration of CoG (x''G) was calculated by the ratio Rx/m according to Newton's second law, where Rx represents the A/P ground reaction force recorded from the force plate and m the participant's mass. The CoG velocity (x'G) was obtained by single integration of CoG acceleration. The duration of stepping APAs was measured as the time elapsed from the onset of deviation in x''G trace to foot-off (i.e., the onset of swing phase), as calculated in previous studies (e.g., Couillandre, Maton, & Brenière, 2002; Do et al., 1999; Michel & Do, 2002; Yiou & Do, 2001). The amplitudes of APAs were defined as values of CoG forward acceleration and CoP backward displacement at foot-off. The duration of the swing phase (*PHI*) corresponded to the time-interval between swing foot-off and swing foot-contact, and the total duration of the step initiation to the time-interval between the onset of APAs and the time of the maximal CoG velocity (t_v, as defined in Brenière et al., 1987). The stepping performance was quantified with the maximal CoG velocity (V_{GMAX}) and with the time to reach the V_{GMAX} value (t_v).

The swing foot-off and foot-contact were detected from the force plate data and from foot-switches firmly fixed under the heel and big toe of the swing leg. On the force plate data, swing foot-off corresponded to the instant when the vertical CoG acceleration trace reached its first positive peak variation (*FO1*, see Fig. 1; see also Brenière, Do, & Sanchez, 1981). The swing foot-contact corresponded to an abrupt variation of the A/P and medio-lateral (M/L) CoP trace indicating that CoP begins to move from the rear stance foot to the other (*FC1*, see Fig. 1). The step length was measured on the A/P CoP displacement trace at the time of rear foot-contact (*FC2*, see Fig. 1). This time corresponded to an abrupt variation of the M/L CoP trace indicating that the CoP began to move laterally from the forward stance foot to the rear (a similar method was used in Do, Brenière, & Brenguier, 1982 and related studies). All parameters were visually detected on the experimental traces by two experimenters.

2.4.3. Combined task-specific variables

Two indexes (referred to as indexes of synchronization, ISs) were calculated in each trial to determine the time elapsed between stepping and pointing onsets in the combined task. A first index represented the time-interval between the onset of pointing (t_p, see insert of raw traces on Fig. 3) and swing foot-off. IS values were calculated in each combined task for all participants, ordered per increasing value and then averaged per time-interval of 100 ms. This helped test the relationship between IS and duration of APAs as follows: the APAs duration corresponding to the trial (among 15) having the shortest IS were identified per participant and were then averaged amongst participants to be compared to trials with longest ISs.

A second IS was computed as the time-interval between the maximal wrist acceleration occurrence (t_{max}, see Fig. 3) and foot-off. The maximal effect of pointing on the xP and xG″ values at foot-off (i.e., on the stepping APA amplitude) may occur when the maximal wrist acceleration and foot-off are simultaneous (the index of synchronization is then null). IS was averaged amongst participants as previously described.

To detect when the effect of pointing on stepping occurred, we measured the averaged time (t_D) at which the trace of the CoG acceleration (x''G) became different in the combined task compared to the isolated stepping. The t_D value was determined trial per trial in each participant by superimposing the 15 individual x''G traces of the combined task on the mean x''G trace of the isolated stepping. Individual and mean traces were aligned to the onset of x''G deviation (onset of APAs), and t_D was expressed with respect to the onset of pointing. We considered that the two traces dissociated when the x''G trace in the combined task became different to the mean x''G trace in the isolated stepping by ±2 SD.

2.5. Statistics

A one-way analysis of variance (ANOVA) identified stepping task differences in EMG and biomechanical variables. Correlations (Pearson) identified relationships between combined task-specific and biomechanical variables. The level of statistical significance was set at $p < .05$. Reported descriptive statistics are overall means ±1 SD for all participants.

3. Results

Results are presented in four sections. We first emphasize the similar initial position of the CoP in the three tested tasks. We then describe EMG and biomechanical profiles characterizing the pointing task. We present indexes of synchronization between the two elementary actions in the combined task and show that, in most trials, the onset of pointing and the maximal acceleration of the arm occurred prior to and around the onset of stepping, respectively. In the last section, we present evidence that, in the combined task compared to isolated stepping, the duration of the swing phase was reduced following the increase of CoG acceleration at foot-off. The whole duration of stepping was also reduced and the step length shortened without any significant changes in EMG activity and duration of APAs.

3.1. Initial position of the center of foot pressure

ANOVA analysis showed that the initial CoP position during quiet standing was not significantly different in the three tasks along A/P, $F(2,16) = 0.70$, $p = .51$, and M/L axes, $F(2,16) = 2.36$, $p = .12$, see Table 1. Hence, any between condition changes in biomechanics or EMG features during stepping could not be ascribed to differences in either the initial forward or backward body leaning or the distribution of pressures between feet. Relatively large SD values obtained in the initial A/P CoP position ($\approx$7 cm) can be ascribed to the fact that foot position on the force plate was not exactly the same between participants for protocol requirements (see Section 2).

3.2. EMG and biomechanics profiles in the pointing task

In traces presented in Figs. 1 and 2 (left panel), the isolated pointing was performed with the right arm. Fig. 1 shows that the onset of pointing (t_p) was preceded by a forward CoG acceleration (upward deviation of x''G trace) concomitant with a backward CoP displacement (1–2-cm downward deviation of xP trace). Such APAs reached their maximal amplitude approximately once pointing was triggered. Fig. 2 shows that the onset of pointing could be preceded by a bilateral *soleus* deactivation. The *soleus* was reactivated at the onset of pointing. However, this modulation was not observed systematically. Asynchronous action potentials of TA were also observed during pointing. The reciprocal modulation of ankle muscle EMG activity was of small amplitude and doomed to control the slight forward and backward CoP displacements reflected by the up- and downward deviations of xP trace in Fig. 1.

3.3. Synchronization between pointing and stepping in the combined task

Fig. 3 presents the distribution of trials with respect to Indexes of Synchronization (*ISs*) between pointing and stepping. IS was measured as the time elapsed from the onset of pointing (t_p, see insert of raw traces in Fig. 3) to the onset of voluntary stepping (foot-off, *FO* in Fig. 3A), or the time elapsed from the peak of wrist acceleration (t_{max}) to foot-off in Fig. 3B. Fig. 3A shows that pointing was initiated during the stepping APAs for 87% of the trials (negative IS, prior to foot-off) and during the swing phase for 13% of the trials (positive IS, after foot-off). Visual analysis of Fig. 3 shows that the distribution-curve was approximately bell-shaped with a peak time neighbouring foot-off time. Moreover, the shortest

Table 1
Mean coordinates of the center of foot pressure during the 200-ms time-interval preceding the Go signal along the antero-posterior ($xP0$) and medio-lateral ($yP0$) axes with respect to the force plate center

	$xP0$ (cm)	$yP0$ (cm)
Isolated pointing	48.7 (5.4)	101.3 (1.6)
Isolated stepping	48.7 (7.3)	101.0 (1.3)
Combined task	49.5 (7.9)	101.1 (1.4)

Values represent all participants means (±1 SD).

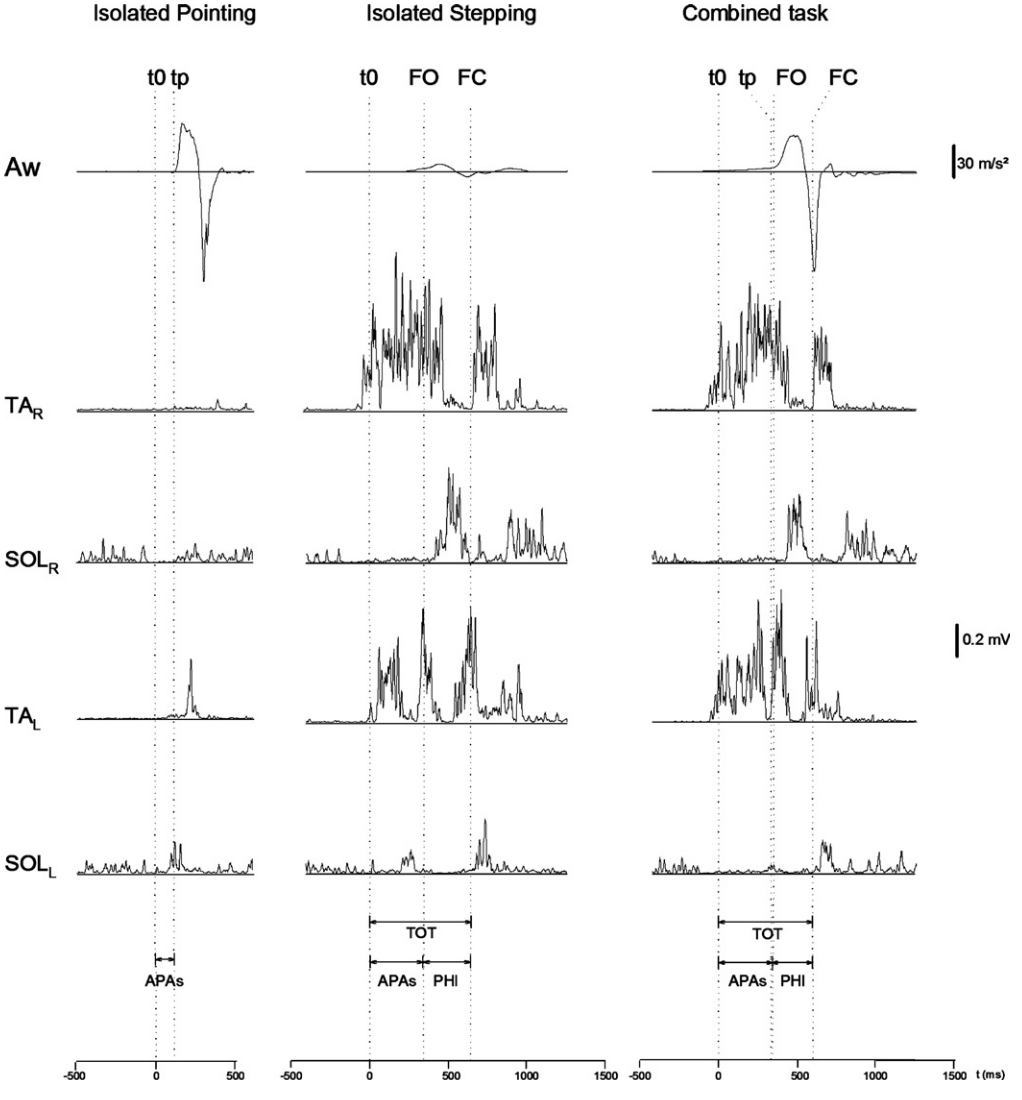

Fig. 2. EMG recordings in the isolated pointing, isolated stepping and the combined task along with the wrist acceleration (Aw trace) for one representative participant. Pointing was performed with the right arm and stepping was initiated with the left leg (swing leg). TA_R, TA_L, SOL_R, SOL_L: right and left *tibialis anterior* and *soleus*, respectively; t_0: onset of biomechanical deviation (onset of APAs); t_p: onset of pointing; FO and FC: swing foot-off and foot-contact; APAs: anticipatory postural adjustments; PHI: swing phase; TOT: whole stepping initiation process.

IS corresponded to 28% of the trials where pointing was triggered at 66 ± 28 ms prior to foot-off, i.e., at 90% of the duration of APAs. In addition, the next shortest IS represented 21% of the trials where pointing was triggered at 130 ± 30 ms prior to foot-off, i.e., at 80% of the duration of APAs. Overall, these two ISs represented 49% of the trials (56% of the 87% trials with a negative IS), where pointing was triggered at 80–90% of the duration of APAs. Fig. 3B shows that peak wrist acceleration occurred ±45 ms around foot-off for 70% of the

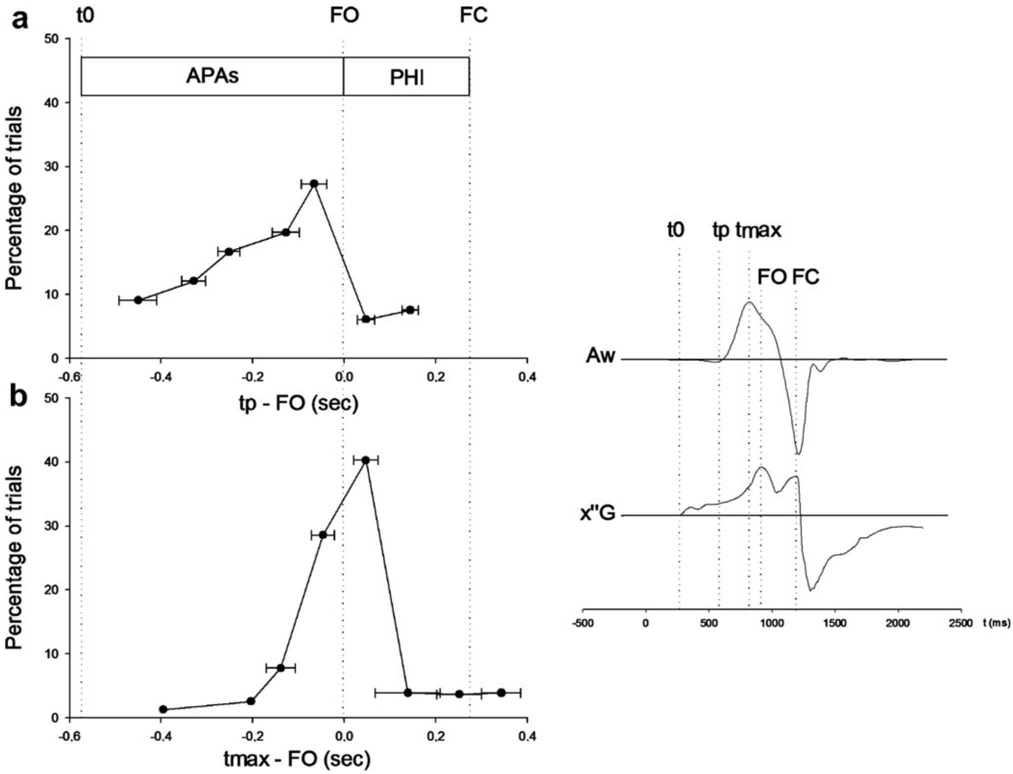

Fig. 3. Synchronization between the two elementary actions in the combined task for all participants. All trials ($n = 130$ trials) are distributed against the time elapsed from the onset of pointing (t_p) to foot-off (FO) (panel a) and against the time elapsed from the onset of the peak of wrist acceleration (t_{max}) to foot-off (panel b). Each symbol represents the mean (±1 SD) per 100-ms increment. A negative vs. positive value means that pointing was triggered before vs. after the foot-off (panel a) or that the peak of wrist acceleration occurred before vs. after the foot-off (panel b). The raw traces on the right panel represent wrist (Aw) and CoG accelerations (x''G) during the combined task. t_0: onset of biomechanical deviation (onset of APAs); FC: swing foot-contact.

trials. Superimposed mean CoG acceleration trace in the isolated stepping and individual CoG acceleration traces in the combined task (see Section 2.4.3. in Methods section for details) reflect that CoG acceleration in the combined task became higher than in the isolated stepping some 39 ± 41 ms after the onset of pointing. No correlation was detected between IS (onset of pointing minus onset of foot-off) and APAs duration or between IS and any of the spatio-temporal characteristics of stepping. For example, the duration of APAs was not correlated significantly with IS in any participant (mean $r = .36$, r range $.24 \leqslant r \leqslant .45$, with $p \geqslant .19$ to $p \leqslant .50$) and did not differ between trials with the shortest IS (−67 ± 87 ms; APAs duration = 570 ± 134 ms) and the longest IS (IS = −201 ± 134 ms; APAs duration = 579 ± 110 ms; $F[1,8] = 0.07$, $p = .79$).

3.4. Comparative biomechanics and EMG profiles in isolated stepping and combined task

Traces of CoG acceleration, CoP displacement and ankle muscle EMG activity were roughly the same in both stepping tasks. Between tasks comparisons are presented in the three following sub-sections characterizing different phases of the tasks: (1) similar APAs prior to swing foot clearance, (2) significant increase of the first peak acceleration of CoG at swing foot clearance and (3) changes in spatio-temporal parameters of stepping during the swing phase.

3.4.1. Similar APAs prior to foot-off

Figs. 1 and 2 (medial and right panels) present examples of stepping initiated by the left leg and pointing performed with the right arm. In both isolated stepping and combined tasks, the CoP was displaced backward, prior to swing foot-off and concomitantly with CoG forward acceleration, thus creating a disequilibrium torque to initiate stepping from quiet standing. The duration of these APAs was not different in both tasks (see Fig. 4, duration of APAs) (567 ± 122 ms vs. 557 ± 124 ms; $F[1,8] = 0.86, p = .38$). It is known that forward propulsive forces (APAs) generated during stepping are mainly produced by bilateral *soleus* deactivation followed by strong bilateral TA activation (Brenière et al., 1987; Cook & Cozzens, 1976; Crenna & Frigo, 1991; Herman et al., 1973; Lepers & Brenière, 1995). The superimposed pointing task did not alter such ankle muscle synergy (Fig. 2). Moreover, the time elapsed from the onset of *soleus* deactivation to TA activation (T_{SOL}) was not significantly different (see Fig. 5, lower and right panels), both in the stance (135 ± 7 ms and 151 ± 38 ms, respectively; $F(1,8) = 1.12$, $p = .32$) and swing legs ($121 \text{ ms} \pm 52$ and 135 ± 40 ms, respectively; $F(1,8) = 0.90, p = .37$). The duration of TA burst (T_{TA}) was also comparable in both stepping tasks (see Fig. 5, middle and right panels), and both stance (608 ± 59 ms vs. 616 ± 83 ms, respectively; $F[1,8] = 0.19$, $P = .67$) and swing legs (610 ± 90 ms vs. 621 ± 108 ms, respectively; $F[1,8] = 1.00$, $p = .35$). The anticipatory TA EMGi burst did not change (see Fig. 5, upper panel), both in stance (EMGi $= 77.37 \pm 7.32$ arbitrary unit (a.u.) vs. EMGi $= 74.12 \pm 9.49$ a.u.; $F(1,8) = 0.38$, $p = .55$) and swing sides (EMGi $= 68.56 \pm 15.94$ a.u. vs. EMGi $= 71.67 \pm 9.48$ a.u.; $F(1,8) = 0.26$, $p = .63$).

3.4.2. Increase of CoG acceleration at the end of APAs

In line with the literature, the CoG forward acceleration ($x''G_{FO}$) presented a peak around swing foot-off (see Fig. 1; see also Brunt et al., 1999; Couillandre et al., 2002; Gélat & Brenière, 2000). Fig. 6 (upper panel) shows that this forward CoG acceleration, measured at foot-off, was significantly higher in the combined than in the isolated stepping task (3.44 ± 0.79 m/s^2 vs. 3.01 ± 0.75 m/s^2, respectively, $F(1,8) = 25.88$, $p = .0009$); however, there was no concomitant increase in the CoP backward displacement (absolute values of 0.126 ± 0.027 m vs. 0.109 ± 0.051 m, respectively; $F(1,8) = 2.05$, $p = .19$), nor any change in the pattern of EMG activity over the duration of APAs (see Figs. 2 and 5). In both tasks, foot-off was preceded by a small *soleus* burst in the swing leg and a reciprocal TA inhibition. After foot-off, the reciprocal EMG activity observed on the stance side remained unchanged in the combined task and resembled the classic pattern of stance to swing transition already described in the literature (Schneider et al., 1997; Schneider, Lavoie, & Capaday, 2000). Thus, neither the duration of APAs nor the ankle muscle EMG activity and the backward excursion of CoP seemed to contribute to the increase of CoG acceleration when pointing was coordinated with stepping.

3.4.3. Changes in the spatio-temporal parameters of stepping during the swing phase

Fig. 4 presents significant changes in temporal step parameters in the combined task compared to the isolated stepping. The duration of the swing phase (PHI) was reduced

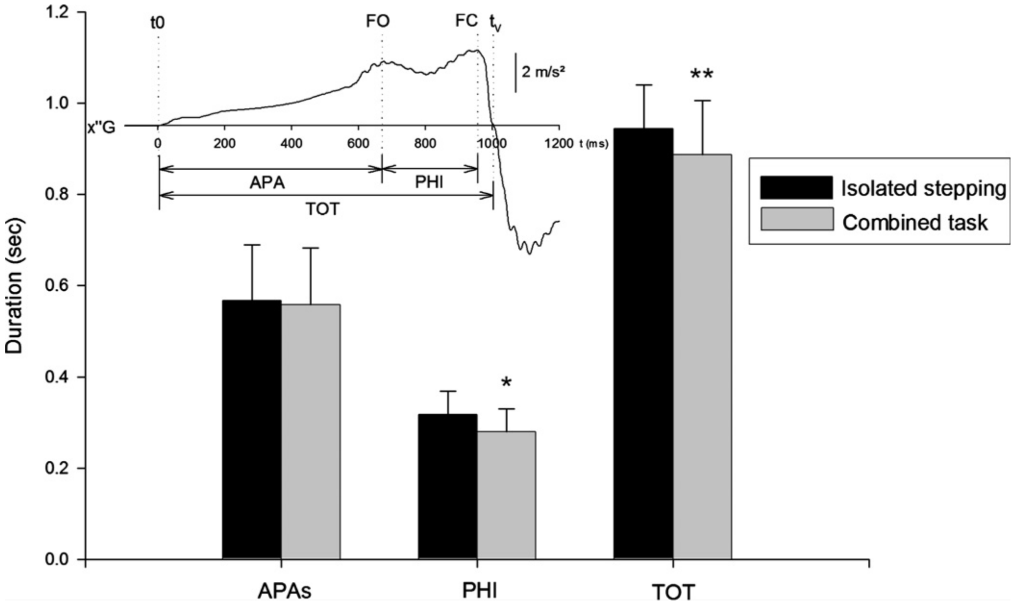

Fig. 4. Duration of biomechanics parameters between the isolated stepping and the combined task. The raw trace inserted is an example of the A/P CoG acceleration recorded during stepping. APAs: anticipatory postural adjustments; PHI: duration of swing phase; TOT: duration of the whole stepping initiation process; x''G: forward acceleration of center of gravity; FO and FC: foot-off and foot-contact; t_V: peak of maximal CoG velocity time. *: $p < .05$; **: $p < .01$.

(280 ± 50 ms vs. 318 ± 50 ms; $F(1,8) = 8.78$, $p = .02$), as well as the duration of the whole stepping initiation (887 ± 118 ms vs. 944 ± 96 ms; $F(1, 8) = 11.56$, $p = .01$). Fig. 6 (right lower histograms) illustrates that step length was significantly shorter in the combined task ($L = 0.95 \pm 0.17$ m vs. $L = 1.02 \pm 0.12$ m; $F(1,8) = 5.37$, $p = .04$).

Surprisingly, in spite of the changes detected in the combined task, i.e., the increased CoG acceleration at foot-off and the decreased step length and step duration, CoG maximal velocity, measured at t_V approximately 40–50 ms after foot-contact, was not statistically different ($V_{GMAX} = 1.76 \pm 0.23$ m/s vs. $V_{GMAX} = 1.67 \pm 0.33$ m/s in the isolated stepping; $F(1, 8) = 4.59$, $p = .07$). It is noteworthy that the decrease of swing phase duration was correlated to CoG acceleration measured at foot-off for all participants but one (mean $r = .67$, r range $.43 \leqslant r \leqslant .82$, with $p \geqslant .22$ to $p \leqslant .004$); however, it did not co-vary with step length in any participant in the combined task (mean $r = .22$, r range $.002 \leqslant r \leqslant .35$, with $p \geqslant .33$ to $p < .99$).

4. Discussion

Three new observations were made in the current study. (1) When participants had to synchronize arm pointing and stepping, pointing was triggered prior to stepping in most cases. (2) A mean 15% increase in forward CoG acceleration was detected at foot-off in correlation with the reduction of the swing phase duration. Backward CoP displacement,

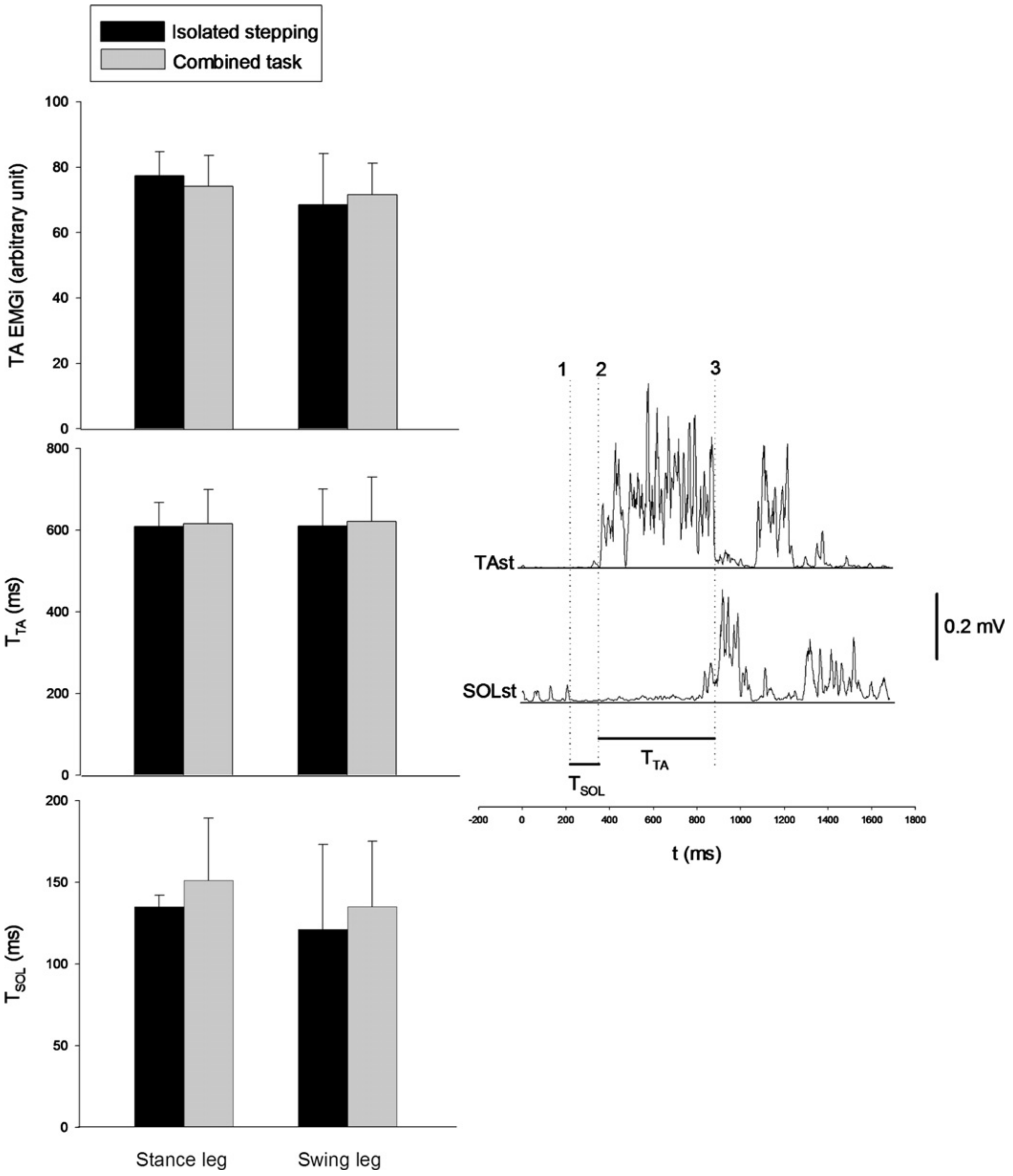

Fig. 5. Comparison of EMG variables during APAs in the isolated stepping and the combined task. The raw traces on the right panel are examples of TA and *soleus* EMG activity for the stance leg (st). TA EMGi: integrated EMG activity of *tibialis anterior*; T_{TA}: duration of TA burst; T_{SOL}: time elapsed from the onset of the *soleus* inhibition to the onset of TA burst; Line 1, 2, 3 indicate the onset of *soleus* inhibition and the onset and end of TA burst respectively.

APAs duration and ankle muscle EMG activity did not change. (3) Unexpectedly, the time required to reach maximal progression velocity (duration of step initiation) was reduced and step length shortened without any change of the CoG maximal velocity.

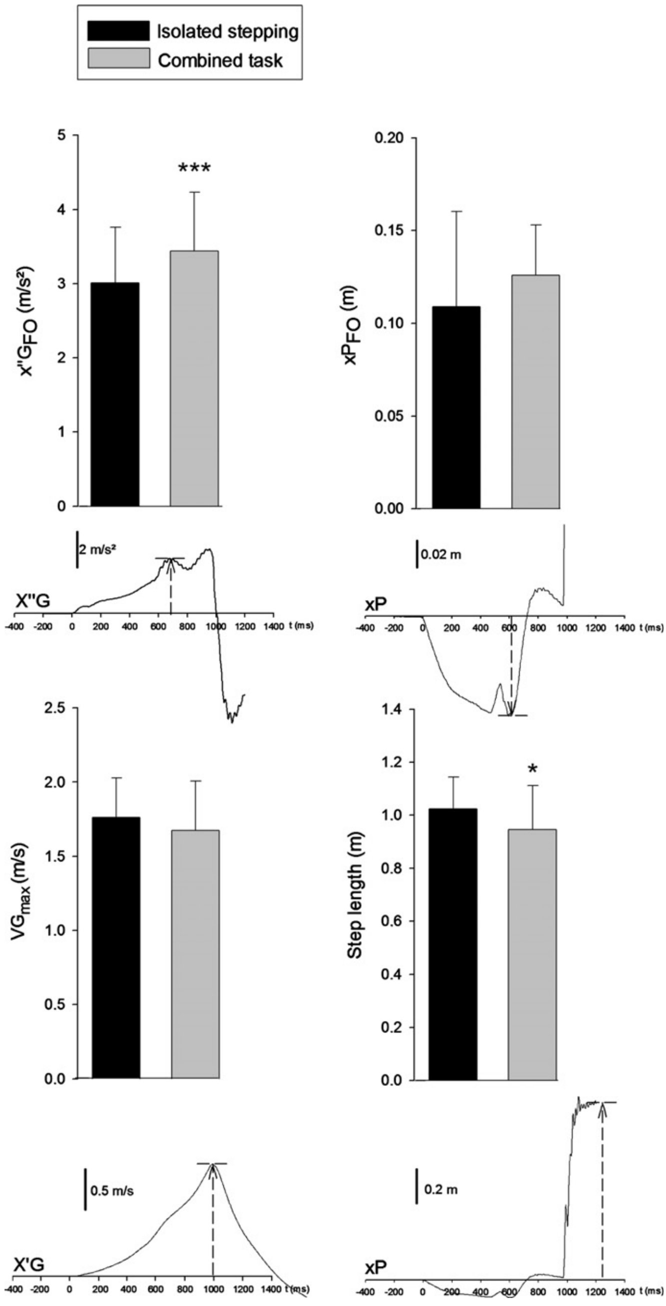

Fig. 6. Comparison of the spatial biomechanics parameters in the isolated stepping task and the combined task. $x''G_{FO}$: CoG forward acceleration at foot-off, xP_{FO}: CoP backward displacement at foot-off, VGmax: maximal CoG velocity; $*$: $p < .05$; $***$: $p < .001$. For legends in the lower panel traces, see Fig. 1.

The discussion that follows is organized in three sections. We first discuss the effect of the upper limb pointing on spatio-temporal parameters of stepping initiation. Then, the current results are compared to studies using externally triggered stepping, and further functional implications are presented.

4.1. Influence of synchronized pointing on the temporal parameters of stepping initiation

Brenière and Do (1986, 1991) first showed that the duration of stepping initiation was invariant, and was only dependent on participant's biomechanical invariance: moment of inertia and mass of the body, distance between the ground and the CoG. As compared to slow (or short) stepping, fast (or long) stepping requires a longer APAs period (to develop higher initial propulsive forces) and a shorter swing phase (PHI) duration, so that the sum of APAs and PHI remains invariant whatever the intended speed (or step length). This temporal invariance stems from laws of pendulum motion, which can be applied to the body initiating a single step or initiating gait (Brenière & Do, 1986, 1991; Brenière et al., 1987; Lyon & Day, 1997). Such results were established during experimental conditions where stepping was voluntarily performed in isolation, i.e., when upper limbs were not involved in an associated task (cf. also Brunt et al., 1999; Jian et al., 1993). The fact that, in the present study, the duration of step initiation was shorter in the combined task compared to isolate stepping is not in agreement with previous studies (the mean difference was approximately 60 ms). This finding suggests that the body does not strictly behave like a "normal inverted pendulum" (Brenière et al., 1987) when stepping initiation is combined with an upper limb task. Moreover, the duration of this step initiation is not exclusively constrained by anthropometry, but can be modulated by voluntary upper limb movements.

Results further showed that the decrease in step initiation duration can be ascribed to a shorter swing phase duration in the combined task and not to a shorter APAs duration (this latter parameter being equivalent in both stepping conditions). Lepers and Brenière (1995) and Lyon and Day (1997) showed that stepping could be compared to a ballistic fall around the stance ankle following swing foot-off. In line, it was found that swing phase duration values were negatively correlated with CoG acceleration at foot-off ($x''G_{FO}$), i.e., the higher $x''G_{FO}$, the shorter the swing phase. A similar finding was reported by Brenière et al. (1987) when comparing rapid and slow stepping tasks. These results suggest that a shorter swing phase duration in the combined task – and, consecutively a shorter duration of the stepping initiation – can be ascribed to higher propulsive forces generated at foot-off.

4.2. Influence of synchronized pointing on the spatial parameters of stepping initiation

We questioned whether enhanced propulsive forces at foot-off in the combined task might be ascribed to a modification of stepping APAs programming and/or to a mechanical interaction between both elementary actions. It is agreed that the motor program for stepping APAs includes bilateral *soleus* inhibition followed by strong TA activation. Such ankle synergy has been shown to promote backward CoP displacement which, in turn, is responsible for the generation of forward propulsive forces during stepping APAs (Brenière et al., 1987; Cook & Cozzens, 1976; Crenna & Frigo, 1991; Herman et al., 1973; Lepers & Brenière, 1995). Results of the current study showed that the time-interval between the onset of the *soleus* inhibition and the onset of the TA activation, as well as the level of TA activation during APAs, was equivalent in the isolated stepping and the combined task. This was true for both stance and swing legs. Anticipatory TA EMG bursts were also generated for an equivalent time. Overall, such observations suggest that the programming of stepping APAs remained unchanged for the coordination of pointing and stepping. Moreover, the fact that CoG acceleration traces became different [in both stepping conditions] only after pointing initiation is in agreement with the hypothesis of a mechanical effect of pointing on stepping APAs. The mass difference between the arm (m_f, *focal chain*) and the rest of the body (m_p, *postural chain*, Bouisset, 1991) is relatively important, as reflected by an m_f/m_p ratio of about 0.05 (see Miller & Nelson, 1973). However, pointing acceleration (around 20–25 m/s^2 at maximum, see Yiou & Do, 2001) is much higher compared to CoG acceleration at foot-off ($x''G_{FO} = 3.01$ m/s^2 in the isolated pointing). Consequently, the synchronized pointing task might have increased CoG acceleration at foot-off by as much as approximately 1.25 m/s^2 (5% $*$ 25 m/s^2). Our results showed that the actual increase was only 0.44 m/s^2. This can be explained by the fact that pointing peak acceleration (t_{max}) did not systematically occurred at foot-off (see Fig. 3B); thus, it was not always summated with anticipatory propulsive forces for stepping, yielding a sub-maximal effect. It is proposed that training in the combined task may help participants take better advantage of the dynamics elicited by the pointing to further hasten stepping. This could be done by synchronizing both elementary tasks so that foot-off and t_{max} coincide. This hypothesis will be further investigated.

Pointing increased initial propulsive forces and hastened stepping. It also reduced the step length ($\Delta \approx 7$ cm). In contrast, pointing had no effect on the maximal CoG velocity (V_{GMAX}). Participants had to recover balance within the first step with both feet parallel: had the step length remained unchanged, the additive effect of pointing on APAs may have increased V_{GMAX}, thus hindering the control of postural equilibrium in the final position. It is indeed known that step length and V_{GMAX} increase co-vary (Brenière & Do, 1991). In this case, a strategy to avoid forward fall may have been the displacement of the rear foot in front of the swing in the final posture (thus enlarging the base of support) or the execution of an additive step. However, instructions given to participants excluded such compensation. Hence, we propose that the reduction of step length in the combined task reflects the adaptation of stepping to keep V_{GMAX} stable. In support, maximal CoG velocity is known to be tuned according to the individual capacity to control equilibrium at the end of stepping (Brenière et al., 1987; Gélat & Brenière, 2000), i.e., according to the *Posturo-Kinetics Capacity* (Bouisset & Lebozec, 2002).

4.3. Self- vs. externally triggered stepping and associated mechanisms

Our findings contrast with studies on externally triggered stepping following support surface translation. The duration of APAs was reduced for voluntarily triggered stepping (Burleigh & Horak, 1996; Burleigh et al., 1994) and might even be abolished when stepping helps recovering balance (Mc Ilroy & Maki, 1993, 1995). In contrast, in the current experiment and in our previous studies (e.g., Do & Yiou, 1999; Yiou, 2005; Yiou & Do, 2001), APAs duration remained unchanged when the lower limb task (lunging task/leg flexion/stepping) was coordinated with a fast upper limb task. Four intertwined points are discussed thereafter to explain such discrepancy.

(1) The perturbation was different in nature, i.e., internal (pointing task) in our study vs. external (support surface translation) in other studies. However, postural responses to both kinds of perturbations were reported to be similar and were all assigned to

balance recovering (e.g., Layne & Abraham, 1991). It was also proposed that postural outcomes induced by perturbations of a different nature (voluntary arm movement and surface translation) were expressed via common neural networks (Cordo & Nashner, 1982; Massion, 1992; Mori, Iwakiri, Homma, Yokoyama, & Matsuyama, 1995). Thus, the nature of the perturbation on its own may not explain the discrepancies between studies.

(2) We could wonder whether the pointing-induced postural disturbance was sufficient to alter the duration of stepping APAs in our study. The CoG acceleration increased at foot-off up to 30% in some individuals (15% overall average). For an equivalent increase of the initial disequilibrium torque, Burleigh and Horak (1996) reported a 60% reduction of APAs duration when stepping was triggered by a support surface translation. We never detected a reduction in APAs duration.

(3) The support surface translation occurred prior to onset of APAs (Burleigh et al., 1994; Burleigh & Horak, 1996; Dietz, Kowalewski, Nakazawa, & Colombo, 2000; Zettel et al., 2002), whereas the pointing-related perturbation in our study occurred *during* (or *after*) APAs (see Fig. 3). Hence, it could be argued that time was not sufficient in our case for the sensory feedback elicited by the postural perturbation to tune the adaptation of APAs. However, results showed that APAs duration was not reduced even when the arm pointing was triggered at the very beginning of APAs (i.e., around 600 ms prior to foot-off).

(4) The instruction given to participants differed between studies. In our study, the voluntary stepping was self-initiated and performed as rapidly as possible, whereas in the above mentioned studies, the step had to be performed as soon as possible in a reaction-time paradigm, without any instruction on step velocity (e.g., Burleigh et al., 1994; Burleigh & Horak, 1996). It is proposed that in our experiment, participants intended to reach the highest propulsive forces as possible during APAs to hasten step execution following instruction. Reduction in APAs duration could have countered this strategy (Brenière et al., 1987).

5. Conclusions

The current study showed that coordinating arm pointing with stepping increased the initial propulsive forces for stepping initiation, and enabled to reach the maximal velocity earlier. Therefore, the upper limb movement might facilitate step initiation, promoting overall forward oriented whole-body tasks, as suggested for rising-up from a seat to walk in Tremblay, Malouin, and Schneider (2004). Balance control depends in part on the combination of biomechanical constraints and cognitive processes, including participant's interpretation of instructions, evaluation of the risk of fall and fear of falling, as shown for stepping induced by a forward fall (Do et al., 1999). In respect, the coordination of a forward upper limb(s) task and stepping could be proposed as a new model to enhance step initiation in persons living with mobility impairments.

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References

Bouisset, S. (1991). Relationship between postural support and intentional movement: Biomechanical approach. *Archives Internationales de Physiologie, de Biochimie et de Biophysique, 99*, A77–A92.

Bouisset, S., & Lebozec, S. (2002). Posturo-kinetics capacity and postural function in voluntary movement. In M. L. Latash (Ed.), *Progress in motor control* (pp. 25–52). Champaign, IL: Human Kinetics.

Bouisset, S., & Zattara, M. (1987). Biomechanical study of the programming of anticipatory postural adjustments associated with voluntary movement. *Journal of Biomechanics, 20*, 737–742.

Brenière, Y., Do, M. C., & Sanchez, J. (1981). A biomechanical study of the gait initiation process. *Journal de Biophysique et Médecine Nucléaire, 5*, 197–205.

Brenière, Y., & Do, M. C. (1986). When and how does steady state gait movement induced from upright posture begin? *Journal of Biomechanics, 19*, 1035–1040.

Brenière, Y., Do, M. C., & Bouisset, S. (1987). Are dynamic phenomena prior to stepping essential to walking? *Journal of Motor Behaviour, 19*, 62–76.

Brenière, Y., & Do, M. C. (1991). Control of gait initiation. *Journal of Motor Behaviour, 23*, 235–240.

Brunt, D., Liu, S. M., Trimble, M., Bauer, J., & Short, M. (1999). Principles underlying the organization of movement initiation from quiet stance. *Gait and Posture, 10*, 121–128.

Burleigh, A. L., & Horak, F. B. (1996). Influence of instruction, prediction, and afferent sensory information on the postural organization of step initiation. *Journal of Neurophysiology, 75*, 1619–1628.

Burleigh, A. L., Horak, F. B., & Malouin, F. (1994). Modification of postural responses and step initiation: Evidence for goal-directed postural interactions. *Journal of Neurophysiology, 72*, 2892–2902.

Cook, T., & Cozzens, B. (1976). The initiation of gait. In R. M. Herman, S. Grillner, R. S. Stein, & P. S. G. Stuart (Eds.), *Neural control of locomotion* (pp. 65–76). New York: Plenum Press.

Cordo, P. J., & Nashner, L. W. (1982). Properties of postural adjustments associated with rapid arm movement. *Journal of Neurophysiology, 47*, 287–302.

Couillandre, A., Maton, B., & Brenière, Y. (2002). Voluntary toe-walking gait initiation: Electromyographical and biomechanical aspects. *Experimental Brain Research, 147*, 313–321.

Crenna, P., & Frigo, C. (1991). A motor programme for initiation of forward oriented movements in man. *Journal of Physiology (London), 437*, 635–653.

Dietz, V., Kowalewski, R., Nakazawa, K., & Colombo, G. (2000). Effects of changing stance conditions on anticipatory postural adjustment and reaction time to voluntary arm movement in humans. *Journal of Physiology (London), 524*, 617–627.

Do, M. C., Brenière, Y., & Brenguier, P. (1982). A biomechanical study of balance recovery during the fall forward. *Journal of Biomechanics, 15*, 933–939.

Do, M. C., Schneider, C., & Chong, R. K. (1999). Factors contributing to onset of stepping in man. *Journal of Biomechanics, 32*, 795–802.

Do, M. C., & Yiou, E. (1999). Do centrally programmed anticipatory postural adjustments in forward stepping movement affect the performance of an associated pointing task? *Experimental Brain Research, 129*, 462–466.

Friedli, W. G., Cohen, L., Hallet, M. S., Stanhope, S., & Simon, S. R. (1988). Postural adjustments associated with rapid arm movements. II. Biomechanical analysis. *Journal of Neurology Neurosurgery, and Psychiatry, 51*, 232–243.

Gélat, T., & Brenière, Y. (2000). Adaptation of the gait initiation process for stepping on to a new level using a single step. *Experimental Brain Research, 133*, 538–546.

Herman, R., Cook, T., Cozzens, B., & Freedman, W. (1973). Control of postural reactions in man: The initiation of gait. In R. B. Stein, K. G. Pearson, R. S. Smith, & J. B. Redford (Eds.), *Control of posture and locomotion* (pp. 363–388). New York: Plenum Press.

Jian, Y., Winter, D. A., Ishac, M. G., & Gilchrist, L. (1993). Trajectory of the body CoG and CoP during initiation and termination of gait. *Gait and Posture, 1*, 9–22.

Layne, C. S., & Abraham, L. D. (1991). Interactions between automatic postural adjustments and anticipatory postural patterns accompanying voluntary movement. *International Journal of Neuroscience, 61*, 241–254.

Lee, W. A., Michaels, C. F., & Pai, Y. C. (1990). The organization of torque and EMG activity during bilateral handle pulls by standing human. *Experimental Brain Research, 82*, 304–314.

Lepers, R., & Brenière, Y. (1995). The role of anticipatory postural adjustments and gravity in gait initiation. *Experimental Brain Research, 107*, 118–124.

Lyon, I. N., & Day, B. L. (1997). Control of frontal plane body motion in human stepping. *Experimental Brain Research, 115*, 345–356.

Massion, J. (1992). Movement, posture and equilibrium: Interaction and coordination. *Progress in Neurobiology, 38*, 35–36.

Mc Ilroy, W. E., & Maki, B. E. (1993). Do anticipatory postural adjustments precede compensatory stepping reactions evoked by perturbation? *Neuroscience Letters, 164*, 199–202.

Mc Ilroy, W. E., & Maki, B. E. (1995). Adaptive changes to compensatory stepping responses. *Gait and Posture, 3*, 43–50.

Michel, V., & Do, M. C. (2002). Are stance ankle plantar flexor muscles necessary to generate propulsive force during human gait initiation? *Neuroscience Letters, 325*, 139–143.

Miller, D. I., & Nelson, R. C. (1973). *Biomechanics of sports*. Philadelphia: Lea and Febiger.

Mori, S., Iwakiri, H., Homma, Y., Yokoyama, T., & Matsuyama, K. (1995). Neuroanatomical and neurophysiological bases for postural control. Negative motor phenomena. In S. Fahn, M. Hallett, H. O. Lüders, & C. D. Marsden (Eds.), *Advances in neurology* (pp. 289–303). Philadelphia: Lippincott-Raven Publishers.

Nashner, L. M., & Cordo, P. J. (1981). Relation of automatic postural responses and reaction-time voluntary movements of human legs muscles. *Experimental Brain Research, 43*, 395–405.

Schneider, C., Do, M. C., & Bussel, B. (1997). Increase in the contraction of the stance *soleus* in man does not delay the swing phase in steps elicited by forward fall. *Comptes Rendus de l'Académie des Sciences, Paris, Neurosciences Section, 320*, 709–714.

Schneider, C., Lavoie, B. A., & Capaday, C. (2000). On the origin of the *soleus* H-reflex modulation pattern during human walking and its task-dependent differences. *Journal of Neurophysiology, 83*, 2881–2890.

Thomas, A. (1940). *Equilibre et équilibration*. Paris: Masson.

Tremblay, F. R., Malouin, F., & Schneider, C. (2004). Influence of the sitting position on the impaired modulation of spinal excitability during rising-up to walk after stroke. *Abstract Viewer/Itinerary Planner*, Washington, DC: Society for Neuroscience, 417.13.

Yiou, E. (2005). Performance and postural interactions during synchronous pointing and lower limb flexion. *Medicine and Science in Sports and Exercise, 37*, 91–99.

Yiou, E., & Do, M. C. (2001). In a complex sequential movement, what component of the motor program is improved with intensive practice, sequence timing or ensemble motor learning? *Experimental Brain Research, 137*, 197–204.

Zettel, J. L., Mc Ilroy, W. E., & Maki, B. E. (2002). Can stabilizing features of rapid triggered stepping reactions be modulated to meet environmental constraints? *Experimental Brain Research, 145*, 297–308.