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Factors influencing the quick onset of stepping following postural perturbation

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Abstract

It has been shown that the stepping to recover balance following a forward fall occurs at a constant time (on average 293 ms) (Do et al. Journal of Biomechanics 15, 1982, 933–939). In this study, we tested the hypothesis according to which programming to make fast movement could trigger the movement earlier than when programming self-pace movement. The same experimental paradigm of forward fall was used (see Do et al., 1982) to induce stepping. Different extents of stepping were manipulated by instructions: Subjects were instructed to step to recover their balance naturally (control condition); to make shorter steps than in the control condition; longer steps; faster steps. Lastly, a fast step was also induced by the biomechanical constraint on the initial posture, i.e. by inclining the subject forward at his maximum capacity. Data were collected from 12 subjects. The variables analyzed were the onset latency of step execution and other classical parameters (time of heel-contact, duration of the swing phase, step length, center of mass progression velocity, and step velocity). The results showed that the onset of stepping was unchanged in the longer- and faster-step conditions, relative to the control condition (mean control value = 280 ms). In contrast, the onset of stepping was significantly earlier in the short-step condition, and when the initial inclination was greater (250 and 252 ms, respectively). The swing phase duration in these two conditions averaged 140 and 185 ms, was significantly shorter than in the other conditions, whereas step length was obviously expected to be shorter in the shorter-step condition and longer in the longer-step condition than in the other conditions. Step length was similar between the other conditions.

We conclude that neither step length or step velocity programming could induce an earlier onset latency of stepping. Step programming in relation to these specific instructions seemed to concern the extent of step execution and not the time of triggering of the stepping. We suggest that the control of short swing phase duration resulted in an earlier onset latency of stepping to recover the balance. This control depends on the combination of biomechanical constraints and cognitive processes, including subject's interpretation of the instructions and evaluation of the risk of fall.

Keywords: Onset of stepping; Postural perturbation; Human

1. Introduction

The programming of a ballistic movement, or rapid movement, induces an earlier movement initiation than for a slow or ramp movement (Becker et al., 1976; Beppu et al., 1984; Kagamihara et al., 1992). In the same line, manipulation on the force output at the elbow joint affected the initiation of extension movement (Nagasaki et al., 1983). Extrapolating these findings, one can question whether the onset latency of stepping following a postural perturbation, which is usually constant, could be modified by programming 'quick' stepping. This hypothesis was tested in the stepping to recover balance following a forward fall (Do et al., 1982). More precisely, we examined what factor(s) could induce the shortening of the onset latency of stepping.

In a previous study it was shown that the onset latency of self-paced forward stepping (i.e. time elapsed between the forward fall and time of foot-ground clearance) to recover the balance following a forward fall was constant and independent of the initial acceleration of the body center of gravity (Do et al., 1982). According to the relationship $V = L^*F$, where V, L and F represent the velocity of progression, the step length and step

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frequency, it is possible to manipulate the speed of step movement with different extents of step execution. Subjects were instructed to make shorter steps than in the control condition; longer steps; faster steps. To fulfill the 'shorter step' instruction, subjects would have to decrease the CoM progression velocity but increase the step frequency. In the 'longer step' condition, the CoM progression velocity should increase according to the relationship $V = L*F$. Lastly, fast steps were also induced by inclining the subject near the limit of the subject's capacity to regain balance after the forward fall. The identification of the factor(s) which affect the onset latency of stepping can help to explain the different onset latency of stepping between the different experimental paradigms involving postural perturbation and stepping (cf. Burleigh et al., 1994, 1996; Maki et al., 1996).

2. Methods

The experimental set-up has been described in a previous paper (cf. Do et al., 1982). Briefly, subjects were barefooted, and maintained in a forward leaned posture by a restraining device wrapped around the abdomen and connected with a steel cable to a dynamometer mounted on an electro-magnet. The initial inclination was fixed at approximately 20°. This value was chosen to allow the subject to fulfill the experimental instructions. To reproduce the same initial inclination between trials of an individual experimental session a unique length cable was used and the subject was replaced in the same foot marks drawn on the force plate. The dynamometer voltage output was used to control the initial inclination. Because of the initial leaned posture, the release of the cable induced a forward fall. The time of release was unknown to the subject who was instructed to walk to recover balance. Before each series of ten trials subjects received one of four instructions regarding the manner of stepping: to walk "normally" to recover balance (self-pace movement), i.e. control condition (Control) and, relative to control condition, shorter steps (ShortStep), longer steps (LongStep), faster steps (FastStep). Before each series, the subject executed some practice trials. Twelve healthy subjects participated in the experiment (9 men, 3 women; mean age 28 yr; mean height 1.69 m $\pm$ 6). Five of the male volunteers performed an additional fifth experimental condition (10 trials in each subject) in which the initial inclination was increased to 35–40°, i.e. at the maximum subject's capability to recover his balance. The instruction was to walk to recover balance. The great initial inclination, i.e. great postural perturbation (GreatIncline), induced very fast steps. For all subjects, the Control series was always performed first, with the GreatIncline condition performed last. The other four conditions were presented in a pseudo-random order from one subject to another. All subjects gave their informed consent to participate in the experiment.

The experiment was performed on a large equilateral triangle force plate (2 m side) (see Breniere et al., 1981), which measured ground reaction forces and displacement of center of foot pressure (CoP). The precision was 1 N for force determination and 3 mm for the displacement of the CoP. Accelerations of subject's center of mass and the CoM velocity were calculated from the ground reaction force measurements, according to the fundamental principle of mechanics. More precisely, the CoM velocity was obtained by integration of the antero-posterior CoM acceleration from time of release to the end of the data acquisition.

Force plate signals were acquired using an A/D converter (CED 1401) and sampled at 250 Hz. Data acquisition was triggered by the unloading of the dynamometer. Acquisition software recorded data 200 ms before and 800 ms after release. Statistical analyses of the data used Two-Way Analysis of variance (MANOVA, STATISTICA software) with Subjects taken as the Random factor, and Experimental Conditions as the Fixed factor. Fisher's-LSD post-hoc test was used to test differences between means (threshold of significance was $P = 0.01$). The results of the post-hoc test are presented under the form of contrast-matrices.

3. Results

3.1. Description of the different extents of stepping

The typical biomechanical traces of a "normal" balance recovery movement is shown in Fig. 1. The forward fall provoked by the release of the restraining force induced a fall ($\ddot{z}_G < 0$) which was rapidly decelerated (change in sign of $\ddot{z}_G$). This biomechanical reaction, due to ankle plantar flexion (Do et al., 1988), reached a peak before step execution was carried out (TO, toe-off). Step was executed while the CoM was accelerated downward. End of swing phase occurred at the time of heel-contact (HC). Following the progression axis (x-axis), the $\ddot{x}_G$ trace shows a continuous forward CoM acceleration followed by a short period of braking ($\ddot{x}_G < 0$), which occurs shortly after heel-contact. In contrast to normal gait initiation from an upright posture (cf. Breniere et al., 1987), the antero-posterior displacement of center of foot pressure (x_P) showed a displacement towards the forefoot while the biomechanical reaction developed. The step length was measured when x_P trace reached a second plateau, i.e. when the subject was again on unipedal stance. Following the lateral axis, the traces (y_P and $\ddot{y}_G$) showed that the CoP moved towards the stance foot and the CoM was accelerated in the opposite direction, like in some compensatory stepping response evoked by postural perturbation (cf. McIlroy and Maki, 1993a,b,c).

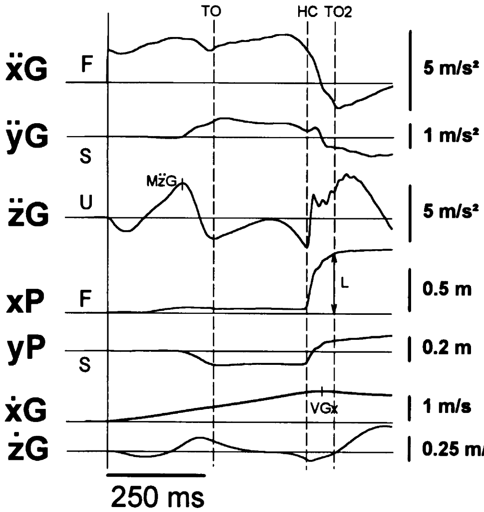


Fig. 1. Kinetics and kinematics of step following a forward fall (single trial), of the Control series: Vertical line, time of forward fall release; TO, HC, TO2 times of step execution (toe-off), heel-contact and second step execution, respectively; $\ddot{x}_G$, $\ddot{y}_G$, $\ddot{z}_G$, antero-posterior, lateral and vertical component of CoM acceleration; x_P and y_P, antero-posterior, lateral displacement of center of foot-pressure; $\dot{x}_G$ and $\dot{z}_G$ antero-posterior and vertical CoM velocity. $M\ddot{z}_G$, L, V_Gx, peak of biomechanical reaction to the fall, step length, peak of CoM progression velocity, respectively. F, S, U, forward, stance side, upward direction.

However, this is in contrast to what was observed in natural gait initiation (Breniere et al., 1987), in perturbation-cued 'reaction time' stepping (Burleigh et al., 1996), or in lower-limb flexion movement (Do et al., 1991).

Visual inspection of the biomechanical traces of the different experimental conditions (Fig. 2) showed one striking difference between the conditions. In contrast to Control, LongStep, or FastStep conditions, the ShortStep and GreatIncline conditions showed no deceleration phase after heel-contact (see $\ddot{x}_G$ trace), i.e. the CoM was still in forward acceleration.

3.2. Effects of experimental conditions (Matrices of contrasts and Histograms, Schemes 1 and 2)

The parameters which were tested statistically were: the first positive peak of vertical CG acceleration ($M\ddot{z}_G$), i.e. the magnitude of the biomechanical reaction to the fall; times of step execution (TO) and heel-contact (HC); antero-posterior CoM velocity (V_Gx) following heel-contact; step length (L); duration of the swing phase (ϕ), i.e. the difference between HC and TO; mean velocity of step execution (V_S) which is the ratio between step length and swing phase duration, $V_S = L/\phi$. The initial antero-posterior acceleration (Rx_0) which is proportional to the initial inclination was also analyzed because it could reveal changes in the subject's postural preparation.

While it is obvious that the antero-posterior initial acceleration (Rx_0) was higher in the GreatIncline condition relative to the other conditions, the contrast matrix (Scheme 1) showed that Rx_0 was higher in LongStep and FastStep conditions with respect to the Control condition, whereas it should be the same (see methods). That means that to fulfill the instructions (longer and faster steps) subjects change their initial posture. This postural change was subtle and was not observed visually during data collection. As the pelvis and feet positions were standardized, to increase the initial acceleration, i.e. to increase the restraining force, the subjects likely inclined the trunk or activated their distal and/or proximal muscle flexors.

Onset latency of step execution (TO) in GreatIncline and ShortStep conditions (239 ± 32 and 258 ± 27 ms, respectively) was significantly shorter than in the other conditions in which TO was greater than 280 ms (Histogram Scheme 1). Time of heel-contact (HC) in ShortStep and GreatIncline conditions (385 ± 55 and 404 ± 35 ms) was also significantly earlier. HC was similar between FastStep, Control and LongStep and occurred roughly at 500 ms. Swing phase duration (ϕ) in ShortStep and GreatIncline conditions (140 ± 35 and 160 ± 27 ms, respectively) was shorter than the other conditions ($P < 0.001$) (see Scheme 1). ϕ was similar among the conditions Control, FastStep, and LongStep (approximately 220 ms).

The step length (L) was obviously shorter in the ShortStep condition (0.47 ± 0.14 m) and longer in the LongStep condition (1.00 ± 0.11 m). Step length was comparable between the Control, FastStep and GreatIncline conditions and between the FastStep, GreatIncline and LongStep conditions (see Scheme 1).

The biomechanical reaction force to the fall ($M\ddot{z}_G$) was similar between FastStep and LongStep conditions, and between LongStep, GreatIncline, ShortStep and Control conditions (Scheme 2). However, the biomechanical reaction was significantly lower in FastStep than in the Control condition (2.68 ± 1.27 m/s^2, mean and $\pm$ S.D, vs. 3.9 ± 1.11 m/s^2). The lesser biomechanical reaction in FastStep could be due to subjects letting themselves fall to use potential energy to increase step velocity.

The contrast matrix showed that the vertical CoM acceleration at heel contact ($\ddot{z}_{HC}$) was similar between the GreatIncline and ShortStep conditions (value ranging between -5.78 ± 1.53 and -4.70 ± 1.61m/s^2), and was higher in absolute value than in the Control, LongStep and FastStep conditions (Scheme 2).

The matrix contrast (Scheme 2) of CoM progression velocity (V_Gx) showed that V_Gx was comparable between the LongStep, FastStep and GreatIncline conditions. Otherwise, V_{Gx} was significantly lower in the ShortStep (1 ± 0.2 m/s) than in the other conditions; and higher in the GreatIncline (1.77 ± 0.28 m/s) than in Control condition.

Step velocity (V_S) was comparable between the ShortStep and Control conditions, and between the Control,

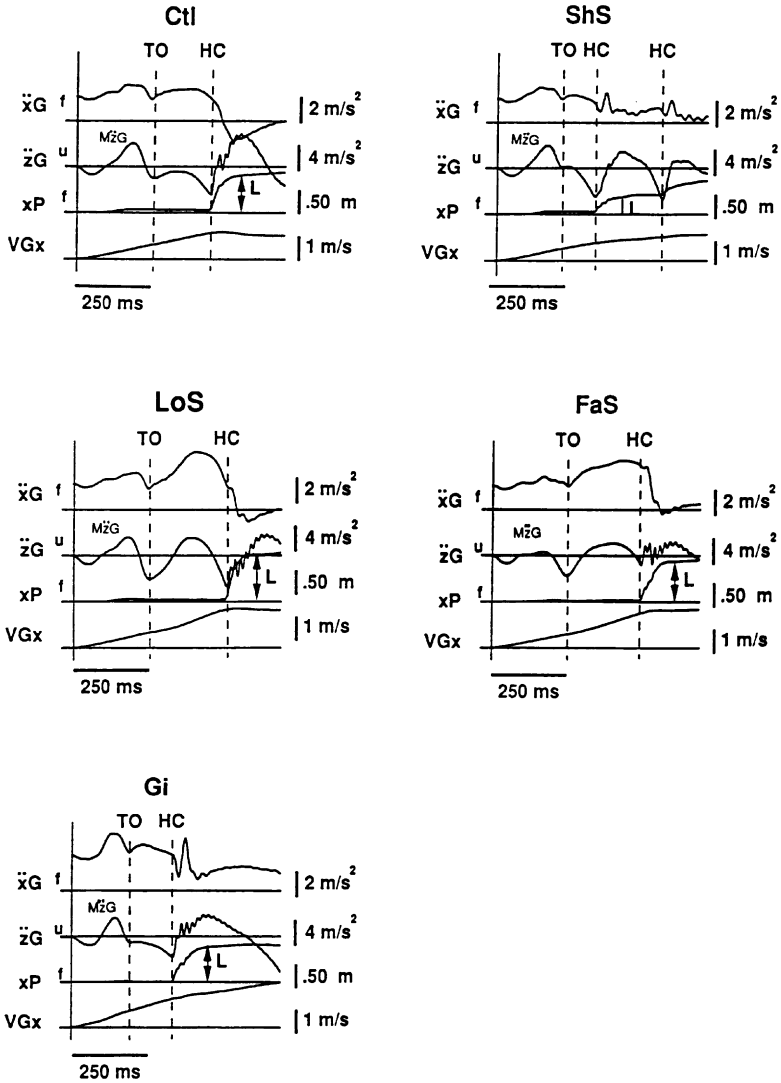


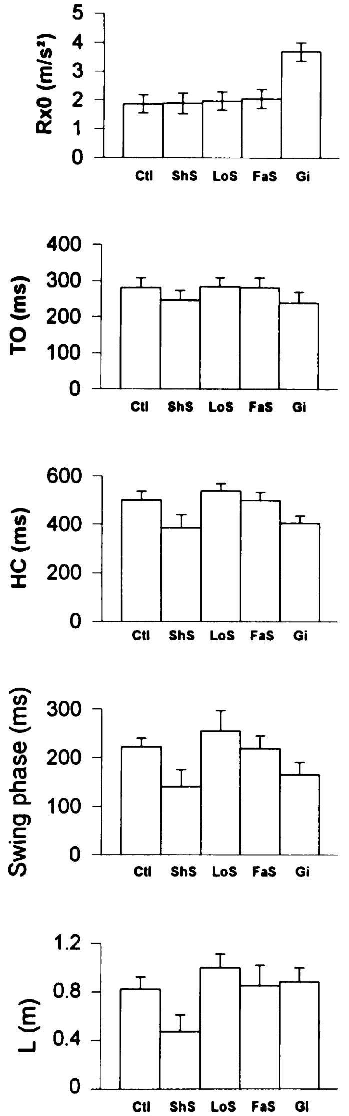
Fig. 2. Averages (10 trials) of the biomechanical traces of the 5 experimental conditions (one subject): Vertical line, time of forward fall release; TO, HC, times of step execution (toe-off) and heel-contact, respectively; Ctl, control series; ShS, LoS, FaS, Gi, ShortStep, LongStep, FastStep and GreatIncline experimental conditions. $\ddot{x}_G$, $\ddot{z}_G$, antero-posterior and vertical component of CoM acceleration; x_P, antero-posterior displacement of center of foot-pressure $M\ddot{z}_G$, L, peak of biomechanical reaction to the fall (vertical CoM acceleration), step length, respectively. F, S, U, forward, stance side, upward direction.

FastStep, and LongStep conditions. V_S was the lowest in the ShortStep condition (3.33 $\pm$ 0.49 m/s) and the highest in the GreatIncline condition (4.77 $\pm$ 0.47 m/s). Note that V_S is more than twice the value of V_{Gx} in any condition.

4. Discussion

The objective of this study was to examine the factor(s) that could induce an earlier onset of stepping following a forward fall. The results showed that the onset latency of stepping (TO, Toe-Off) was earlier when subjects had to perform short steps (ShortStep condition) and in the condition of great postural perturbation (GreatIncline condition) induced by a large initial inclination. In these experimental conditions, the CoM progression velocity at the end of the first step was lower and higher than in the Control situation, respectively. In contrast, in the LongStep or FastStep conditions where the CoM progression velocity was higher, the onset latency of stepping (TO, Toe-Off) was similar to Control condition.

What could be the factor(s) which can induce earlier stepping in reaction to a postural perturbation? Although the initial posture could influence the duration of postural adjustments preceding the flexion of the lower limb (Nouillot et al., 1992), in the present paradigm the initial posture would not play a significant role (cf. also Burleigh et al., 1994, 1996), because the initial posture was similar between the ShortStep and the



RX0	mean m/s²	1	2	3	4	5
Ctl (1)	1.87	.	.	S	S	S
ShS (2)	1.89	.	.	.	S	S
LoS (3)	1.98	S	.	.	.	S
FaS (4)	2.07	S	S	.	.	S
Gi (5)	3.71	S	S	S	S	.

TO	mean ms	5	2	1	4	3
Gi (5)	239	.	.	S	S	S
ShS (2)	245	.	.	S	S	S
Ctl (1)	280	S	S	.	.	.
FaS (4)	281	S	S	.	.	.
LoS (3)	284	S	S	.	.	.

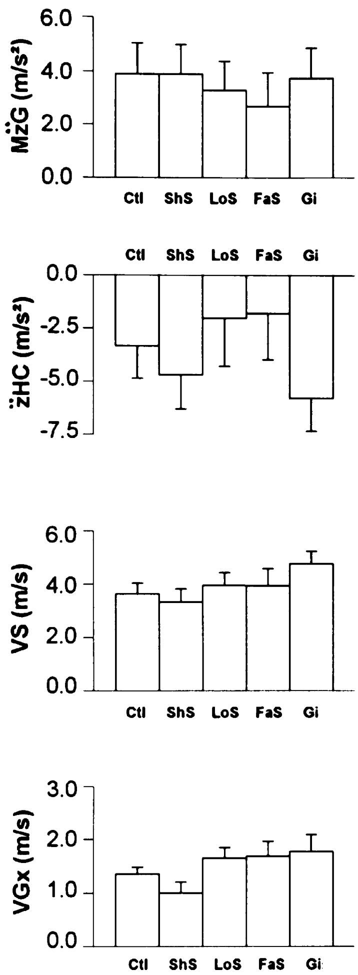
HC	mean ms	2	5	4	1	3
ShS (2)	385	.	.	S	S	S
Gi (5)	404	.	.	S	S	S
FaS (4)	499	S	S	.	.	.
Ctl (1)	501	S	S	.	.	.
LoS (3)	539	S	S	.	.	.

Φ	mean ms	2	5	4	1	3
ShS (2)	140	.	.	S	S	S
Gi (5)	165	.	.	S	S	S
FaS (4)	218	S	S	.	.	.
Ctl (1)	221	S	S	.	.	.
LoS (3)	255	S	S	.	.	.

L	mean m	2	1	4	5	3
ShS (2)	0.47	.	S	S	S	S
Ctl (1)	0.82	S	.	.	.	S
FaS (4)	0.85	S	.	.	.	.
Gi (5)	0.88	S	.	.	.	.
LoS (3)	1.00	S	S	.	.	.

Scheme 1. Histograms (mean values ± S.D.) and matrices of contrast (Fisher's LSD post-hoc test). It is showed the mean and S.D. of the initial acceleration (Rx_0), onset latency of stepping (TO, toe-off), time of heel-contact (HC), swing phase duration (ϕ), step length (L) and the corresponding matrix of contrast on the mean values. In the matrices of contrast, 'S' means a significant difference between the means; the experimental conditions are identified by the number 1 to 5; Ctl = 1 (Control series); ShS = 2 (ShortStep); LoS = 3 (LongStep); FaS = 4 (FastSstep) and Gi = 5 (GreatIncline). Statistical threshold $P = 0.01$.

Control conditions. The onset of stepping in reaction to a sudden forward fall also seemed unlikely to depend primarily on the programming of step length. The shortening of step length could be a factor inducing earlier stepping if we compare the ShortStep condition to the Control condition, it is however not true if we compare ShortStep to GreatIncline conditions, where TO was comparable while the step length was different (almost twice longer in GreatIncline). In addition, TO was comparable between the Control and the LongStep conditions whereas step length was shorter in the Control condition. Findings from multi-directional stepping experimental paradigm also support this interpretation (Maki et al., 1996). These authors effectively showed that although the step length was similar following two different oblique postural perturbations (135 and − 45°), the onset latency of stepping was significantly different. Therefore the step length variation in our study does not seem to constitute an alternative explanation either. Furthermore, changing step length (shortening or lengthening) induced covariations in the other parameters, like the center of mass velocity, the step velocity and the swing phase duration. However, the earlier occurrence of TO in ShortStep and GreatIncline conditions (relative to the Control condition) could not simply be attributed to the variations of the center of mass (CoM) velocity or the



MẑG	mean m/s²	4	3	5	2	1
FaS (4)	2.68	.	.	S	S	S
LoS (3)	3.29	.	.	.	.	.
Gi (5)	3.72	S	.	.	.	.
ShS (2)	3.89	S	.	.	.	.
Ctl (1)	3.90	S	.	.	.	.

z̈HC	mean m/s²	5	2	1	3	4
Gi (5)	-5.78	.	.	S	S	S
ShS (2)	-4.70	.	.	.	S	S
Ctl (1)	-3.40	S	.	.	.	.
LoS (3)	-2.00	S	S	.	.	.
FaS (4)	-1.80	S	S	.	.	.

VS	mean m/s	2	1	4	3	5
ShS (2)	3.33	.	.	S	S	S
Ctl (1)	3.63	.	.	.	.	S
FaS (4)	3.94	S	.	.	.	S
LoS (3)	3.96	S	.	.	.	S
Gi (5)	4.77	S	S	S	S	.

VGx	mean m/s	2	1	3	4	5
ShS (2)	1.00	.	S	S	S	S
Ctl (1)	1.35	S	.	S	S	S
LoS (3)	1.65	S	S	.	.	.
FaS (4)	1.68	S	S	.	.	.
Gi (5)	1.77	S	S	.	.	.

Scheme 2. Histograms (mean values ± S.D.) and matrices of contrast (Fisher's LSD post-hoc test). It is showed the mean and S.D. of the peak of the biomechanical reaction ($M\ddot{z}_G$), vertical acceleration of CoM at time of heel-contact (z_{HC}), step velocity (V_S), and the CoM progression velocity (V_Gx) and the corresponding matrix of contrast on the mean values In the matrices of contrast, 'S' means a significant difference between the means; the experimental conditions are identified by the number 1 to 5; Ctl = 1 (Control series); ShS = 2 (ShortStep); LoS = 3 (LongStep); FaS = 4 (FastSstep) and Gi = 5 (GreatIncline). Statistical threshold $P = 0.01$.

step velocity (Burleigh et al., 1996). Indeed, the CoM velocity was lower in the ShortStep than in the Control condition, but it was higher in the GreatIncline than in the Control condition. The step velocity was comparable between the Control and the ShortStep conditions ($p > 0.05$), but it was significantly higher in the GreatIncline condition ($p < 0.001$). Results from the multi-directional stepping paradigm (Maki et al., 1996) also suggest that the onset latency of stepping is unrelated to the step velocity. For example, the foot-off time of a backward step following a forward sagittal translation or a forward-leftward translation of the support surface occurred at 433 ms and 326 ms, respectively, whereas the step velocity was not different, 148 and 134 cm/s, respectively.

Sensory information in the GreatIncline condition, where the plantarflexor muscle length is more stretched than in the Control condition, could explain the earlier TO. However, this cannot explain the earlier TO in the ShortStep condition relative to the Control condition, as the ankle angular was the same between these conditions. Furthermore, TO was similar between the GreatIncline and ShortStep conditions whereas the ankle angle was different.

Short swing phase duration, which also means high-frequency stepping, is very likely the principal control parameter which induced earlier onset of stepping. Programming to step with high frequency is similar to programming a fast single movement. It was shown that the fast single movement was initiated earlier. The earlier onset of the movement was related to the facilitation of agonist motoneurons (Kagamihara et al., 1992; Ruegg and Drews, 1991). Amazingly, in this study, subjects stated that they felt having to take "fast steps", in the ShortStep condition. Yet the CoM velocity under this condition was lower than in the other conditions, whereas the step velocity was comparable to the Control condition.

Combining our previous study (Do et al., 1982) which showed that TO is constant (mean onset of stepping of subjects, 293 ms) whatever the initial inclination, and the present findings which showed earlier onset of TO in the ShortStep and the GreatIncline conditions, these results suggests the existence of a swing phase duration threshold under which the onset of stepping occurs earlier. In the previous study, the initial inclination was varied in a 'normal' range, i.e. approximately between 10 and 25°, and the instruction was to walk to recover the balance (similar to the present Control condition). The swing phase duration also varied in a 'normal' range, i.e. approximately between 280 and 200 ms. When a short swing phase duration was induced either by biomechanical constraint, as in GreatIncline condition (160 ms), or by a cognitive process involved in the evaluation of risk of fall, especially when the recovery of balance becomes more challenging as in the ShortStep condition (140 ms), an earlier onset of stepping occurred. The great initial inclination in the GreatIncline condition at the time of release gave rise to a higher forward CoM acceleration to which the subject has to make high-frequency steps (i.e. short swing phase duration) to recover balance. Although the subject's initial inclination was similar between the ShortStep and the Control conditions, i.e. the postural perturbation was similar, the risk of fall in the ShortStep condition was higher because the short-steps demand made the CoM position still ahead of the feet after heel-contact. Therefore subjects can fully recover balance with high step frequency. In the GreatIncline condition, the risk of fall is also obviously high because of the initial body lean. Moreover, the existence of a subjective threshold is suggested by findings of other works. The fear of a fall affected the maximum body lean angle in old subjects compared to young subjects, although subjects were securely maintained in a static inclined posture (Thelen et al., 1997).

Two of our experimental conditions, the LongStep and the FastStep did not show earlier onset of stepping whereas the CoM progression velocity increased. A possible explanation is that the step programming in relation to these specific instructions would concern the extent of step execution and not the time of triggering of the stepping. Moreover, there was no balance challenge in these two conditions as compared to the ShortStep or GreatIncline conditions.

The biomechanical context and cognitive process associated with the evaluation of risk of fall explain the difference in the value of onset latency of stepping between the current experimental paradigms. The earliest stepping time is measured in forward fall paradigm vs. all experimental conditions where steps were carried out from upright posture. In the forward fall paradigm, due to the initial body inclination a disequilibrium torque i.e. also the propulsive force was present at the time of release, and the stepping time would reflect postural adjustments associated with the equilibrium conditions required by the forthcoming movement. In natural gait initiation the disequilibrium torque (which induces the propulsive force, reciprocally) has to be self-generated and varied according to the intended progression velocity (Breniere et al., 1987). The higher the torque needed, the longer the time required to achieve it. Relative to these two extreme experimental situations, the support surface translation paradigm inducing steps represents an intermediate biomechanical constraint situation. In the scale of risk of fall, the risk of fall is null in normal gait initiation, except probably in pathological subjects, and is higher in the forward fall paradigm than in the support surface perturbation paradigm. In summary, the time of stepping depends on the combination of biomechanical constraints and cognitive process including subject's interpretation of the instructions and evaluation of the risk of fall.

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