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RESEARCH ARTICLE

Directional specificity of postural threat on anticipatory postural adjustments during lateral leg raising

Manon Gendre[1,2] · Eric Yiou[1,2] · Thierry Gélat[3] · Jean-Louis Honeine[4] · Thomas Deroche[1,2]

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Abstract This study explored the directional specificity of fear of falling (FoF) effects on the stabilizing function of anticipatory postural adjustments (APA). Participants ($N = 71$) performed a series of lateral leg raises from an elevated surface in three conditions: in the "Control condition", participants stood at the middle of the surface; in the two test conditions, participants were positioned at the lateral edge of the surface so that the shift of the whole-body centre-of-mass during APA for leg raising was directed *towards* the edge ("Approach condition") or was directed *away* from the edge ("Avoidance condition"). Results showed that the amplitude of APA was lower in the "Approach condition" than in the "Control condition" ($p < .01$); this reduction was compensated for by an increase in APA duration ($p < .05$), so that both postural stability and motor performance (in terms of peak leg velocity, final leg posture and movement duration) remained unchanged. These changes in APA parameters were not present in the "Avoidance condition". Participants further self-reported a greater FoF ($p < .001$) and a lower ability to avoid a fall ($p < .001$) in the "Approach condition" (but not in the "Avoidance condition") than in the "Control condition". The results of this study show that the effects of FoF do not solely depend on initial environmental conditions, but also on the direction of APA relative to the location of the postural threat. These results support the so-called Motivational Direction Hypothesis, according to which approach and avoidance behaviours are primed by emotional state.

Keywords Fear of falling · Postural threat · Motivational direction · Anticipatory postural adjustment · Motor control · Approach–avoidance behaviours

✉ Manon Gendre
manongendre@gmail.com

1 Université Paris Sud, Université Paris-Saclay, CIAMS, 91405 Orsay, France

2 CIAMS, Université d'Orléans, 45067 Orléans, France

3 Université Paris Ouest Nanterre, Paris, France

4 Università Degli Studi di Pavia, Pavia, Italy

Introduction

Recently, researchers in motor control have made considerable efforts to understand the relationship between emotion and postural control during both static (e.g. Azevedo et al. 2005; Facchinetti et al. 2006; Hillman et al. 2004; Roelofs et al. 2010; Stins and Beek 2007) and dynamic tasks (e.g. Naugle et al. 2011, 2012; Stins and Beek 2011; Gélat et al. 2011; Yiou et al. 2014; Fawver et al. 2015; Stins et al. 2015). In most of these studies, the theoretical framework used to predict the influence of emotion on postural control was based on the "Motivational Direction Hypothesis" established by emotion theorists (Lang et al. 1990, 2005; Lang 1995, 2000; Bradley and Lang 2000; Bradley et al. 2001; Lang and Bradley 2008). According to this "Motivational Direction Hypothesis", unpleasant events facilitate avoidance behaviours and impede approach behaviours, whereas pleasant events facilitate approach behaviours and impede avoidance behaviours. In these studies, emotion was typically manipulated by exposing participants to standardized pictures extracted from the International Affective Picture System (IAPS). These showed an unpleasant (e.g. mutilation, attacks), pleasant (e.g. erotica, baby faces) or neutral (e.g. usual objects, landscapes) valence (cf. also Fawver et al. 2014; Kang and Gross 2015 for endogenous manipulations of emotional states). At the onset or completion of the picture presentation, depending on the study, participants had to initiate gait or to perform a single-step forward or backward from the quiet standing posture so as to reduce (approach behaviour) or increase (avoidance behaviour) the distance between the self and the stimulus [cf. also Kang and Gross (2015) on sit-to-walk movement].

In these studies, postural control was investigated through so-called Anticipatory Postural Adjustments (APA), which correspond to the posturo-kinetic phenomena that occur before the triggering of a voluntary movement [cf. Bouisset and Do (2008), Yiou et al. (2012a) for recent reviews]. It is admitted that their function counters in advance the postural disturbance elicited by the voluntary movement itself and/or provides the dynamic conditions for whole-body progression. For example, during motor tasks that involve lateral leg raising (Mouchnino et al. 1992), leg flexion (Nouillot et al. 2000; Yiou et al. 2012b) or gait initiation (Lyon and Day 1997; Caderby et al. 2014; Yiou et al. 2015), the act of lifting the swing foot from the ground induces a drastic reduction in the base of support. If the centre-of-mass is not repositioned above (or closer to) the limits of the new base of support (the stance foot), the body tends to topple towards the swing leg side. This tendency is invariably counterbalanced in advance by a centre-of-pressure shift towards the swing leg during APA, which promotes the acceleration of the centre-of-mass in the opposite direction, i.e. towards the stance leg. As emphasized in the literature, mediolateral APA are essential to maintain postural stability (Lyon and Day 1997; McIlroy and Maki 1999; Caderby et al. 2014). APA also serve to provide the dynamic conditions for whole-body progression in the desired direction. For example, during gait or step initiation, APA along the anteroposterior direction include a backward centre-of-pressure shift that promotes the forward propulsive forces necessary to reach the intended centre-of-mass velocity (Brenière et al. 1987).

Exposing participants to affective pictures has been shown to induce disparate effects on anticipatory postural control. In comparison with pictures with an unpleasant valence, pictures with a pleasant valence have been shown to have no effect (Stins and Beek 2011), to have a facilitative effect (Naugle et al. 2011, 2012) and to have an impeding effect on APA associated with gait or single-step initiation (cf. Yiou et al. 2014 for erotic pictures). These disparate results may be ascribed to the fact that affective pictures may not evoke a unitary response of the postural system. For example, Naugle et al. (2011, 2012) emphasized that unpleasant pictures may elicit the activation of a “fight or flight” response, potentially invoking a conflict of motivations in humans. Participants may indeed engage and fight (approach motivation) or take flight and flee (avoidance motivation), probably depending on the nature of the aversive image (e.g. scenes of attack, violence and mutilation). In addition, Stins and Beek (2007) suggested that the viewing of unpleasant images may only be weakly coupled to posture, because images solely induce a “virtual” threat.

It is noteworthy that the above-reported studies on the relationship between emotion and APA have solely focused on the postural dynamics along the anteroposterior direction and related motor performance. In fact, the gait initiation model used to investigate motivation-oriented behaviours favours such a restriction, because APA along this direction serve to advance or withdraw the self from the affective stimulus presented to the participants. Hence, the question as to whether and how APA along the mediolateral direction and the related postural stability are modulated by emotion remains to be investigated.

It is well established that standing over an elevated surface provokes a unitary response of the emotion-posture system, i.e. a fear of falling (FoF). In this situation, people perceive the height of the surface as a “real” threat to posture because of the increased consequences of falling (e.g. Adkin et al. 2000; Carpenter et al. 2001, 2004, 2006; Brown et al. 2006a, b; Adkin et al. 2008; Hauck et al. 2008; Davis et al. 2009; Yiou et al. 2011). This FoF paradigm may offer a relevant alternative to the emotion-inducing pictures used to test the “Motivational Direction Hypothesis”. Thus, in our study, we asked participants to perform a whole-body movement towards or away from the edge of the elevated surface. To date, only three studies have used this paradigm to investigate the influence of FoF on APA associated with a voluntary whole-body task, namely through rise-to-toes (Adkin et al. 2002; Zaback et al. 2015) and leg flexion (Yiou et al. 2011) tasks. These studies reported that FoF induces a reduction in APA amplitude that may (Yiou et al. 2011) or may not (Adkin et al. 2002) be compensated for by APA of longer duration. However, these studies did not investigate the effect of the direction of the whole-body movement relative to the postural threat location (edge of the surface) on APA, because movements were systematically oriented in the same direction, i.e. towards the threat. For example, in Yiou et al. (2011), participants stood with the lateral side of their stance foot at the edge of an elevated surface and with the toes at the forward edge. The postural threat was therefore mainly bi-directional (i.e. directed laterally towards the stance leg side and anteriorly). But, because the surface was relatively narrow (44 × 30 cm), it is not excluded that the postural threat was, in fact, multi-directional, i.e. simultaneously directed towards the swing/stance leg side and anteriorly/backwardly. Because the APA for leg flexion were systematically directed laterally towards the same surface side, the relationship between APA direction and postural threat location, if any, could not be revealed. To date, similar remark can be formulated in regard to all previous studies focusing on the influence of postural threat on postural control (e.g. Adkin et al. 2000, 2002, 2008; Carpenter et al. 2001, 2006; Brown et al. 2006a, b; Hauck et al. 2008; Davis et al. 2009). Therefore, it is not known from these studies whether APA parameters are dependent on the direction of the whole-body movement relative to the postural threat location—as would be expected from the "Motivational Direction Hypothesis"—or, conversely, whether APA are direction-independent, being solely sensitive to specific environmental parameters (e.g. surface height and edge proximity).

As stressed in the literature (e.g. Brown and Frank 1997; Carpenter et al. 1999, 2001; Adkin et al. 2002; Yiou et al. 2011), understanding the modalities of FoF effects on postural control is clinically relevant, because it may, in part, explain the postural changes observed in people with balance deficits. For example, an FoF might be more important when injured or elderly people move their body laterally towards their affected or most frail side (e.g. due to a unilateral hip or shoulder fracture, or hemiparesis) or towards the side affected by a history of falls, than when they move towards their unaffected side. Such a directional effect might potentially exacerbate postural asymmetries during motor tasks that involve a sideways shift (e.g. locomotion), with negative consequences on postural stability. In addition, it is known that sideways falls are more common in older adults compared with falls in other directions and are associated with an elevated risk of hip fracture (e.g. Maki et al. 2000; Maki and McIlroy 2006). The influence of FoF on the control of lateral stability may thus be an important area for fall-preventative intervention in this population.

Thus, this study aimed to investigate the directional specificity of FoF effects on the stabilizing function of APA during a lower limb task. Participants purposely performed series of lateral leg raising at different positions on an elevated surface: in the middle ("Control condition") and with the swing or stance foot at the edge of the surface. These two latter conditions are referred to as the "Edge conditions". When the stance foot was positioned at the edge of the surface, raising the leg required a lateral whole-body centre-of-mass shift towards the surface edge during APA (i.e. APA are directed towards the threat) in order to maintain stability in the final posture: this condition was therefore termed the "Approach condition". In contrast, when the swing foot was positioned at the edge of the surface, raising the leg required a lateral whole-body centre-of-mass shift away from that edge during APA: this condition was therefore termed the "Avoidance condition". Based on the "Motivational Direction Hypothesis", APA are expected to be more impeded in the "Edge conditions" than in the "Control condition" (attenuation of the peak lateral centre-of-pressure shift). This impeding effect of postural threat on APA is expected to be more pronounced in the "Approach condition" than in the "Avoidance condition", thus revealing a directional specificity of FoF effect.

Methods

Experimental population

Two separate experiments were carried out with two different groups of participants ($N = 71$). Forty participants were involved in a preliminary experiment (17 males; 25 ± 7 years; 65 ± 14 kg; 172 ± 10 cm) that aimed to ensure that the experimental set-up could effectively prime a FoF. Thirty-one participants were involved in the main experiment (15 males; 24 ± 6 years; 67 ± 12 kg; 172 ± 7 cm), through which we collected kinetic and kinematic data. Different participants were involved in the preliminary and main experiments in order to bring about the most implicit motor response possible in the main experiment and to avoid any potential biases induced by the questionnaires themselves on motor behaviour. There are indeed available data in the literature showing that describing features of the task to be performed might influence the performance of that task (e.g. Chauvel et al. 2013). By doing so, our goal was thus to obtain the most "natural" behaviour as possible in the main experiment. All participants were healthy, active young adults. They gave written consent after having been informed as to the nature and purpose of the experiment, which was approved by local ethics committees. They completed a medical history and physical activity questionnaire. Exclusion criteria included any self-reported neurological, balance, musculoskeletal disorders and any history of falls in the past 6 months. None of the participants were regularly involved in height-related activities (e.g. rock climbing and skydiving). The study conformed to the standards set by the Declaration of Helsinki.

Induction of FoF, experimental set-up

In order to induce FoF, all participants ($N = 71$) were placed over a force-plate (AMTI, OR6-5, 50 cm × 50 cm) embedded in an elevated modular surface especially designed for the experiment. The environmental conditions were thus the same in the preliminary and the main experiments. Howe ver, the force-plate was active only in the main experiment to collect kinetics data. The surface was made of wood (8 cm thick), and its distance to the ground was 1 m. The lateral borders of the wooden surface could be raised to horizontal or lowered thanks to hinges (Fig. 1a). When these lateral borders were raised, the dimensions of the surface on which

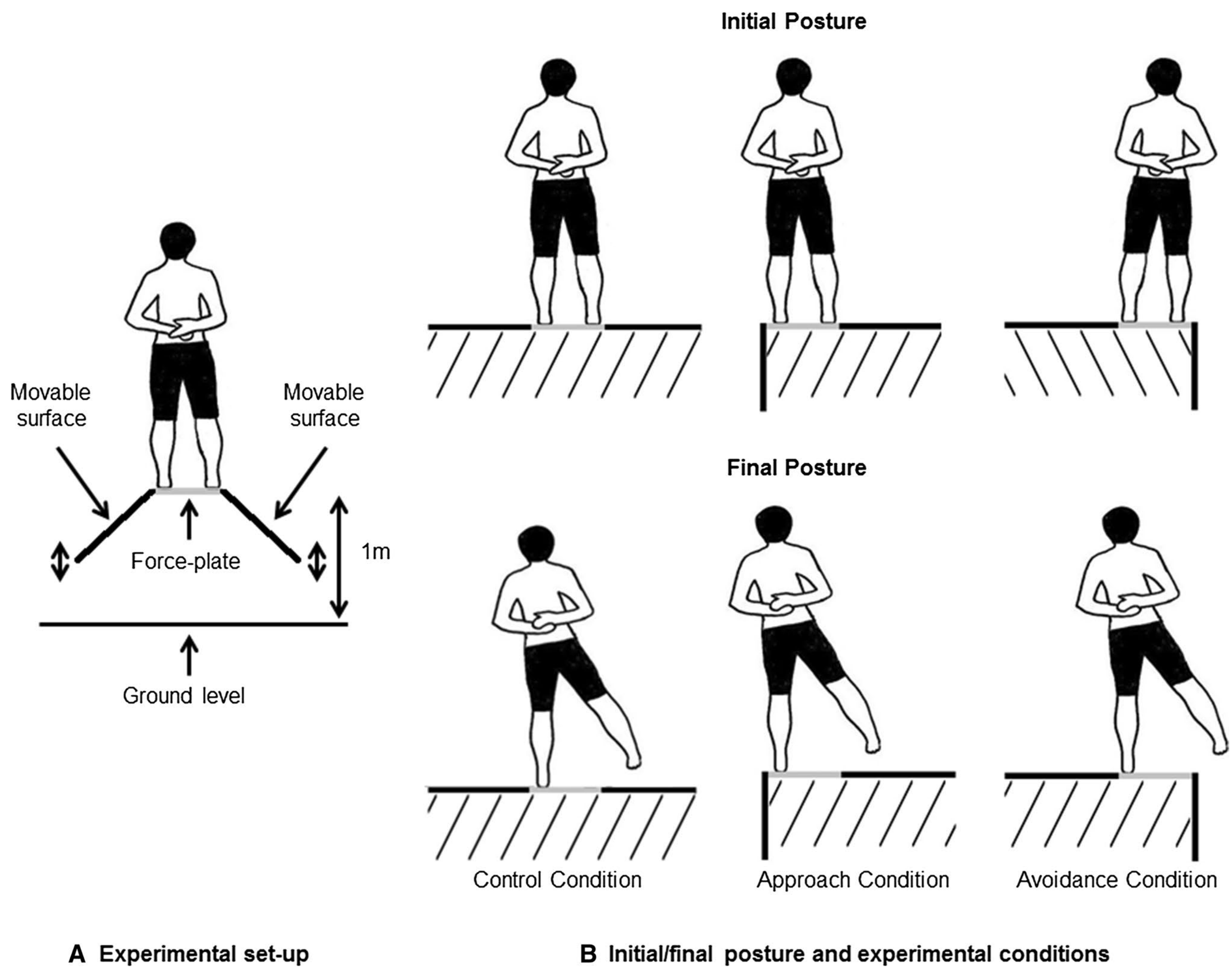

Fig. 1 Experimental set-up (**a**), initial/final posture and experimental conditions (**b**)

participants stood were maximal (150 cm long × 150 cm wide; unfolded surface). In this position, the force-plate was located in the middle of the surface. The distance between the four sides of the force-plate and the four edges of the surface was thus 100 cm in all directions (backward, forward, leftward and rightward). When one of the two lateral borders was lowered (folded surface), the surface dimensions were 150 cm long × 100 cm wide. One side of the force-plate was then located at the edge of the surface. The distance between the three other sides of the force-plate and the corresponding surface edge was the same as for the unfolded surface (100 cm). According to this experimental set-up, participants could be positioned in the middle of the unfolded surface or at the edge, depending on the condition. This set-up thus allowed us to vary the distance between the participant's stance/swing foot and the lateral edge of the surface, and thus to modulate the level of FoF.

Task and conditions

A similar task and conditions were used in the preliminary and main experiment. In the main experiment, only biomechanical data were recorded, while in the preliminary experiment, only psychological measures were evaluated. All participants ($N = 71$) performed a series of 10 lateral raises with their preferred leg at maximal velocity and as soon as possible after an auditory GO signal (reaction time situation). In the final posture, the angle between the stance leg and the elevated leg was approximately 45°. This angle was maintained for 5 s before participants returned to their initial posture. Unsuccessful trials correspond to trials where participants could not maintain the final unipodal posture for 5 s. These unsuccessful trials were discarded from analysis and immediately repeated. The motor task was performed in three conditions, which differed only in terms of the position of the participant on the elevated surface (Fig. 1b). In the "Control condition", participants stood over the force-plate located in the middle of the unfolded surface. As stated above, the distance between the sides of the force-plate and the edge of the surface was 100 cm in all directions (this distance was obviously slightly larger when considering the distance between the feet and the edge). This distance allowed participants to safely step over the surface in all directions to recover balance if necessary. In the "Approach condition", the lateral border of the surface beneath the stance foot side was lowered. The lateral side of the stance foot was then located at the edge of the surface. The distance between the lateral side of the stance foot and the lateral edge of the surface was approximately 2 cm. In the "Avoidance condition", the lateral border of the surface beneath the swing foot side was lowered. The lateral side of the swing foot was then located at the edge of the surface. These two latter conditions corresponded to the "Edge conditions". As stated in the Introduction, raising the leg required that the centre-of-mass be shifted towards the lateral edge of the surface in the "Approach condition"; however, in the "Avoidance condition", it is shifted away from the lateral edge during APA.

In order to avoid the effect of practice on movement production, each participant first performed a series of 20 lateral leg raises at ground level (not recorded) before experimental conditions were put in place. The instructions provided for these practice trials were the same as described above for the experimental conditions. A two-minute rest was imposed between the "Control" and "Edge" conditions. No harness system was used; however, two spotters were present to prevent any actual falls (Carpenter et al. 2006; Yiou et al. 2011).

All 71 participants performed the "Control condition". In order to avoid the effects of fatigue, and to further avoid the practice effect, only half of the participants involved in the main experiment ($N = 15$; 8 males; 25 ± 7 years; 174 ± 6 cm; 67 ± 11 kg) performed the "Approach condition"; the other half of the participants ($N = 16$; 8 males; 24 ± 5 years; 171 ± 8 cm; 68 ± 13 kg) performed the "Avoidance condition" only. Similarly, only half of the participants involved in the preliminary experiment performed the "Approach condition" ($N = 20$; 9 males; 21 ± 3 years; 172 ± 10 cm; 62 ± 10 kg); the other half performed the "Avoidance condition" only ($N = 20$; 8 males; 29 ± 7 years; 172 ± 9 cm; 67 ± 17 kg).

Initial posture

In each condition, participant stood barefoot with feet shoulder width apart and arms crossed behind their backs (Fig. 1b). The location of each foot was marked on the platform. These marks were used as a visual reference for participants to position themselves under the supervision of the experimenters. For each participant, these marks were the same in the "Control condition" and the two "Edge conditions". Participants were required to evenly distribute their weight between the legs. In each condition, participants directed their gaze ahead towards a target (4 cm in diameter), which was placed at eye level 5 m in front of the participants. The participants were repeatedly reminded of the task constraint instructions.

Biomechanical recordings

We used the force-plate to record the ground reaction forces and moments for 31 participants in the main experiment. Movement kinetics was analysed along the mediolateral and the anteroposterior direction. However, it was found that the amplitude of movement kinetics along the anteroposterior direction was negligible as compared to the mediolateral direction. For example, along the anteroposterior direction, the centre-of-mass velocity at foot-off and the peak velocity of the centre-of-pressure during APA were <3 % of the same variables calculated along the mediolateral direction. This result was in fact expected since the leg raises were directed along the mediolateral direction. Therefore, only data related to this latter direction were reported in the present study. Instantaneous acceleration of the centre-of-mass along the mediolateral direction (y''_G) was obtained with the ratio [ground reaction force/subject's mass] following Newton's second law ($\Sigma F = my''_G$, where ΣF: sum of external forces applied to the whole body; m: body mass). The centre-of-mass velocity was obtained through simple numerical integration of the centre-of-mass acceleration using integration constants equal to zero, i.e. initial velocity and displacement null (Brenière et al. 1987). Instantaneous displacement of the centre-of-pressure along the mediolateral direction (yP) was computed using the formula:

$$yP = \frac{Mx + Fy \times dz}{Fz}$$

where Mx is the moment around the anteroposterior direction; Fy and Fz are the mediolateral and vertical ground reaction forces, respectively; dz is the distance between the surface of the force-plate and its origin.

A reflective skin marker (9 mm in diameter) was placed on the malleolus of the swing leg. A V8i VICON eight-camera (Mcam2) motion capture system (Oxford Metrics Ltd., UK) was used to record swing foot kinematics along the vertical direction. Kinematic and kinetic data were collected simultaneously at a rate of 500 Hz. Data acquisition were controlled by a custom-made program written in Matlab™ (Version 5.3–R11) (The MathWorks Inc., USA). Data acquisition was triggered 4 s prior to the acoustic GO signal, which allowed post hoc calculation of the centre-of-mass position in the initial posture.

Biomechanical dependent variables

We considered variables related to the initial and final posture, APA and focal movement performance. The mediolateral position of the centre-of-mass in the initial quiet standing posture was estimated with the mean centre-of-pressure position during a 250-ms time window prior to the GO signal (McIlroy and Maki 1999; Yiou et al. 2011). The reaction time of the motor task corresponded to the time between the GO signal and the onset-rise of the mediolateral centre-of-pressure displacement trace (t0; Fig. 2). This onset-rise corresponded to the time when the centre-of-pressure displacement trace exceeded the mean baseline trace value (±2 standard deviations). The duration of APA corresponded to the time between t0 and foot-off time (t1), and t1 corresponded to the instant when the mediolateral centre-of-pressure trace reached a plateau. APA amplitude was estimated with the peak of mediolateral centre-of-pressure displacement during the APA time window and with the centre-of-mass velocity at foot-off (e.g. Hussein et al. 2013). The performance of the focal leg movement was estimated with the peak velocity of the swing malleolus, the duration of the swing leg execution and the position of the swing leg in the final posture (estimated with the swing malleolus marker). The shorter the duration of swing leg execution and the greater the peak swing malleolus velocity are, the higher the focal movement performance is. The duration of swing leg execution corresponded to the delay between t1 and the instant when the trace of the swing foot shift reached a plateau (t2). Finally, the position of the centre-of-mass in the final posture was computed as the mean centre-of-pressure position during a time window of 4 s following t2; postural stability in the final posture was estimated as the mean velocity of the centre-of-pressure during this time window (total centre-of-pressure shift along the mediolateral direction/4 s). The larger this velocity is, the lower the postural stability is (Raymakers et al. 2005).

Evaluation of FoF, balance confidence and coping efficacy

There is evidence that psychological measures relating to gait and balance are task-specific (Carpenter et al. 1999) and that there is a need to involve independent evaluation tools to measure balance confidence and FoF. As such, task-specific tools have been developed, which are sensitive to change in postural threat and related to concomitant change in postural control (Carpenter et al. 2006). Self-reported perceptions were assessed in each experimental

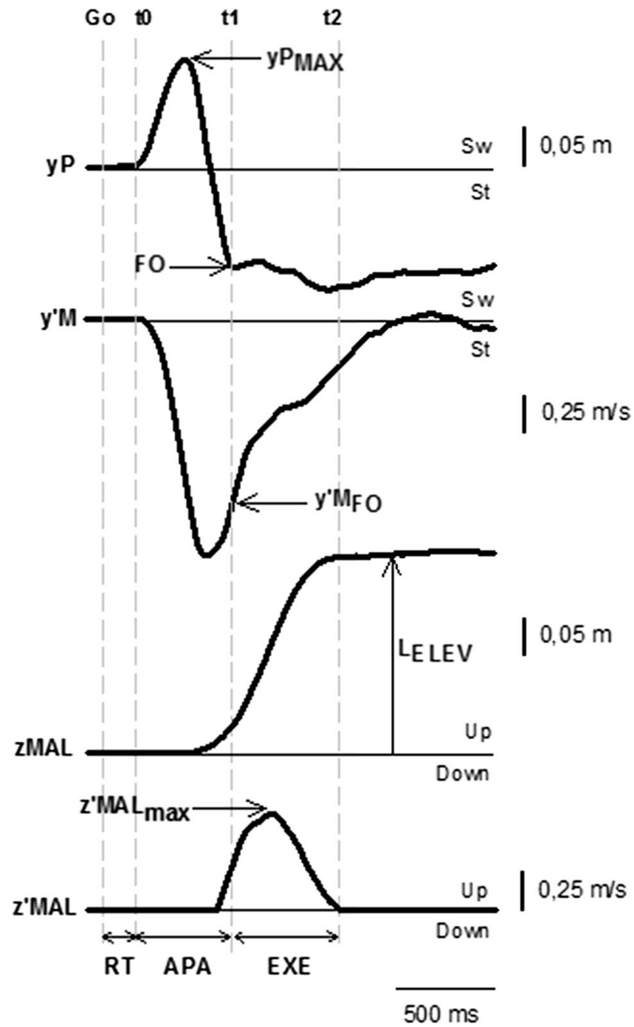

Fig. 2 Typical biomechanical traces of the lateral leg raising task and presentation of the main variables (one representative participant in the “Approach condition”). *Legends of traces*. yP, y’M: mediolateral displacement of the centre-of-pressure and mediolateral velocity of the centre-of-mass; Sw, St: swing and stance leg side. Main variables. zMAL, z’MAL: vertical displacement and velocity of the malleolus; yP_{MAX}, FO, $y'M_{FO}$, L_{ELEV}, $z'MAL_{max}$: peak of mediolateral centre-of-pressure shift, foot-off, mediolateral centre-of-mass velocity at foot-off, leg elevation and peak of vertical malleolus velocity. RT, APA, EXE: reaction time, anticipatory postural adjustments and leg execution phase. *Vertical lines*. GO, t0, t1, t2: onset of acoustic signal, onset of biomechanical traces variation, foot-off and onset of leg stabilization

condition. Balance confidence and FoF were assessed prior to the task. Participants rated how confident they felt and how fearful they felt using a 100-mm visual analogue scale (VAS) anchored by two labels: low levels of confidence and fear on the left side, and high levels of confidence and fear on the right side. By using an incremental scale between 0 % (“not at all”) and 100 % (“completely”), participants were also required to estimate their coping efficacy through their ability to avoid a fall, maintain concentration, overcome worry and reduce nervousness about balancing or falling during the experimental task.

Statistics

A mixed model 2 × 2 ANOVA was conducted with edge Proximity (Control vs. Edge) as a within-subjects factor and edge Direction (Approach vs. Avoidance) as a between-subjects factor. When necessary, follow-up analyses were carried out using Tukey's test. The level of statistical significance was set at $\alpha = .05$.

Results

Unsuccessful trials

There was no significant effect of Proximity, Direction and Proximity × Direction interaction on the percentage of unsuccessful trials. This percentage was 18 ± 1 % (mean value for all conditions together).

Description of the biomechanical traces

The biomechanical traces obtained from the force-plate and from the motion capture system were globally similar in the three experimental conditions (Fig. 2). Therefore, only the traces in one condition ("Approach condition") were reported. Swing foot-off was systematically preceded by dynamic phenomena along the mediolateral direction that corresponded to APA. These APA included centre-of-pressure displacement towards the swing leg side, which promoted centre-of-mass acceleration in the opposite direction, i.e. towards the stance leg side (not shown in Fig. 2). The mediolateral centre-of-mass velocity increased progressively until it reached a peak value of a few milliseconds before the time of swing foot-off. Swing malleolus velocity sharply increased before stabilization in the final posture.

Influence of FoF on the postural and focal components of leg raising

Initial and final posture. Statistical analysis showed that there was no significant effect of Proximity, Direction or Proximity × Direction interaction on the initial and final centre-of-pressure position, nor on the final postural stability.

Anticipatory postural adjustments. Statistical analysis revealed a significant Proximity × Direction interaction on APA duration [$F(1,29) = 7.35$, $p < .01$]. Specifically, a post hoc test revealed that the APA duration was significantly longer in the "Approach condition" than in the "Control condition" ($p < .05$; Fig. 3). In contrast, APA duration was not significantly different between the "Avoidance condition" and the "Control condition". There was also a significant main effect of Direction on the peak of anticipatory mediolateral centre-of-pressure shift [$F(1,29) = 7.67$, $p < .01$]. A post hoc test revealed that this peak was smaller in the "Approach condition" than in the "Control condition" ($p < .01$). In contrast, there was no difference between the "Avoidance condition" and the "Control condition". There was no significant effect of Proximity, Direction or Proximity × Direction interaction on the reaction time and on the centre-of-mass velocity at swing foot-off.

Focal movement performance. There was no significant main effect of Proximity, Direction or Proximity × Direction interaction on the duration of focal leg movement duration, final leg position and peak velocity of the swing malleolus (Fig. 4).

Perceived balance confidence, FoF and coping efficacy. There was a significant main effect of Proximity on perceived balance confidence [$F(1, 38) = 44.01$, $p < .001$]. Participants evaluated their balance confidence as being weaker when standing at the edge than when standing in the middle of the surface ("Control condition"). Similarly, edge Proximity decreased participants' coping efficacy in terms of their ability to overcome worry [$F(1, 38) = 10.20$, $p < .01$] and reduce nervousness about balancing or falling during the experimental task [$F(1, 38) = 5.68$, $p < .05$]. In contrast, coping ability in terms of their ability to maintain concentration was not significantly influenced by edge Direction. Of particular interest, a significant Proximity × Direction interaction was found for the perceived FoF [$F(1, 38) = 4.09$, $p < .05$] and coping efficacy in terms of the ability to avoid a fall [$F(1, 38) = 8.84$, $p < .01$]. Participants reported a higher FoF ($p < .001$) and a lower ability to avoid a fall ($p < .001$) in the "Approach condition" (but not in the "Avoidance condition") compared with the "Control condition" (Fig. 5).

Discussion

This work investigated the directional specificity of FoF effects on the stabilizing function of APA during rapid lateral leg elevation. Based on the "Motivational Direction Hypothesis", APA were expected to be impeded to a greater extent in both "Edge conditions" (i.e. the "Approach condition" and the "Avoidance condition") compared with the "Control condition". With specific reference to this study, this impeding effect was expected to be more pronounced in the "Approach condition" than in the "Avoidance condition".

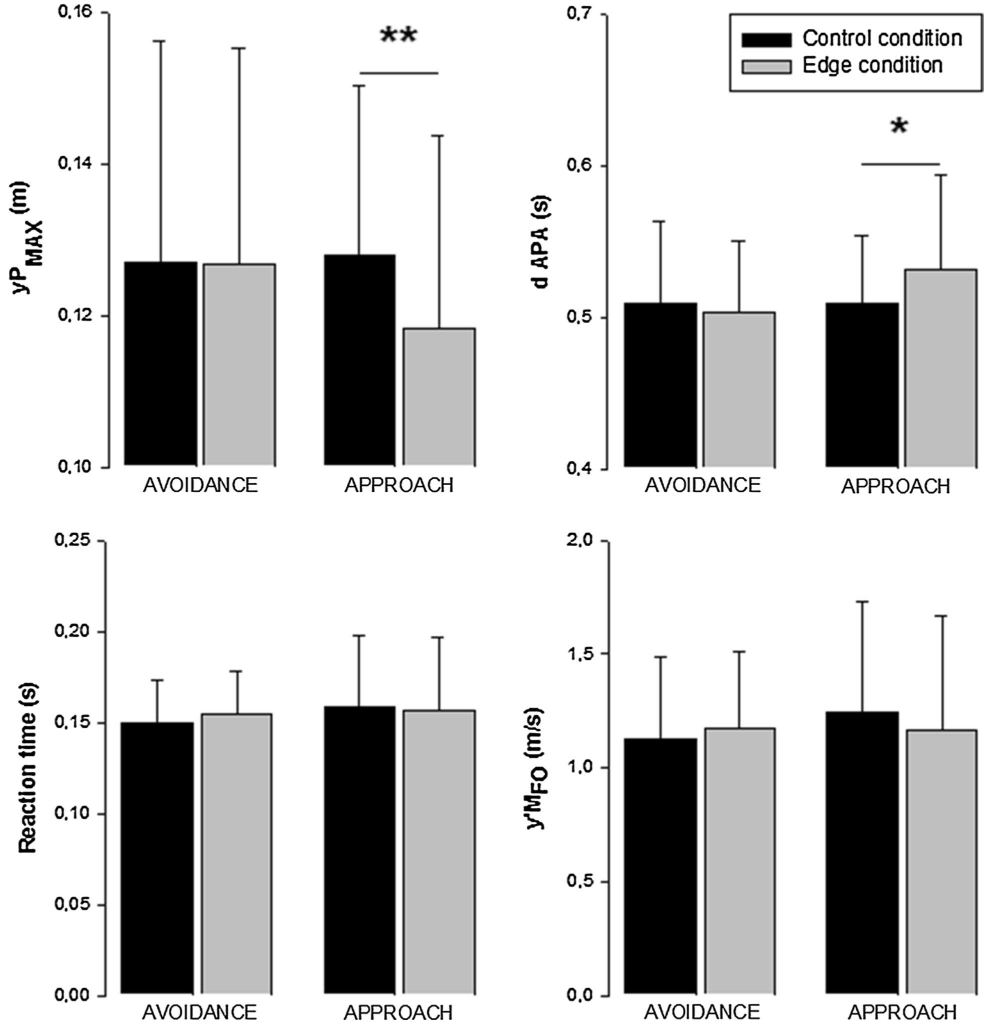

Fig. 3 Comparison of spatiotemporal parameters of anticipatory postural adjustments (APA) between the "Control condition" and each "Edge condition". yP_{MAX}, $y'M_{FO}$, dAPA: peak of mediolateral centre-of-pressure shift, mediolateral centre-of-mass velocity at foot-off and APA duration. *, ** Significant difference with $p < .05$ and $p < .01$

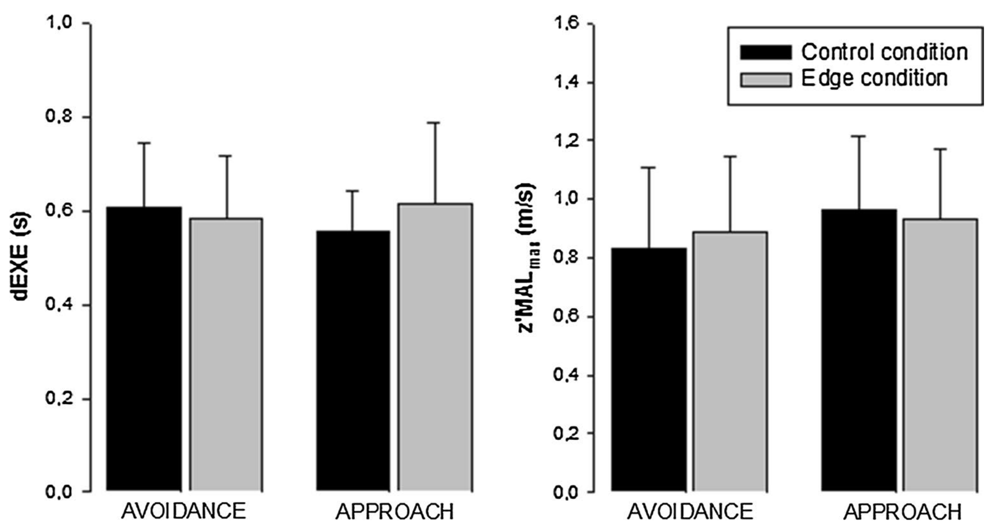

Fig. 4 Comparison of spatiotemporal parameters of focal movement between the "Control condition" and each "Edge condition". dEXE, $z'MAL_{max}$: duration of leg elevation and peak vertical malleolus velocity

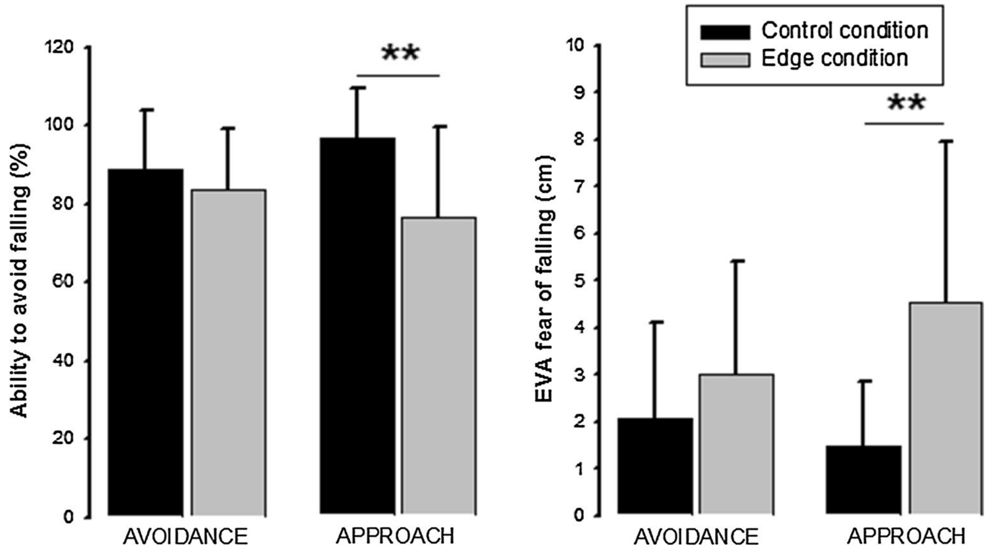

Fig. 5 Comparison of coping efficacy in terms of ability to avoid falling and self-report of fear of falling between the "Control condition" and each "Edge condition". ** Significant difference with $p < .01$

Adaptability of spatiotemporal APA features to FoF

To our knowledge, the effect of edge proximity on APA associated with a voluntary whole-body movement has only been investigated in one study (Adkin et al. 2002). In this study, participants performed a series of rise-to-toe movements at the edge of an elevated surface ("high edge condition") or 0.5 m away from the edge ("high away condition"; participants also performed the same task at ground level). This motor task implies a whole-body centre-of-mass shift towards the edge of the surface. The "high edge condition" can be compared with the "Approach condition" and the "high away condition" can be compared with the "Control condition". Adkin et al. (2002) found that the amplitude of the anticipatory backward centre-of-pressure shift was reduced in the "high edge condition" compared with the "high away condition". Thus, our finding that the peak of anticipatory mediolateral centre-of-pressure shift was reduced in the "Approach condition" compared with the "Control condition" is in line with this previous study. It reinforces the idea that, in the initial posture, the proximity of the surface edge has an impeding effect on APA through its influence on FoF. We further found that this reduction of APA amplitude in the "Approach condition" was accompanied by a lengthening of APA duration. Therefore, the propulsive forces that act on body centre-of-mass were applied for a longer time than in the "Control condition". During this additional time, the centre-of-mass velocity at foot-off (which is proportional to the time integral of these propulsive forces during the APA time window) could remain the same as in the "Control condition". Thus, we can propose that this lengthening of APA reflects the adaptation of the central nervous system to the reduced APA amplitude. APA along the mediolateral direction are directed towards maintaining stability in the final unipodal posture. Our finding that both the centre-of-mass position and postural stability in the final posture were similar in the "Control condition" and the "Approach condition" further supports the existence of an adaptive lengthening of APA duration. This concomitant increase in APA duration and decrease in APA amplitude may reflect tighter control of the centre-of-mass so as to minimize the risk of fall. Note, however, that more time was consequently required to reach the same initial velocity, which further highlights the impeding effect of postural threat on APA. This statement is in line with Bouisset and Do (2008) who proposed to estimate the efficiency of APA with the ratio [motor performance/APA duration], with a lower ratio indicating a decreased APA efficiency.

Interestingly, a similar adaptive strategy for APA lengthening was reported in Couillandre et al. (2002) and Couillandre and Brenière (2003) when gait initiation was performed from an initial standing posture on the toes. Compared with normal standing, the capacity to shift the centre-of-pressure backwards during APA to generate forward propulsive forces was reduced due to the diminution in size of the anteroposterior base of support. In this constrained posture, the authors found that the duration of APA increased, as was the case in our study. As a consequence, the forward centre-of-mass velocity reached at foot-off remained the same as in normal standing. Thus, participants could reach the same step length and peak forward centre-of-mass velocity at the end of the gait initiation process. A similar effect of support base reduction on spatiotemporal features of anteroposterior APA was also reported in Yiou et al. (2009). In their study, a bilateral pushing task was performed with the upper arms in a unipodal (constrained posture) or bipodal standing posture. In our study, however, the lower peak centre-of-pressure shift found in the "Approach condition" cannot be ascribed to any reduction in the size of the support base, although the adaptive mechanisms for compensation between APA amplitude and duration may very well be similar.

It is important, however, to stress that the compensations between APA duration and amplitude are not systematically found in the literature. For example, Adkin et al. (2002) reported that the attenuation of APA amplitude in the "high edge condition" was not accompanied by a lengthening of APA duration, as was the case in the "high away condition". Because these APA serve to propel the whole-body forwardly above the new base of support, the percentage of unsuccessful rise-to-toes trials (trials in which participants could not maintain the final posture on their toes) was greater, and the percentage of whole-body elevation on the toes was lower in the former condition. This was not the case in our study, i.e. the percentage of unsuccessful trials and the angle of leg elevation in the final posture were both unchanged across conditions. Based on their results and on the observation that individuals with Parkinson's disease (Diener et al. 1990; Frank et al. 2000) or cerebellar dysfunction (Diener et al. 1990, 1992) demonstrate alterations in both the amplitude and timing of APA, Adkin et al. (2002) proposed that the alteration of APA amplitude may reflect an FoF effect, while changes in the timing of postural adjustments may reflect an underlying pathology. Our findings, together with those of our earlier study on the effect of FoF on APA (Yiou et al. 2011), suggest, however, that changes in APA timing, especially APA lengthening, may reflect an adaptive strategy to compensate for a reduction in APA amplitude. In the study by Adkin et al. (2002), this discrepancy in the effect of FoF or postural threat on APA duration may possibly be ascribed to a greater level of FoF or postural threat induced by the "high edge condition". In their study, participants stood 3 m above the ground, whereas in our study, participants stood 1 m above the ground. The greater potential danger incurred by participants may thus have constrained the approach behaviour (i.e. the rise-to-toes) towards the postural threat to a greater extent than in our study. In such a situation, safety may have been detrimental to task execution.

Directional specificity of FoF effects on the postural and focal components of leg raising

The finding that the effects of edge proximity on both FoF and APA parameters vanished in the "Avoidance condition" (i.e. when the centre-of-mass was shifted away from the threat) is in line with the existence of a directional specificity of FoF effects, which supports the Motivational Direction Hypothesis. Note that this change in the direction of APA relative to the threat location was sufficient to completely offset the fear generated by edge proximity, while a simple attenuation was, in fact, expected as stated in the hypotheses. The effects of FoF are therefore not solely dependent on the initial environmental conditions (e.g. surface height and edge proximity); they are also strongly dependant on the direction of APA relative to the threat location.

This directional specificity of FoF effects only relates to postural response; the focal response (expressed in terms of peak leg velocity, movement duration and final leg position) remained unchanged across conditions. In other words, it seemed that the postural and focal components of the motor task were sensitive to FoF in a different way. A functional explanation may be given to interpret this apparent difference. It is noteworthy that raising the leg towards the edge of the surface (or away) does not represent a risk of imbalance because of the central nervous system's capacity to generate in fine efficient APA to counter the disturbance elicited by the focal movement, as argued above. Because this capacity is preserved in each condition, the focal performance may remain optimal whatever the direction of the leg movement. This statement is in line with the concept of posturo-kinetics capacity (Bouisset and Do 2008), according to which "voluntary movement involves a perturbation of body balance and a counter-perturbation has to be developed to limit the perturbation effects, which is a condition necessary to perform the movement efficiently" (Le Bozec and Bouisset 2004). A similar finding was revealed in our earlier study (Yiou et al. 2011), where a leg flexion task was performed at both ground level and on an elevated surface, i.e. FoF effects were not observed on the focal movement parameters, but on APA only. The nature of the threat used in our study may thus not have been suited to inducing a motivated directional response of the focal component, e.g. a response in the form of a decrease in peak of leg velocity in the condition where the swing foot pointed towards the threat ("Avoidance condition"). In contrast, displacing the whole-body centre-of-mass towards the edge of the elevated surface represents a greater threat for body integrity than does displacing the centre-of-mass away from this edge, because it is associated with an elevated risk of moving the centre-of-mass over the surface. Thus, the threat used in our study was well-suited to inducing a motivated directional response of the postural component only. The directional effects of FoF are, therefore, not globally applied to all components of the motor task by the central nervous system; instead, these effects are selectively applied to the task component that is most functionally linked to the threat, i.e. in our study, the postural component. This selective effect allows an optimal focal performance to be maintained even under the most threatening condition. Although not directly connected with our study, this latter result may be discussed with regard to the different models of coordination between posture and movement that are put forward in the literature (e.g. Massion 1992 for review): (1) the "hierarchical model", in which APA and focal movement are the results of a single motor command; and (2) the "parallel model", in which there are two independent motor commands. According to the hierarchical model, the effect of a FoF might be expected to extend to both the postural and focal components of the task. The observed decoupling of these effects on the two components of the leg elevation task thus clearly favours the parallel model. This statement is in line with conclusions drawn in recent studies (e.g. Robert et al. 2007; Ilmane and LaRue 2011), which were based on various whole-body movements (e.g. ball throwing, reaching beyond arm's length). Now, it can be recalled that each participant of the present study first performed a series of 20 lateral leg raises at ground level (not recorded) before experimental conditions were put in place (cf. "Methods"). It is not excluded that the postural and focal component of the task would be both affected by FoF if no practice trials were provided. Change in the control of complex movements with practice has indeed been reported in the literature (e.g. Yiou and Do 2011). Future studies will investigate the influence of task repetition on the relationship between FoF and the control of posture and movement.

Conclusion

In conclusion, our study suggests the existence of a directional specificity of FoF effects on the stabilizing function of APA associated with rapid lateral leg raising. This directional effect was in line with the predictions made by the Motivational Direction Hypothesis, i.e. APA amplitude was more depressed in the "Approach condition" than in the "Control condition" and this effect completely vanished in the "Avoidance condition". The impeding effect on APA amplitude in the "Approach condition" was compensated for by a longer duration of APA so that the level of initial propulsive forces required to maintain final stability could be reached. Our results further showed that, in contrast to APA, leg performance was not sensitive to threat location, i.e. the directional FoF effects were selectively applied to the sole postural component of the motor task, thus suggesting that control of posture and movement remains independent during leg raising. The results of this study provide new insight into the relationship between FoF and balance control. They may contribute to a better understanding of the balance disorders in individuals with increased FoF, e.g. the elderly. They may also contribute to the prevention of the risks of fall in young healthy adults performing tasks on an elevated surface, e.g. professional or recreational workers.

Compliance with Ethical Standards

Ethical standards All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Human subjects This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent Informed consent was obtained from all individual participants included in the study.

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