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REVIEW/MISE AU POINT

Comparison between investigations of induced stepping postural responses and voluntary steps to better detect community-dwelling elderly fallers

Comparer les analyses des réponses posturales lors des pas de rattrapage et des pas volontaires pour mieux détecter les personnes âgées autonomes à risque de chute

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Summary In this paper, we review a physiological task that is predominant in preventing humans from falling, but that simultaneously also challenges balance: taking a step. In particular, two variants of this task are presented and compared: the voluntary step versus a step induced by an external and unpredictable perturbation. We show that, while these contribute different information, it is interesting to compare these. Indeed, they both are relevant in a global balance assessment and should be included within this, at the same level as tests usually dispensed in the clinical environment such as posturography. We choose to focus on the community-dwelling elderly population, to discuss means of early detection of risk of falls, in order to prescribe an appropriate prevention. An overview of posture-movement coordination and balance recovery strategies is also provided. Finally, a working hypothesis is suggested

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Compensatory postural adjustments (CPA)

on how ''compensatory protective'' steps are controlled and how their evaluation could bring additional information to the global balance assessment of risk of fall.

MOTS CLÉS
Chute ;
Personnes âgées autonomes ;
Rattrapage de l'équilibre ;
Faire un pas ;
Ajustements posturaux anticipés (APA) ;
Ajustements posturaux compensateurs (APC)

Résumé Dans cet article, nous passons en revue une tâche prédominante dans la capacité des humains à se prémunir de la chute et qui, dans le même temps, met en jeu l'équilibre : faire un pas. Plus particulièrement, deux variantes de cette tâche sont présentées et comparées : le pas volontaire et le pas provoqué par une perturbation à la fois externe et imprévisible. Nous montrons que si les informations qu'elles apportent sont différentes, il est intéressant de les comparer. En effet, ces tâches restent toutes les deux pertinentes au regard d'une évaluation globale de l'équilibre et nécessitent d'en faire partie, au même titre que des tests plus classiques dispensés en clinique comme la posturographie. Nous avons choisi d'orienter notre revue vers une population de personnes âgées autonomes, afin de discuter d'un moyen de détecter au plus tôt le risque de chute pour être en mesure de prescrire une prévention adaptée aux personnes à risque. De rapides rappels sont aussi fournis sur comment se coordonnent la posture et le mouvement ainsi que sur les différentes stratégies de rattrapage de l'équilibre. Enfin, nous proposons une hypothèse de travail sur comment les pas « protectifs compensatoires » sont contrôlés et comment leur évaluation pourrait compléter les informations sur l'évaluation globale du risque de chute.

Introduction

Fall and risk of fall

Falls are a major and concerning health problem for the elderly population, because they are responsible for body injuries (pains, fractures or death), psychological effects (fear of falling, depression) and sociological issues (loneliness, loss of independence, costs of medical care). As normal ageing is responsible for declines in muscular [46,47,6], sensorial [1,37] and neural control [48,44,11,25] systems, 1/3 of people aged 65 years old and more fall at least once per year [100]. Consequently, the elderly suffer from more severe consequences than young [93] and have been identified at an increased risk of falls [89,26]. Fall-related injuries also constitute an increasingly expensive public health concern with a future cost estimated at about 240 billion in 2040 [100,85].

Defining falls is not straightforward. Particularly for community-dwelling elderly adults, the circumstances leading to a fall must be considered. Thus, a definition could be ''an event, which results in a person coming to rest inadvertently on the ground or other level regardless of whether an injury was sustained, and not as a result of a major intrinsic or overwhelming hazard'' [89]. This definition could be completed with ''a fall involves an impact'' [31] with the lower level, showing ''a failure in recovery responses'' [81]. Indeed, during a fall the center of mass (CoM) is transversely and downwardly accelerated. Recovery responses that result in braking the CoM drop are necessary to prevent it. According to these clarifications, current recommendations take into account both the inadvertent character of the fall and the recovery responses [52].

Why do healthy community-dwelling elderly subjects fall? As a fall comes first from an unbalance, the system (i.e. individual's body) has to recover from this unbalance to restore equilibrium. Interestingly, Granacher et al. [27] distinguish ''steady-state'' balance (very stereotyped and predictable behaviors like vertical quiet standing or normal gait) from ''reactive'' balance (recovery from the perturbation of a steady-state involving an unpredictable reaction). This reactive balance corresponds to the automatic responses that allow deceleration of the drop of the CoM, avoiding the fall [34,50]. So, the mechanisms to prevent falls are inseparable from successful reactive recovery responses (see model in Fig. 1). In this way, paying attention to both balance recovery behavior and understanding its underlying mechanisms appear to be determinant in identifying current and future risk of falls [33]. This is particularly true for healthy community-dwelling elderly adults, in whom avoiding a fall could prevent the first event of a negative spiral leading to more complex problems.

Clinical identification of the risk of falls

The origin of falls is considered to be multifactorial. Many different clinical tests are available in the literature to assess different underlying balance mechanisms. While the topic of this paper is not to review these (see Mancini and Horak [53] for a review), we noticed that none of these assessments involve reactive recovery tasks, relying mostly on steady-state situations that concern known and predictable interactions with the environment. To our knowledge, only one assessment is available to test a balance recovery situation: the BESTest [37]. Likewise, many authors have recently emphasized that current clinical tests are limited in identifying balance capacities or risk of fall [53,64,94,30] and that methods identifying individuals at risk of fall are still needed [49]. In fact, while clinical assessments usually focus on identifying the impairment, it should be remembered that impairments alone do not lead to functional deficits, because subjects may be able

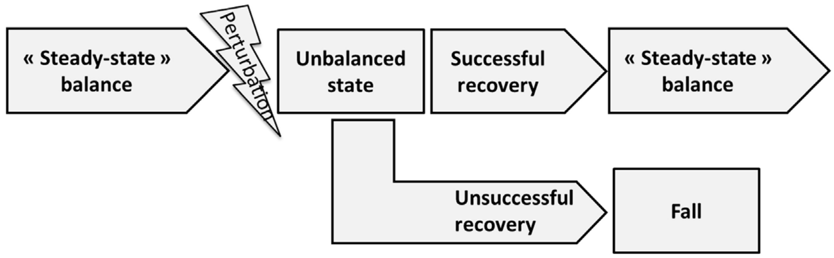

Figure 1 Balance recovery and fall model. A perturbation (lightning) of a ''steady-state'' leads to an unbalanced state of the body. Then, the subject will engage a recovery behavior to keep equilibrium with the objective to reach a new ''steady-state''. If the person succeeds to recover (straight way), he/she will avoid fall but if he/she does not (downward way) he/she will fall.

to compensate with other functions [33]. As the body is an exceptionally adaptive machine, effective assessment and rehabilitation of balance disorders requires an understanding of many systems (see Fig. 2). Notably, the balance control alone involves three objectives: maintaining posture, facilitating movement and recovering equilibrium [53]. Therefore, if balance assessment needs to be contextual and to test different variables, clinical evaluations should assess both steady states and reactive balance strategies [37,52,49,61,82]. In this way, making subjects perform reactive balance strategies could complement information on the current clinical assessment procedure. This situation is more difficult for the subject because it is closer to the fall, but may reveal early deficits in community-dwelling subjects, which could then be used to implement prevention methods long before any fall actually occurs [16].

Aims of the review

Reactive balance recovery has been much less studied than steady states. Particularly in the situation of reactive balance recovery, the system reacts both to the unpredictable and involuntary characters of the fall because it cannot predict in advance the unbalancing characteristics (moment, duration, intensity, direction, etc.) and does not wish to impact an external object or lower level. A decision to select the right recovery response has to be taken very quickly by the central nervous system (CNS), considering the current environmental context, movement possibilities and the goal of the task. Thereby, the analysis of a balance recovery response induced by an unpredictable perturbation surely provides much information on the ability of the subject to prevent the fall. However, using an unpredictable

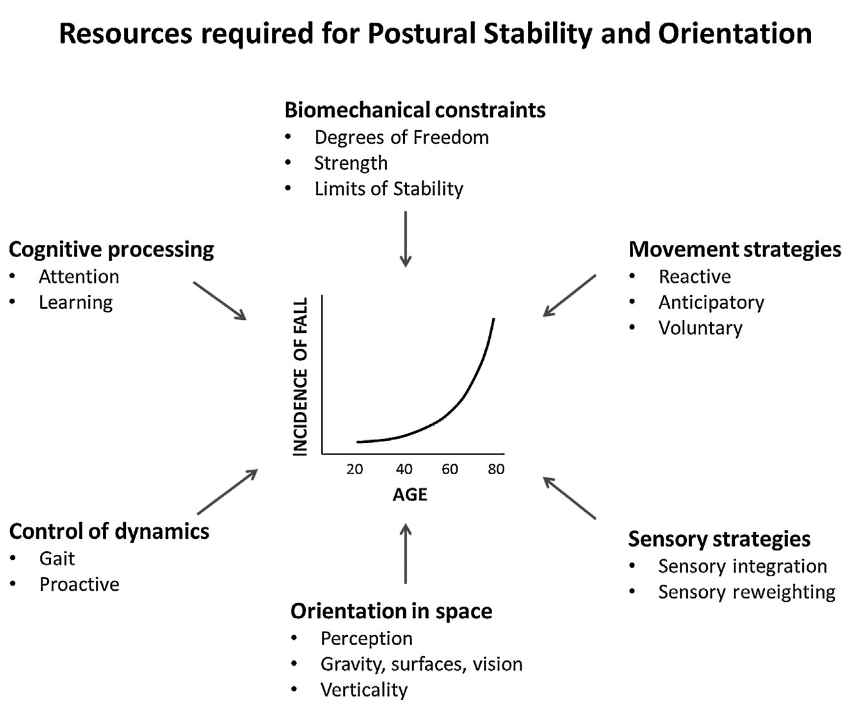

Figure 2 Multifactorial resources required for the effective control and execution of postural stability. All of these resources are involved in postural control and could be the source of deficits in balance maintain. They thus need to be considered in a postural evaluation to determine current and future risk of fall.
Adapted from Horak [33].

balance perturbation methodology to investigate this is still risky, costly and not easy to implement. In this paper, we will review data about how reactive recovery responses are controlled and executed, compared to voluntary triggered movement. Voluntary movements are simpler for the subjects and may reveal sufficient information about risk of falling. Firstly, a brief description on how posture is controlled and coordinated to movement will be provided. Then the discussion will concentrate on the results from the literature about recovery reactions, paying attention to the context in which the subject is placed. Finally, voluntary and compensatory actions tested in a same study are presented and discussed. This review focuses on a particular balance recovery strategy: taking a step. This strategy is prevalent and offers many mechanical advantages to prevent falls. The question is not to reach a consensus on how these two kinds of steps are executed and controlled, but to provide information about these two apparently similar tasks, and discuss how they could be used for clinical applications.

Posture, postural adjustments and recovery strategies

Posture and context characteristics that affect balance

Horak [33] defines postural control as a complex motor skill based on interactions of dynamic sensorimotor processes. Indeed, since humans can be viewed as mechanically instable systems, they constantly have to keep (i.e. recover) their equilibrium in order to not fall. So, equilibrium is a dynamic task constantly controlled by the CNS that has to deal with different constraints: biomechanical (e.g. height and speed of the CoM relative to the size and position of the base of support [BoS] [69,32]), movement strategies at the subject's disposal, time for cognitive processing and sensorimotor capacities (see Fig. 2). In particular, the two main posture functions are orientation and equilibrium [34]. If orientation is the relative positioning of body segments with respect to each other and the environment, equilibrium is the state in which all the forces acting on the body are balanced, so that the body tends to stay in the desired position and orientation (static equilibrium) or to move in a controlled way (dynamic equilibrium). Also, there are several sources of body destabilization: external forces (gravity, interactions with surrounding environment) and internal forces (generated by the body's own movement). According to the expectation of balance disturbance, the CNS use two principal context-dependent mechanisms, involving CoM and center of pressure (CoP) displacements, to maintain equilibrium while standing: compensatory postural adjustments (CPA) to unexpected disturbances and anticipatory postural adjustments (APA) accompanying voluntary movements (well described in the literature [12,56,71,3,4,10,79,80,42]). These are executed to offset — or at least reduce — the destabilizing effects of the perturbation, with active muscle forces and external indirect forces coordination, in a time-dependent manner. As we know that the CNS is directly impacted by advancing age, particularly in cognitive processing, postural adjustments — and consequently the quality of the response — are inevitably affected in elderly subjects even if they remain in good physical condition.

Postural adjustments used by the system

Anticipatory postural adjustments (APA)

Paradoxically, performing a voluntary movement, such as taking a step, produces reaction forces that affect all the linked segments of the body and can produce a loss of balance [34,56]. Nevertheless, the main advantage for the system is that this movement is voluntarily decided and initiated according to complete integration of the environment. Thus the CNS, through prior experience learning and adaptation, anticipates the mechanical effects of the forthcoming unbalanced state (i.e. modification of the BoS, displacement of the CoM). By muscular activity changes resulting in early activation and/or inhibition, the CNS adjusts magnitude and timing of internal forces. This action creates new mechanical conditions that will reduce the induced-by-the-individual perturbation effect on the general balance of the system and conditions the subsequent focal action [61,3]. As anticipation, these APA appear mostly prior (also simultaneously) to a voluntary limb movement. Because the perturbation is predictable, they are referenced as pre-planned and preprogrammed, using a feedforward mode [12,56,3]. There are 2 different views regarding their control mode: separate controllers for focal and postural commands [56] versus an unique controller with APA being an inherent part of the voluntary motor command [3,15]. Indeed, observations showed that APA can also be modified by task constraints and be programmed after the first feedback integration [14]. Consequently, they can sometimes be enhanced, reduced or totally absent [80,17,51,40]. Also, they can be scaled with respect to the anticipated consequence of the coming action [3]. When the perturbation is predictable, strong anticipatory activations are observed in all the muscles before the onset. Consequently, the motions of both the CoP and the CoM are strongly reduced resulting in a stability that is reached sooner and more efficiently [79,80]. To conclude, in order to maintain postural stability during the subsequent movement, the system is using APA in two ways:

- to maintain the individual's equilibrium ;
- to create ''sufficient'' mechanical conditions [3] to movement accomplishment (see [56] or [10] for a more complete review).

Compensatory postural adjustments (CPA)

Reactive control is the only recourse in the case of unexpected perturbation [50]. By reactive control, the only available information for the CNS results from a comparison between ascending sensory inputs and internal representation. CPA are muscle activations or inhibitions that cannot be predicted and are initiated by the ascending sensory signals [42,70]. Their main objective is to help in stabilizing the system by minimizing the perturbation effect, when the CNS has identified in which balance state the system currently is and — with primitive estimation — will be [14,35]. So, the body reacts after the onset of the perturbation with corrective recovery actions. CPA characteristics depend on the predictability, direction and magnitude of the perturbation, the dimensions of the BoS and the given instructions [79,80,14,35,57]. If the coming perturbation is unknown, and particularly if the timing is short, it is the responsibility of the CNS to re-weigh the objectives by order of priority to react efficiently [33,72]. Indeed, it has been shown that the CNS can reduce the magnitude of the CPA if the perturbation is known [15] or does not use excessive CPA muscular activity [28,29], preferring to use anticipatory activations to prevent the further destabilization of balance [80]. This last point may refer to the capacity of the CNS to switch control modes from feedback (CPA) to feedforward (APA) in order to select the most suitable strategy and increase the probability to prevent falling.

Conclusion

Several studies have highlighted the importance of APA in the control of posture and the relationship between anticipatory and compensatory components of postural control. Their functions are distinct: APA reduce the effect of the forthcoming perturbations with anticipated corrections while CPA help to restore the CoM position after the perturbation has occurred. Nevertheless, they are both muscular activations depending on predictability, direction and magnitude of the perturbation and given instructions. In the situation of body instability (i.e. not a ''well-known'' situation), APA can be reduced, thus maximizing use of CPA [4,62]; and inversely in very well-known conditions [80]. Indeed, the CNS is able to use information from both ascending sensory inputs and descending postural pathways to produce the best response in a minimum of time [15]. In elderly adults, APA are usually delayed and CPA larger than in younger subjects, but postural muscle recruitment is not affected [42]. Based on these observations, experimenters need to be very clear and careful on the choice of the balance perturbation characteristics and instructions given to the subjects. These should be clearly detailed when results are reported as they will clearly influence the postural adjustment activations that are different in fallers compared to non-faller subjects [78,90].

Movement strategies to recover balance

Balance function depends on strategies that individuals use to reach a steady state [27,33]. Nevertheless, the selection of the response strategy depends on many information: characteristics of the external perturbation, individual's expectations, goals and prior experience, central set (automatic responses based on expectation of stimulus and task characteristics), initial position, given instructions and the nature of the ongoing motor task that is disturbed. The focal responses to face the perturbation are rapid and automatic movement strategies used by the CNS whenever there is a disturbance applied to a body segment that tends to cause disequilibrium or changes in postural orientation [34]. Individuals have two distinct classes of strategies to reactively recover balance: ''fixed-support'' and ''change-in-support'' strategies (see Fig. 3). They are distinguished by modification or not of the contact configuration with the environment, i.e. a limb movement modifying the BoS [50].

Fixed-support strategies

When individuals are standing quietly without any additional support, the area under and between their feet represents their BoS. The so-called ''fixed-support'' strategies are performed to control the movement of the CoM without changing that BoS. They are usually used for very small and/or slow perturbations or particular context, in which the CNS detects that the system does not need to — or cannot — change the size of the BoS. Two main strategies have been identified: the ankle strategy and the hip strategy [35]. A large majority of the published studies focus on these. The ankle strategy is the most commonly response used during quiet stance. In this situation, the human body mechanically acts like an inverted pendulum (see Fig. 3), oscillating around the ankles. It consists of creating torques that move the CoP under the feet in order to accelerate or decelerate the motion of the CoM [35,97]. Interestingly, this is the first — and probably the least energetically costly — human response to postural perturbations, appearing even before a significant displacement of CoM [35] or stepping strategy initiation [40,57]. Likewise, if the CoM is for example projected forward, the CNS will automatically respond to move the CoP forward too, in order to reduce the CoM falling torque and to try to reverse its direction of displacement to drive it closer from its initial position. However, this strategy is limited both by the size of the foot and torques developed by muscular activation, that are reduced with age [43].

The hip strategy consists of oscillating around the hip joints in both frontal and sagittal plane (see Fig. 3) with a counter-rotation at the neck and ankle joints. This strategy mechanically allows creation of a horizontal force to accelerate or decelerate the CoM [35]. It is usually combined with an ankle strategy [34] and mostly seen in a particular context, where producing ankle torque is difficult, such as if the stance platform is narrow and/or the subject is instructed to not step. Nevertheless, it is not preferred when other strategies — like change-in-support — are available [50].

Change-in-support strategies

Change-in-support strategies allow, by definition, to modify and mostly to extend the area of the contact configuration (i.e. the BoS) after a balance perturbation. These reactions are prevalent against instability and play an important functional role in maintaining upright stance [50]. Indeed, increasing the BoS gives the opportunity to develop greater torques to break the fall of the CoM and provides a much larger degree of stabilization than fixed-support [52]. They also involve lower initial ankle flexors and extensor activations [15,14,29]. Thereby, the critical aspects the CNS has to deal with are spatiotemporal characteristics of the response preparation and execution (limb trajectory, latency and speed). There are 2 different strategies two: stepping and grasping. This review will focus only on the stepping strategy, which is a commonly executed strategy for maintaining standing balance in the natural environment [78]. This is not a strategy of last resort, particularly for elderly people [65,66,41], which is often initiated well before the body approaches the limits of the BoS and even when instructions are given to avoid stepping [50]. Thus, steps can be triggered even when the unbalance is small and a new steady state could have been reached without moving a limb.

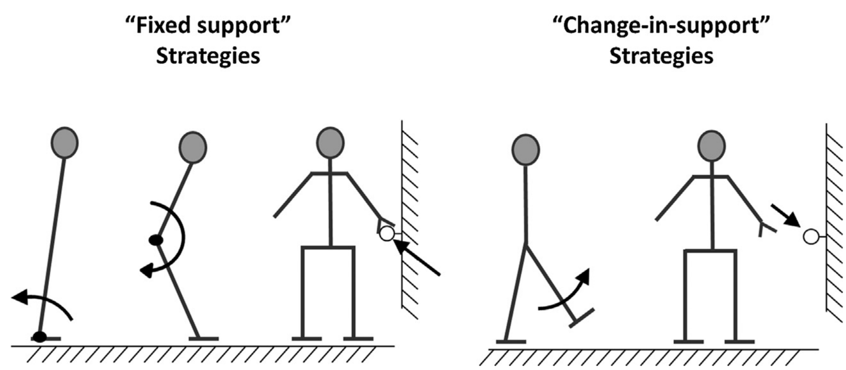

Figure 3 Fixed-support and change-in-support balance recovery strategies. On the ''fixed-support'' column, both ankle (left) and hip strategies (middle) are represented in the sagittal plane. On the ''change-in-support'' column, strategies are stepping (left) and grasping (right).
Illustration adapted from Maki and McIlroy [50].

However, in the case of a strong perturbation, stepping is the only recourse to recover balance [52]. Moving a foot in the fall direction of the CoM increases the size of the BoS and provides a better opportunity to slow the fall by surpassing ankle strategy limitations [58]. Take a step usually involves APA, which help to create the mechanical conditions to maintain stability during foot swing. However, if we only consider the APA preceding the foot-off (FO), these can be increased, reduced or absent in rapid reactive steps [40,57,62,58]. For McIlroy and Maki [60], APA inclusion delays the lifting and placement of the foot, jeopardizing stability. Therefore, investing postural adjustments in compensatory steps can reveal difficulties in elderly fallers to correctly perform APA during these reactive steps [78,90].

Choice of the strategy is context-dependent

The CNS selects from its repertoire of available solutions the most effective strategies to counteract the balance disturbance, taking into account different information provided by external and internal body sensors. Experimental studies have shown that the choice of the postural strategy is context-dependent. First, the postural response is clearly modulated by the instructions to change — or not — the BoS [15,14,57,59,21] and by the environment that can constrain the step trajectory [101,102]. Secondly the perturbation applied (voluntarily or externally induced) is just as important. As discussed before, a greater degree of induced perturbation will more often involve change-in-support strategies than very small ones [50], triggering earlier and shorter APA [14]. In addition, previous studies have established thresholds for triggering recovery steps where the subject is away from any surrounding object [65,68,39,5]. In that context, the CNS automatically reduces its possibilities to stepping, avoiding grasping. Moreover, the predictability of the perturbation [79,80,14,40,78,74] and the timing in which the body can develop the response are reported to be very important [11,92]. When the forthcoming perturbation is predictable, APA and muscular co-activations minimize the perturbation effects with short step initiation timings [79,80,40,78,58]. On the other hand, in uncertain conditions, APA are shortened with steps triggered even earlier [15,51,78] or elongated with some errors [40]. This may be because the plan could not have been fully prepared [62] or because the body over-responds [36]. Thus, the change in postural orientation due to the external disturbance changes the internal model of body dynamics in the central set [34]. Finally, the subject's ongoing physical and cognitive activity, age, and detection of the perturbation will play a role in the success of the recovery actions.

Conclusion

If the fixed-support strategies seem to be the earliest and the least costly that the CNS can use to reduce unbalance effects, change-in-support strategies offer many more mechanical advantages and are privileged even if they are more costly and present more of a challenge to balance. An interesting theory suggests a parallel, rather than a sequential, control of the two types of reactions [52,50]. The early ankle strategy activation persists, but change-in-support strategies remain predominant, after external and unpredictable balance perturbations. Two main reasons are suggested: the first step can be initiated well before the completion of the early fixed-support reaction and the ankle strategy may be ineffective in a situation where the CNS decides to step. This contradicts earlier theories advocating that a change-in-support strategy is triggered only after the CNS has identified the fixed-support strategies failure [35,19].

Also, if recovering from an unbalanced state strongly depends on physiological capacities of the subject, it should be kept in mind that the external context is just as important. In fact, many indicators integrated by the CNS such as planned and current postural orientation, available attention, muscular capacities, constraints on limb movement imposed by environment, the perturbation characteristics and the specific given instructions (if any) clearly impact both the choice of the strategy to use and the control mode. As the ecological situation of the fall is unexpected, a falls assessment must take place within a context that is as unexpected as possible [50], providing enough challenge to the balance in order to exhibit reactive recovery strategies [49]. To conclude, the context in which the subjects are placed, as the perturbation applied, have to be carefully chosen and should be reported with detail in balance studies.

Stepping: a particular strategy that challenges balance

We can differentiate two kinds of stepping actions, depending on the context in which the subjects are placed: voluntary steps and compensatory/reactive steps. The purpose of this section is to use knowledge about voluntary stepping, which has been well documented, to analyze the compensatory step and discuss whether these are comparable.

Voluntarily initiated stepping: a reference situation to study recovery stepping strategy

We are interested in examining how sufficient disturbance of posture can help to identify the risk of falling, using a balance recovery task induced by an unpredictable perturbation. However, using voluntary tasks as reference values could help to make a comparison, report similarities and/or differences and understand the underlying mechanisms. Actually, in the case of unperturbed stance, the subject can initiate a voluntary step in order to move a leg, for example to initiate gait or reach a target. Obviously, APA preceding this movement, being part of the central motor program, are always present [48,56,3,14,20]. In addition, this is a task where maximal active ankle torques can create the mechanical necessary conditions to raise a foot [71,29]. For example, a forward voluntary step is characterized by a forward and lateral displacement of the CoM toward the stance limb, caused by an initial backward and lateral displacement of the CoP [12,71,57,87]. This mechanism generates the propulsive force to move the whole body CoM forward and over the stance limb, anticipating the forthcoming modification of the BoS. Three main timing phases can be distinguished (see Fig. 4). Two phases concerning the initial stance phase are reported as *preparation* of the step: the reaction time ([RT] — only information processing duration with no measurable change in muscular activation) and the step preparation time (SPT) corresponding to APA before foot-off (FO). The SPT has occasionally been separated into two phases (loading then unloading) [71,78,87]. The third phase corresponds to the focal movement: the swing phase. Most of the studies focused only on the preparation phases and the ability to correctly load then unload the initial stepping leg, which will condition the ability to correctly swing the foot [54]. However, this correlation between APA and foot movement is seen when the velocity is slow and decreases when the movement needs to be performed rapidly [42]. Studies on elderly that have investigated voluntarily initiated movements usually showed a delay in the onset of the movement as well as smaller acceleration peaks and slower movement time [48,11,42,76,99].

Induced-by-perturbation step

Semantic suggestion: a ''compensatory protective'' step?

Four main terms are usually employed in the literature to qualify steps induced by an unpredictable balance perturbation: ''recovery steps'' or ''steps to recover balance'' [29,88,24,38,98,86], ''protective steps'' [49,78,66,41,73,45], ''reactive steps'' [27,16,7] and ''compensatory steps'' [11,50,57,13,55]. We suggest a term composed of two of these: ''compensatory protective step'' to describe steps induced by an external and unpredictable perturbation of the body. The term ''compensatory'' refers to the control mode (compensating the detected differences between how the system currently is and how it should be) while ''protective'' is better suited to the finality of the response (protecting the physical integrity of the subject by not falling).

Literature data on compensatory protective steps

In the case of an unpredictable and sufficiently strong perturbation, compensatory protective steps will be triggered. In contrast to voluntary steps, they involve both CPA and APA (usually reduced). Similar to voluntary steps, they have two main phases: preparation and swing (see Fig. 5). In particular, the preparation phase involves timing, when the decision to step — or not — is taken. Since many different paradigms have been designed to disturb balance, we will focus this review on results from the two most commonly used situations that disturb a quiet stance steady-state: platform movement and waist-pull. Despite providing relevant data, the tether-release paradigm [39,24,22] has been removed from this analysis. Indeed, in this paradigm, the only external mechanical action that disturbs the balance is the acceleration of the gravity, which is a well-known rather than an uncertain perturbation.

Mechanical description of the two paradigms. Platform movement involves that the subject stands on a moving platform that can translate or rotate in one or several directions. Mechanically, the subject is accelerated at the level of his/her BoS that drives the vertical CoM projection away from it. This paradigm has been used often, notably by authors that first reported the main balance recovery strategies [35,57]. It presents the advantage of being close to the type of balance disturbance occurring on everyday situations, such as in public transportation. However, the big inconvenience is that this is very costly, requiring a dedicated room. In addition, perturbation profiles are trapezoidal, with acceleration, plateau and braking varying in duration and jerk. Unfortunately, it is difficult to distinguish how accelerating and braking of the platform affect the balance recovery actions of the subject and particularly the braking part which is usually not completely reported in studies [9].

In waist-pull destabilizations the subject stands with a cable attached to the waist, where on the other side a weight can be dropped [49] or a motor can wind in the cable [73]. Mechanically, the force applied at the — more or less — CoM level of the subject tends to put the CoM into motion. This paradigm is not very ecological but is less costly than a motorized platform. Also, it presents the advantage of precisely measuring the perturbation applied to the subject. Indeed, it allows testing a multitude of perturbation durations that do not involve any re-stabilization phase related to a deceleration (compared to platform movement).

Results on observation of the step phases. All of the studies on compensatory protective steps reported an early modifiable ''automatic'' response [57,29,78] that follows

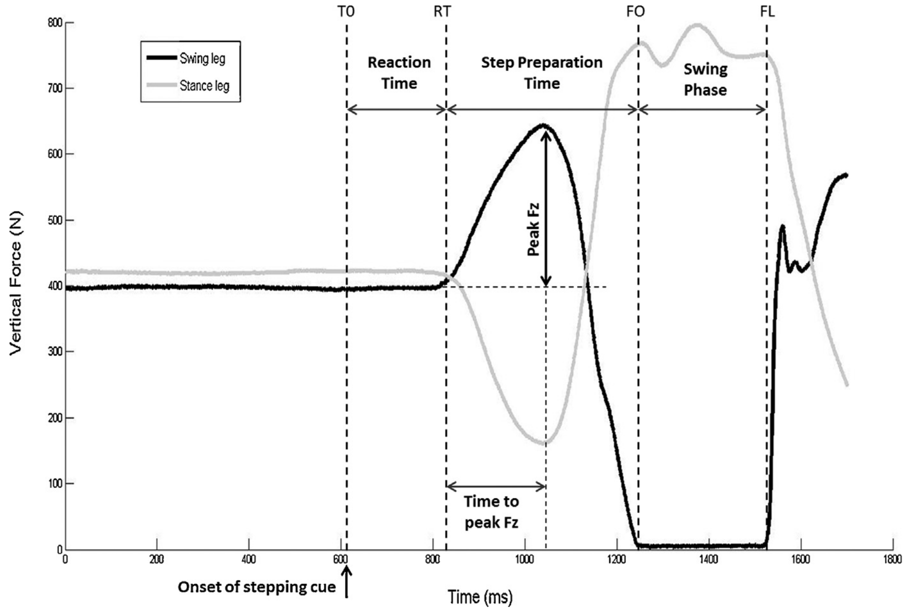

Figure 4 Illustration of the step timing phases in voluntary step. Figure shows the vertical ground reaction forces under the ''swing'' (dark grey) and ''stance'' (light grey) legs where, after a normal reaction time (RT — information processing and decision), a weight transfer time (SPT) starts from the first deviation. The swing leg is first loaded (increase in Fz vertical force that moves the CoP under) and then unloaded (decrease in vertical force) in order to raise it (when force reaches zero is the foot off [FO]). Vertical force under the stance leg is symmetrically opposed during the SPT phase. Finally, the stance leg supports almost all the weight during swing phase. T0 is the onset of the stimulation, while RT corresponds to the APA latency. FL is the foot landing, when force under swing leg starts to increase from zero.

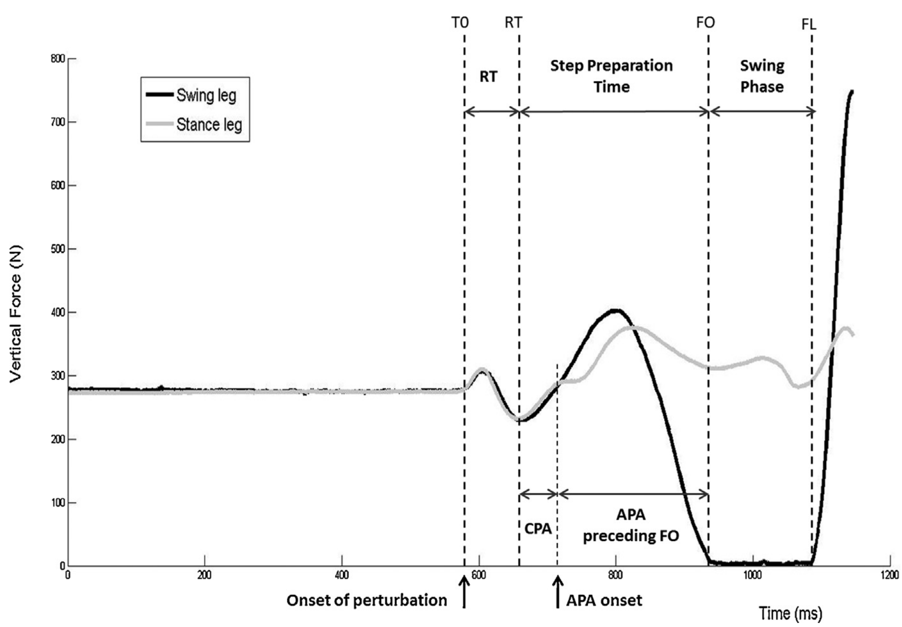

Figure 5 Illustration of step timing phases during a compensatory protective step induced by a forward square profiled waist-pull perturbation (force = 30% of the subject's body weight, duration = 200 ms). Figure shows the vertical ground reaction force under the ''swing'' (dark grey) and ''stance'' (light grey) legs. First, we see a passive mechanical loading-unloading under both feet during the reaction time (RT) when the CoM passively falls. Then, an ankle strategy identified as a compensatory postural adjustment (CPA) is automatically performed by both legs. Still during the SPT, the subject initiates a weight transfer action like in the voluntary step task, visible by the divergence of the two leg curves. Unfortunately, the time constraint is high, so coordination is not symmetrical and amplitude is lower than in voluntary step. Finally, the stance leg supports only half of the total weight during swing phase, resulting in a fall on the swing leg side during swing phase and a strong impact when landing.

the initial destabilization of the whole body. This helped to identify two phases before APA. First, a mechanical effect on the body resulting in a passive fall is seen. Then, this automatic response appears activating ankle muscles as the body sways in a direction, i.e. a CPA corresponding to an ankle strategy. Taking a look at the CoP displacement shows that its first move from initial position is in the direction of the perturbation, to follow the movement of the CoM [8]. This is seen when a step is taken [14,40,78,66,86,8] or not [35]. Then, when taking a step has been decided by the CNS, APA can be engaged or not [62,78,58,8] and, if they are, with very variable amplitude and duration [40]. Studies showed that the most important constraint is the timing remaining before the moment when the velocity reached by the CoM would be too high to be slowed and the its position too far from the BoS to be driven back. Consequently, the CNS is able — and will — reduce the preparation phase to quickly raise a foot to increase the BoS [15,62]. The CNS can disrupt this execution because the perturbation mechanically plays the role of the APA. Thereby, the system determines the priority of the actions according to the objective of the task, which is to stop the fall of the CoM. For that, it changes information priority during the task with a sensorial re-weighting [33,72]. Indeed, sensorial inputs influence the preparation phase prior to the stepping reaction [61,14,40] that may provoke a conflict between voluntary planned APA and actual state of the body that is changing [57].

Not many results are given about how the swing phase is specifically performed. However, we know that the duration is short [62] (about 140 ms compared to 200 ms for voluntary in young adults [8]) with limbs moving very fast [45] (mean peak of the swing foot velocity superior to 2,6 $m.s^{-1}$ [8]). Also, we noticed that subjects can ''fall'' on the side of the swing foot (Fig. 5). Moreover, data about the kinematics of the whole body could be interesting, like the body configuration at first step Foot Landing (FL), because this predicts the future success of the recovery [38,95]. These data could be a marker of the effectiveness of the recovery actions deployed by the CNS.

Community-dwelling age effects depends on the perturbation. Interestingly, only relatively small age effects on characteristics of the first recovery step (with no particular instruction on recovery behavior) have been reported on the response from platform movement. For example, elderly and young subjects have a similar RT [45] and the only strong difference between them is the probability of taking an additional step that is twice as high and more laterally directed in elderly subjects [61]. Thereby, the reduction in musculoskeletal capacity does not interfere in generating movement fast enough to recover balance [28,29]. Notably, Gu et al. [28] showed very small differences between young and elderly subjects, concluding that first ankle strategy responses used in reactive balance are submaximal and magnitude of joint torque are perturbation-specific.

On the contrary, in waist-pull, some elderly subjects are able to trigger the step even before young adults, probably because they pre-selected their recovering strategy independently of the actual body state [78]. Elderly also use multiple-steps strategy more often than young, to respond to external disturbance, initiating the stepping strategy at lower levels of instability [65]. These observations are probably due to reduced APA to trigger the first step and considered as a marker of a greater fall risk [67]. In medio-lateral destabilizations, elderly showed longer reactions with a greater proportion using crossed steps than loaded-leg-side steps but with many collisions [66,67]. In forward destabilizations, elderly fallers showed a longer SPT than non-fallers, regardless of the perturbation impulse and duration [90]. On the other hand, authors reported elderly subjects being as fast as young ones in taking protective steps [49] with similar SPT between elderly non-fallers and fallers [86].

If there is no consensus on the SPT phase being modifiable or not (probably because of the differences in context in which subjects were put), it is in this phase that we can see changes with regards to voluntary step. The presence — or not — of APA could indicate when the first actions coming from a choice to switch control mode are initiated. Indeed, by testing the uncertainty of balance context Rogers et al. [78] demonstrated that taking a step comes from a voluntary decision, because subjects are able to delay its triggering. They conclude that steps taken to compensate an unpredictable external perturbation are not a strategy of last resort. Testing compensatory protective steps in a waist-pull protocol implies adequate manipulation of the certainty of the perturbation. The ageing effect is more noted in the waist-pull than the platform movement paradigm, probably because platform perturbations are usually short in duration.

Conclusions about compensatory protective steps mechanisms

As a synthesis, the control of compensatory protective steps involves the same timing phases as voluntary steps but the big difference in term of behavior is during the SPT phase (see Figs. 4—6). First, the balance is externally disturbed so the body passively and mechanically falls, because of the time that the CNS needs both to get and to process sensory inputs indicating that balance is compromised. Then, an early automatic postural response, being very important in the maintenance of stability, is seen with activation of the ankle flexors and extensors [33]. This phase is typically a CPA, moving the CoP in the BoS to firstly reduce the fall of the CoM, which is — in this case — probably controlled by subcortical networks [14,45]. Indeed, a perturbation causing forward sway of the CoM will evoke early activations serving to arrest the forward progression of the CoM, but their latencies are too long to be reflexive and too short to be purely voluntary [14,58,23]. On the following, if the body still falls, the decision to take a step will be taken [78]. If the subject is in a totally unexpected situation, he/she will probably not develop APA and will step very quickly [57,62] or will try to use APA with more or less success [40,78,58]. These APA induce a weight shift (as in voluntary steps) but appear with considerable quicker latencies and both shortened duration and magnitude. This weight shift has been reported as one of the most frequent cause of falling if it is not correct [75]. These early postural components are modified because they are influenced by afferent information that can conflict within the planned strategy [14,58] (see Fig. 6).

Finally, the swing leg is raised and rapidly moves the foot in the direction of perturbation, to enlarge the BoS and provide greater braking torques. According to platform

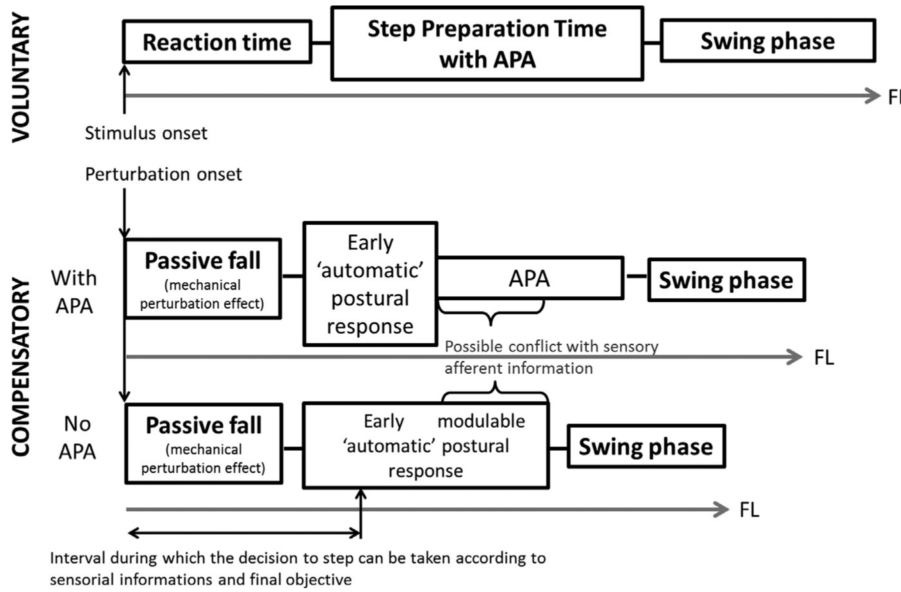

Figure 6 Control mechanisms of voluntary and compensatory steps. This represents the three step phases between perturbation onset and foot landing (FL). In compensatory protective steps, two situations are provided depending on use — or not — of APA preceding the foot off. Grey rows represent the total duration of the three phases. When APA are absent the foot is landed earlier than when there is, offering earlier opportunity to brake the fall of the CoM.
Based on information taken from [58] and [78].

movement and waist-pull literature, the SPT phase is clearly the one that is modified in compensatory protective steps, comparing to voluntary. Taking interest in this phase should help to identify elderly fallers, probably because it is during this phase that first reactions coming from a voluntary decision could modify the response.

Comparison between voluntary and recovery steps

This synthesis shows that compensatory protective steps and voluntary steps are similar in appearance: move a foot in a direction during the swing phase. Nevertheless, during voluntary steps the rate of progression of the CoM as well as the duration of the swing can be planned prior to movement onset at cortical level, with coordination between mediolateral and anteroposterior elements of stepping. Also, the current objective of the CNS is to use forces to accelerate the whole-body CoM and place it over the new forthcoming BoS. Thus, in voluntary stepping everything is known and under the control of the CNS. On the other hand, when the CoM movement is not predictable, this coordination is no longer possible. So, it is about evidence that the question of comparing them can be asked. Are those tasks really comparable? Can we consider that voluntary stepping is a good candidate, considering its facility for comparison with compensatory protective stepping, despite its potential limitations? To our knowledge, only four studies [49,61,45,8] investigated both tasks (voluntary and compensatory steps) with an objective to compare them. Other studies that used these two tasks were mostly concerned about how induced steps are planned and triggered. Their results are summarized in Table 1.

Review of the studies that compared both tasks

Every study reporting a comparison between voluntary and compensatory induced steps showed that compensatory reactions are much more rapid than volitional limb movement. This concerns every step timing phase, leading researchers to interpret its triggering as being mostly subcortical [15,45,8], with a predominance of the automatic early responses. APA are usually observed in compensatory protective stepping. However, their amplitude and duration are systematically strongly reduced [50,62] leading, in some situations, to the total disappearance of the APA. For comparable swing phase characteristics, shortening the preparation phase directly reduce the total step duration, i.e. the mechanical advantage of taking a step arises earlier [57]. Nevertheless, it is interesting to note that APA are always present when the instructions specifically ask the subject to step [61]. So, it can be considered that the presence of APA is mostly necessary to place the foot in a particular place instead of rapidly recovering the balance. Also, step execution could be preceded by a variable APA [61,15,14] revealing that the motor program and the afferent information dynamically interact to accommodate passive CoM velocity constraints. The swing phase remains shorter in compensatory protective steps, with similar but stronger kinematic patterns [45,8] and reduced muscular activations [15,29].

While the CoM displacement is similar [40], i.e. moved in the direction of the perturbation or the target, it is usually longer in compensatory protective steps, with the CoP acting differently between the two tasks. In voluntary stepping, its first move is always opposed to direction of the future displacement of the CoM [15,87] while in compensatory stepping it is in the direction of the perturbation

Table 1 Summarize of the studies comparing both voluntary initiated and compensatory protective step tasks. Abbreviation for voluntary steps (VOL), compensatory protective steps (PRO), older adults (OA) and young adults (YA) are used. Table has been organized to present results from study with young subjects only and then studies showing results for both young and elderly.

Comparison between strict voluntary initiated steps and induced compensatory protective steps							
Authors	Population	Stimuli used	Results of the observations (in PRO compared to VOL)				
			Reaction Time	Step preparation time	Swing phase	CoM and/or CoP	Complements
Burleigh et al., 1994	Young	PRO: platform VOL: platform	Shorter duration	Shorter APA amplitude	CoP displacement and swing leg muscle activations reduced	CoP first moving forward in PRO while backward in VOL	—
McIlroy and Maki 1996	Young	PRO: platform VOL: visual	—	APA shorter and always present when stepping is previously asked	Shorter duration	—	Temporal patterns stereotyped
McIlroy and Maki 1999	Young	PRO: platform VOL: visual	—	APA shorter and reduced or absent	Shorter duration	CoM falls more laterally and is not influenced by APA	—
Jacobs and Horak 2007	Young	PRO: platform VOL: visual	Shorter duration	Shorter duration with presence of multiple APA	—	CoM more moved forward	Errors on foot to swing with
Berthollet et al., 2014	Young	PRO: waist-pull VOL: visual	Shorter duration	Shorter duration	Shorter duration Similar but stronger kinematic patterns	—	Task finality different
Luchies et al., 1999	Young Elderly	PRO: waist-pull VOL: waist-pull	VOL: OA slower than YA	PRO: OA equal to YA	—	—	Tasks are too different
Rogers et al., 2003	Young Elderly	PRO: waist-pull VOL: visual	—	Unloading longer APA reduced or absent APA shorter in OA	—	—	PRO steps come from a decision
Lee et al. 2014	Young Elderly	PRO: platform VOL: cutaneous vibration	No age effect	Shorter duration Longer in OA	Swing leg moving faster	—	Subcortical regions involved

[15,40,8]. Also, it has been shown that the CoM tends to fall more laterally in compensatory protective steps and that APA are ineffective in reduce falling, producing a greater risk for the person [62].

Few studies have compared the postural responses in both tasks in healthy elderly. Only Rogers et al. [78] showed that aging changes the initiation triggering of both voluntary (with longer latency) and perturbation-induced (with shorter latency) steps associated with falls. Paradoxically to what it is usually observed in voluntary steps, shorter preparation timing is noticed in elderly subjects in compensatory protective steps compared to younger subjects [78,66,67]. Notably when the context is uncertain, elderly fallers probably pre-select a strategy and do not trust their—or have impaired—sensory inputs. Since much information about the control mechanisms have been extracted from experiments on young subjects, there is still a need about information on how ''normal'' ageing effects could impact upon balance recovery mechanisms, particularly for community-dwelling elderly fallers. An explanation of the low number of studies is the complexity of investigating compensatory steps (complex and costing assemblies, greater risk of injury for frail people, etc.).

Conclusions

To the question ''are voluntary and compensatory steps comparable?'' the response is no. The only visible similarity concerns the foot kinematics profile shapes during the swing phase, although the swing foot always moved faster in compensatory steps (larger velocity, acceleration and deceleration peaks) [8]. These tasks are different, firstly because of the shortening of each timing phase in compensatory protective steps [52,15,8]. The body reacts to a different context, as soon as it can, soliciting different control areas — cortical and probably subcortical [14,45] — in order to break the CoM acceleration due to the external perturbation. So, as a second point, the tasks are differently controlled using different initial information. Thirdly, the mechanics of these two tasks are different: in voluntary stepping, the subject has to accelerate his/her CoM whereas in compensatory stepping the subject has to break it [61,15,8].

Thus, Luchies et al. [49] reported no significant differences between young and elderly subjects in a compensatory protective step, concluding that investigating voluntary stepping, even if performed ''as soon and as quickly as possible'', does not reflect the ability to perform a compensatory step. A possible explanation could concern the ankle torques produced, which are high in voluntary [71], much more higher than in compensatory protective steps [29]. Data from the literature thus provide strong evidence that these two tasks are too different to draw conclusions on the ability to perform one from the assessment of the other [52,49]. However, they can both contribute interesting data to assess fall risk. Voluntary steps could inform on the ability of the individual to correctly choose and program an adapted response, notably the ability to organize APA. Compensatory protective steps would rather inquire about automatic subcortical control and the ability to compose a motor response in a very constraining context (i.e. a short time). If these two tasks are different, they have to be both investigated in clinical balance assessments for complete detection and prevention in community-dwelling elderly fallers.

Clinical utility of voluntary versus compensatory steps

It has been recently demonstrated that investigation of recovery actions in compensatory protective steps does provide predictive information on the risk of falls in the elderly population [16]. Nevertheless, from older studies, voluntary steps assessment also revealed differences between elderly fallers and non-fallers. As an argument, inducing compensatory protective steps remain expensive if researchers or clinicians want to properly control the perturbation. Voluntary steps could be a much simpler task for elderly and a marker to detect fallers in a clinical environment. Does this detect and/or predict the risk of fall? Self-initiated steps have been studied to evaluate the effect of age on cognitive capacities [48,63] or the type of stimulus used to trigger it [77]. Interesting studies revealed that errors in the initial weight transfer (i.e. during the SPT) lead to slow choice step execution [87,18,91,83] that could be constraining in balance recovery task. They all took as reference the ''Choice Stepping Reaction Time Test'' [48] where it is reported that an increase in the preparation phase duration (RT + SPT) to perform a voluntary step is strongly correlated with the risk of fall. This is correlated to normal ageing in cognitive processing and the future risk of fall [64,71,84]. Studies also investigated only lateral steps with similar results [83,96]. The reason evoked is the presence of deficits in response inhibition [18,83]. The test of Lord and Fitzpatrick involves taking the right decision, because the context offers the subject to step with right or left leg, on a forward or lateral target. So if the pre-programmed APA can be released with no difficulty, they have to be planned after correct identification of the stimulus to allow the displacement of the corresponding foot in the associated direction. This identification is probably also done during the SPT [87]. Contextually, this step is getting close to a compensatory protective step task where the subject also has to correctly identify the unknown direction of the perturbation and then plan his/her appropriate answer. The differences are in the timing allowed by the unbalance and the uncertainty to have to take a step or not, identified during the preparation phase. Concerning the swing phase, no markers of fall risk were identified on voluntary steps. Researchers have only detected decrease due to age in swing leg velocity [96] and force peak [71]. So the deficits in elderly fallers should probably come from preparation phase [18,91]. In conclusion, the voluntary step is a simple task that can distinguish elderly fallers from non-fallers [48,64] and provide indications on the ability of the evaluated subject to take a right decision about a motor programmed action [18]. However, it does not allow understanding of the possibly deficient underlying mechanisms involved in postural responses from an unpredictable perturbation, notably because the timing constraint is fixed by the subject himself and not by the environmental context.

Interpretation of differences observed between voluntary step and compensatory protective step: a working hypothesis

In the previous section, we showed that the principal difference between compensatory and voluntary steps is observed during the SPT and concerns the use of APA. It has been reported that both young and elderly probably pre-select the response to unbalance [40,78]. If healthy elderly pre-select to step, do they use the voluntary step schema to prepare their response? This schema involves the use of APA that will delay the FO, and thus reach the final objective: slowing the CoM course. However, the most important constraint of balance recovery against unpredictable perturbation is not the ankle torque production capacity [28,29] but the timing [64,84], becoming shorter and shorter as the magnitude of the perturbation increases [14]. So APA cannot be performed well and are shortened, incomplete and/or ineffective. This is the illustration that the CNS is changing strategy, control mode and priority of the information to elaborate the quickest and the most appropriate — but not the most perfect — response. Since it is possible to perform an effective (very quick and sufficiently long) compensatory protective step without APA [62,58], we can hypothesize that an elderly faller will be more likely to select the longest strategy (with APA that makes him/her fall for a longer time) and then have difficulties to inhibit these ''pre-selected'' APA (regarding prior experience, personal confidence in his/her own capacities and environmental context) before stepping. It could be caused by a stronger fear of falling that will prevent them to ''let go'' and ''use the perturbation''. Letting go will paradoxically help them to earn time in reaching the final goal of the compensatory protective response by creating ''facilitating'' mechanical situation. Indeed, moving a foot to increase the BoS in order to break the fall of the CoM also implicates to move the CoM in the direction of the perturbation. However, the perturbation is already playing this role.

Since it has been shown that APA magnitude and duration are increased in voluntary step or gait initiation to perform quicker steps [12,71], compensatory steps are strongly faster and effective with reduced APA. How can that be possible? Studies that have considered both tasks helped us to understand that both movements are distinguishable by their objectives: accelerate the whole body CoM (voluntary) versus break it (compensatory) [8]. Indeed, the duration of preparation phase does not influence step length [14]. It is also ineffective to slow the mediolateral fall of the CoM [62] and will delay the rapid increasing of the BoS [57], a necessary condition to break the fall of the CoM. In compensatory protective situations, the CoM is accelerated by the perturbation itself. So, most of the ''APA job'' is already done by the mechanical effect of the perturbation, the body has ''only'' to recover equilibrium from its actual state.

Conclusion

Understanding the mechanisms by which the CNS is able to rapidly transform the sensed instability into limb movements that are appropriately patterned and timed, is a priority in determining the effects of ageing [50]. Notably, investigating the reactive stepping strategy remains one of the most relevant fields to study fall prevention. However, volitional and compensatory limb movements are too differently controlled and give contradictory information [52,50,49]. We therefore recommend the development of tests with the application of postural perturbations during clinical assessment that involve change-in-support reactions, in keeping with many other authors [50,33,53,82,55,2]. Particularly, workers should select a perturbation that is as unpredictable as possible, in order to correctly simulate the nature of the events preceding an unbalance and to be predictive of the risk of falls in the elderly [61]. This aspect will play a strong role on the timing the subject has left to recover balance. Nonetheless, studying volitional movement can reveal different but relevant information about balance control and ability to keep equilibrium. They remain simpler and less risky than investigating compensatory protective steps. In the same way, it has been reported that enhancing balance control by improving the APA responses during external perturbations is a valuable modality in the rehabilitation of individuals with balance impairment who are at risk of falls [80]. Interestingly, investigating step timings — and particularly APA — is possible with only one force platform (see Figs. 4 and 5). Since one platform is usually used in clinical environment to assess posturography, manufacturers could develop these, to allow investigation of both voluntary and induced-by-perturbation balance mechanisms.

With a contextual-dependent (including body's own adaptations to impairments due to advanced age) risk of fall [33], we strongly recommend researchers and clinicians to investigate risk of falls with multi-disciplinary assessments (psychological, physiological, biomechanical and cognitive) referring to several control modes (voluntary and automatic). In particular a complete assessment has to contain a test inducing external, unpredictable perturbation of balance that involves compensatory protective reactions, such as steps. Such an assessment protocol has not yet been developed in the clinical environment. This may be the best way to detect early deficits in healthy community-dwelling elderly adults, who have ''only'' normal ageing effects, before they actually fall. The BESTest suggested by Horak et al. [37] is a relevant lead. Training programs could also help subjects becoming familiar with the aspect of ''letting go'' with the unbalance and being aware of the most effective recovery actions, which are the change-in-support strategies [50]. Further research should orient towards developing a complete assessment for the risk of falls, which is drivable by clinicians in order to better prevent falls and to better understand the underlying mechanisms of reactive recovery responses.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

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References

[1] Allum J, Bloem B, Carpenter M, Hulliger M, Hadders-Algra M. Proprioceptive control of posture: a review of new concepts. Gait Posture 1998;8:214—42.

[2] Arampatzis A, Karamanidis K, Mademli L. Deficits in the way to achieve balance related to mechanisms of dynamic

stability control in the elderly. J Biomech 2008;41:1754—61, http://dx.doi.org/10.1016/j.jbiomech.2008.02.022.
[3] Aruin AS, Latash ML. Studied with self-induced and externally triggered perturbations. Exp Brain Res 1995;106:291—300.
[4] Aruin AS, Latash ML. Anticipatory postural adjustments in conditions of postural instability. Electromyogr Mot Control — Electroencephalograpgy Clin Neurophysiol 1998;109:350—9.
[5] Bariatinsky D, Mille ML, Vercher JL. Validation d'une méthode de détermination du seuil de déclenchement d'un pas protectif chez le jeune adulte. Université Sud Toulon-Var; 2013.
[6] Barrett RS, Lichtwark GA. Effect of altering neural, muscular and tendinous factors associated with aging on balance recovery using the ankle strategy: a simulation study. J Theor Biol 2008;254:546—54, http://dx.doi.org/10.1016/j.jtbi.2008.06.018.
[7] Barrett RS, Cronin NJ, Lichtwark GA, Mills PM, Carty CP. Adaptive recovery responses to repeated forward loss of balance in older adults. J Biomech 2012;45:183—7, http://dx.doi.org/10.1016/j.jbiomech.2011.10.005.
[8] Berthollet T, Tisserand R, Robert T. Comparison between protective and voluntary step: preliminary study in young healthy adults. In: SOFPEL Annu. Congr. Rennes, Fr; 2014.
[9] Bothner KE, Jensen JL. How do non-muscular torques contribute to the kinetics of postural recovery following a support surface translation? J Biomech 2001;34:245—50.
[10] Bouisset S, Do MC. Posture, dynamic stability, and voluntary movement. Neurophysiol Clin 2008;38:345—62, http://dx.doi.org/10.1016/j.neucli.2008.10.001.
[11] Brauer SG, Woollacott M, Shumway-Cook A. The influence of a concurrent cognitive task on the compensatory stepping response to a perturbation in balance-impaired and healthy elders. Gait Posture 2002;15:83—93.
[12] Breniere Y, Do M, Bouisset S. Are dynamic phenomena prior to stepping essential to walking. J Mot Behav 1987;19:62—76.
[13] Brown LA, Shumway-Cook A, Woollacott MH. Attentional demands and postural recovery the effects of aging.pdf. J Gerontol Med Sci 1999;54A:M165—71.
[14] Burleigh AL, Horak FB. Influence of instruction prediction and afferent sensory information on the postural organisation of step initiation.pdf. J Neurophysiol 1996;4:1619—28.
[15] Burleigh AL, Horak FB, Malouin F. Modification of postural responses and step initiation evidence for goal directed postural interactions.pdf. J Neurophysiol 1994;6:2892—902.
[16] Carty CP, Cronin NJ, Nicholson D, Lichtwark GA, Mills PM, Kerr G, et al. Reactive stepping behavior in response to forward loss of balance predicts future falls in community dwelling older adults. Age Ageing 2015;44:109—15.
[17] Clement G, Gurfinkel VS, Lestienne F, Lipshits MI, Popov KE. Adaptation of postural control to weightlessness. Exp Brain Res 1984;57:61—72.
[18] Cohen RG, Nutt JG, Horak FB. Errors in postural preparation lead to increased choice reaction times for step initiation in older adults. J Gerontol — Ser A Biol Sci Med Sci 2011;66 A:705—13, http://dx.doi.org/10.1093/gerona/glr054.
[19] Cordo PJ, Nashner LM. Properties of postural adjustments associated with rapid arm movements. J Neurophysiol 1982;47:287—382.
[20] Crenna P, Frigo C. A motor program for the initiation of forward oriented movements in humans. J Physiol London 1991;434:635—53.
[21] Cyr MA, Smeesters C. Kinematics of the threshold of balance recovery are not affected by instructions limiting the number of steps in younger adults. Gait Posture 2009;29:628—33, http://dx.doi.org/10.1016/j.gaitpost.2009.01.011.
[22] Do MC, Breniere Y, Berenguier P. A biomechanical study of balance recovery during the fall forward. J Biomech 1982;15:933—9.
[23] Do M, Breniere Y, Bouisset S. Compensatory reactions in forward fall: are they initiated by stretch receptors? Electroencephalogr Clin Neurophysiol 1988;69:448—52.
[24] Do MC, Schneider C, Chong RK. Factors influencing the quick onset of stepping following postural perturbation. J Biomech 1999;32:795—802.
[25] Donker SF, Roerdink M, Greven AJ, Beek PJ. Regularity of center-of-pressure trajectories depends on the amount of attention invested in postural control. Exp Brain Res 2007;181:1—11, http://dx.doi.org/10.1007/s00221-007-0905-4.
[26] Grabiner MD, Donovan S, Bareither ML, Marone JR, Hamstra-Wright K, Gatts S, et al. Trunk kinematics and fall risk of older adults: translating biomechanical results to the clinic. J Electromyogr Kinesiol 2008;18:197—204, http://dx.doi.org/10.1016/j.jelekin.2007.06.009.
[27] Granacher U, Muehlbauer T, Gruber M. A qualitative review of balance and strength performance in healthy older adults: impact for testing and training. J Aging Res 2012:1—16, http://dx.doi.org/10.1155/2012/708905.
[28] Gu MJ, Schultz AB, Shepard NT, Alexander NB. Postural control in young and elderly adults when stance is perturbed dynamics.pdf. J Biomech 1996;39:319—29.
[29] Hall CD, Woollacott MH, Jensen JL. Age-related changes in rate and magnitude of ankle torque development: implications for balance control. J Gerontol A Biol Sci Med Sci 1999;54:M507—13, http://dx.doi.org/10.1093/gerona/54.10.M507.
[30] Hamacher D, Singh NB, Van Dieën JH, Heller MO, Taylor WR. Kinematic measures for assessing gait stability in elderly individuals: a systematic review. J R Soc Interface 2011;8:1682—98, http://dx.doi.org/10.1098/rsif.2011.0416.
[31] Hauer K, Lamb SE, Jorstad EC, Todd C, Becker C. Systematic review of definitions and methods of measuring falls in randomised controlled fall prevention trials. Age Ageing 2006;35:5—10, http://dx.doi.org/10.1093/ageing/afi218.
[32] Hof a L, Gazendam MGJ, Sinke WE. The condition for dynamic stability. J Biomech 2005;38:1—8, http://dx.doi.org/10.1016/j.jbiomech.2004.03.025.
[33] Horak FB. Postural orientation and equilibrium: what do we need to know about neural control of balance to prevent falls? Age Ageing 2006;35(Suppl. 2):ii7—11, http://dx.doi.org/10.1093/ageing/afl077.
[34] Horak FB, Macpherson JM. Postural orientation and equilibrium. In: Handb. Physiol. Sect. 12 Exerc. Regul. Integr. Mult. Syst.; 1996. p. 255—92.
[35] Horak FB, Nashner LM. Central programming of postural movements: adaptation to altered support-surface configurations. J Neurophysiol 1986;55:1369—81.
[36] Horak FB, Shupert CL, Mirka A. Components of postural dyscontrol in the elderly. Neurobiol Ageing 1989;10:727—38.
[37] Horak FB, Wrisley DM, Frank JS. The Balance Evaluation Systems Test (BESTest) to differenciate balance deficits. Phys Ther 2009;89:484—98.
[38] Hsiao ET, Robinovitch SN. Biomechanical influences on balance recovery by stepping. J Biomech 1999;32:1099—106.
[39] Hsiao-Wecksler ET. Biomechanical and age-related differences in balance recovery using the tether-release method. J Electromyogr Kinesiol 2008;18:179—87, http://dx.doi.org/10.1016/j.jelekin.2007.06.007.
[40] Jacobs JV, Horak FB. External postural perturbations induce multiple anticipatory postural adjustments when subjects cannot pre-select their stepping foot. Exp Brain Res 2007;179:29—42, http://dx.doi.org/10.1007/s00221-006-0763-5.
[41] Johnson-Hilliard M, Martinez KM, Janssen I, Edwards BJ, Mille ML, Zhang Y, et al. Lateral balance factors predict future falls in community-living older adults. Arch Phys Med

Rehabil 2008;89:1708—13, http://dx.doi.org/10.1016/j.apmr.2008.01.023.Lateral.
[42] Kanekar N, Aruin AS. The effect of aging on anticipatory postural control. Exp Brain Res 2014;232:1127—36, http://dx.doi.org/10.1007/s00221-014-3822-3.
[43] King MB, Judge JO, Wolfson L. Functionnal base of support decreases with age. J Gerontol 1994;49:M258—63.
[44] Lajoie Y, Gallagher S. Predicting falls within the elderly community: comparison of postural sway, reaction time, the Berg balance scale and the activities-specific balance confidence (ABC) scale for comparing fallers and non-fallers. Arch Gerontol Geriatr 2004;38:11—26, http://dx.doi.org/10.1016/S0167-4943(03)00082-7.
[45] Lee PY, Gadareh K, Bronstein AM. Forward-backward postural protective stepping responses in young and elderly adults. Hum Mov Sci 2014;34:137—46, http://dx.doi.org/10.1016/j.humov.2013.12.010.
[46] Lin SI, Woollacott MH. Postural muscle responses following changing balance threats in young, stable older and unstable older adults. J Mot Behav 2002;34:37—44.
[47] Lin SI, Woollacott M. Association between sensorimotor function and functional and reactive balance control in the elderly. Age Ageing 2005;34:358—63, http://dx.doi.org/10.1093/ageing/afi089.
[48] Lord SR, Fitzpatrick RC. Choice stepping reaction time: a composite measure of falls risk in older people. J Gerontol A Biol Sci Med Sci 2001;56:M627—32.
[49] Luchies C, Pazdur R, Deyoung A. Effects of age on balance assessment using voluntary and involuntary step tasks. J Gerontol Med Sci 1999;54A:M140—4.
[50] Maki BE, McIlroy WE. The role of limb movements in maintaining upright stance: the ''change-in-support'' strategy. Phys Ther 1997;77:488—507.
[51] Maki BE, McIlroy WE. The control of foot placement during compensatory stepping reactions: does speed of response take precedence over stability? IEEE Trans Rehabil Eng 1999;7:80—90.
[52] Maki BE, McIlroy WE. Control of rapid limb movements for balance recovery: age-related changes and implications for fall prevention. Age Ageing 2006;35(Suppl. 2):ii12—8, http://dx.doi.org/10.1093/ageing/afl078.
[53] Mancini M, Horak FB. The relevance of clinical balance assessment tools to differentiate balance deficits. Eur J Rehabil Med 2010;46:239—48.
[54] Mancini M, Zampieri C, Carlson-Kuhta P, Chiari L, Horak FB. Anticipatory postural adjustments prior to step initiation are hypometric in untrated Parkinson disease: an accelerometer based approach. Eur J Neurol 2009;16:1028—34.
[55] Mansfield A, Peters AL, Liu BA, Maki BE. Effect of a perturbation-based balance training program on compensatory stepping and grasping reactions in older adults: a randomized controlled trial. Phys Ther 2010;90:476—91, http://dx.doi.org/10.2522/ptj.20090070.
[56] Massion J. Movement, posture and equilibrium: interaction and coordination. Prog Neurobiol 1992;38:35—56, http://dx.doi.org/10.1016/0301-0082(92)90034-C.
[57] McIlroy WE, Maki BE. Changes in early ''automatic'' postural responses associated with the prior-planning and execution of a compensatory step. Brain Res 1993;631:203—11, http://dx.doi.org/10.1016/0006-8993(93)91536-2.
[58] McIlroy WE, Maki BE. Do anticipatory postural adjustments precede compensatory stepping reactions evoked by perturbation? Neurosci Lett 1993;164:199—202, http://dx.doi.org/10.1016/0304-3940(93)90891-N.
[59] McIlroy WE, Maki BE. Task constraints on foot movement and the incidence of compensatory stepping following perturbation of upright stance. Brain Res 1993;616:30—8.
[60] McIlroy WE, Maki BE. Early activation of arm muscles follows external perturbation of upright stance. Neurosci Lett 1995;184:177—80.
[61] McIlroy WE, Maki BE. Age-related changes in compensatory stepping in response to unpredictable perturbations. J Gerontol A Biol Sci Med Sci 1996;51:M289—96.
[62] McIlroy WE, Maki BE. The control of lateral stability during rapid stepping reactions evoked by antero-posterior perturbation: does anticipatory control play a role? Gait Posture 1999;9:190—8.
[63] Melzer I, Oddsson LIE. The effect of a cognitive task on voluntary step execution in healthy elderly and young individuals. J Am Geriatr Soc 2004;52:1255—62.
[64] Melzer I, Kurz I, Shahar D, Levi M, Oddsson L. Application of the voluntary step execution test to identify elderly fallers. Age Ageing 2007;36:532—7, http://dx.doi.org/10.1093/ageing/afm068.
[65] Mille ML, Rogers MW, Martinez K, Hedman LD, Johnson ME, Lord SR, et al. Thresholds for inducing protective stepping responses to external perturbations of human standing. J Neurophysiol 2003;90:666—74, http://dx.doi.org/10.1152/jn.00974.2002.
[66] Mille ML, Johnson ME, Martinez KM, Rogers MW. Age-dependent differences in lateral balance recovery through protective stepping. Clin Biomech (Bristol, Avon) 2005;20:607—16, http://dx.doi.org/10.1016/j.clinbiomech.2005.03.004.
[67] Mille ML, Johnson-Hilliard M, Martinez KM, Zhang Y, Edwards BJ, Rogers MW, et al. Directional vulnerability to falls in community-dwelling older people. J Gerontol A Biol Sci Med Sci 2013:1—9, http://dx.doi.org/10.1093/gerona/glt062.
[68] Moglo KE, Smeesters C. Effect of age and the nature of the postural perturbation on the threshold of balance recovery. In: 30th Annu. Meet. Am. Soc. Biomech. Blacksbg. VA; 2006.
[69] Pai Y-C, Patton J. Center of mass velocity position prediction for balance control. J Biomech 1997;30:347—54.
[70] Park S, Horak FB, Kuo AD. Postural feedback responses scale with biomechanical constraints in human standing. Exp Brain Res 2004;154:417—27, http://dx.doi.org/10.1007/s00221-003-1674-3.
[71] Patla AE, Frank JS, Winter DA, Rietdyk S, Prentice S, Prasad Md S. Age-related changes in balance control system: Initiation of stepping. Clin Biomech 1993;8:179—84, http://dx.doi.org/10.1016/0268-0033(93)90012-7.
[72] Peterka RJ. Sensorimotor integration in human postural control. J Neurophysiol 2002;88:1097—118.
[73] Pidcoe PE, Rogers MW. A closed-loop stepper motor waist-pull system for inducing protective stepping in humans. J Biomech 1998;31:377—81.
[74] Porter S, Nantel J. Older adults prioritize postural stability in the anterior—posterior direction to regain balance following volitional lateral step. Gait Posture 2015;41:666—9, http://dx.doi.org/10.1016/j.gaitpost.2015.01.021.
[75] Robinovitch SN, Feldman F, Yang Y, Schonnop R, Leung PM, Sarraf T, et al. Video capture of the circumstances of falls in elderly people residing in long-term care: an observational study. Lancet 2013;381:47—54, http://dx.doi.org/10.1016/S0140-6736(12)61263-X.
[76] Rogers MW, Kukulka CG, Soderberg GL. Age related changes in postural responses preceding rapid self paced and reaction time arm movement. J Gerontol 1992;47:M159—65.
[77] Rogers MW, Kukulka CG, Brunt D, Cain TD, Hanke TA. The influence of stimulus cue on the initiation of stepping in young and older adults. Arch Phys Med Rehabil 2001;82:619—24, http://dx.doi.org/10.1053/apmr.2001.20833.
[78] Rogers MW, Hedman LD, Johnson ME, Martinez KM. Triggering of protective stepping for the control of human balance: age

and contextual dependence. Cogn Brain Res 2003;16:192—8, http://dx.doi.org/10.1016/S0926-6410(02)00273-2.
[79] Santos MJ, Kanekar N, Aruin AS. The role of anticipatory postural adjustments in compensatory control of posture: 2. Biomechanical analysis. J Electromyogr Kinesiol 2010;20:398—405, http://dx.doi.org/10.1016/j.jelekin.2010.01.002.
[80] Santos MJ, Kanekar N, Aruin AS. The role of anticipatory postural adjustments in compensatory control of posture: 1. Electromyographic analysis. J Electromyogr Kinesiol 2010;20:388—97, http://dx.doi.org/10.1016/j.jelekin.2009.06.006.
[81] Segev-Jacubovski O, Herman T, Yogev-Seligmann G, Mirelman A, Giladi N, Hausdorff J. The interplay between gait, falls and cognition: can cognitive therapy reduce fall risk? Expert Rev Neurother 2011;11:1057—75, http://dx.doi.org/10.1586/ern.11.69.The.
[82] Singer ML, Smith LK, Dibble LE, Foreman KBO. Age-related difference in postural control during recovery from posterior and anterior perturbations. Anat Rec 2015;298:346—53, http://dx.doi.org/10.1002/ar.23043.
[83] Sparto PJ, Jennings JR, Furman JM, Redfern MS. Lateral step initiation behavior in older adults. Gait Posture 2014;39:799—803, http://dx.doi.org/10.1016/j.gaitpost.2013.10.021.
[84] St George RJ, Fitzpatrick RC, Rogers MW, Lord SR. Choice stepping response and transfer times: effects of age, fall risk, and secondary tasks. J Gerontol A Biol Sci Med Sci 2007;62:537—42, http://dx.doi.org/10.1016/S0021-9290(06)83244-6.
[85] Stevens J, Corso P, Finkelstein E, Miller T. The costs of fatal and non-fatal falls among older adults. Inj Prev 2006;12:290—5, http://dx.doi.org/10.1136/ip.2005.011015.
[86] Sturnieks DL, Menant J, Delbaere K, Vanrenterghem J, Rogers MW, Fitzpatrick RC, et al. Force-controlled balance perturbations associated with falls in older people: a prospective cohort study. PLoS One 2013;8:1—6, http://dx.doi.org/10.1371/journal.pone.0070981.
[87] Sun R, Guerra R, Shea JB. The posterior shift anticipatory postural adjustment in choice reaction step initiation. Gait Posture 2015;41:894—8, http://dx.doi.org/10.1016/j.gaitpost.2015.03.010.
[88] Thelen DG, Wojcik LA, Schultz a B, Ashton-Miller JA, Alexander NB. Age differences in using a rapid step to regain balance during a forward fall. J Gerontol A Biol Sci Med Sci 1997;52:M8—13.
[89] Tinetti M, Speechley M, Ginter S. Risk factors for fall among elderly persons living in the community. N Engl J Med 1988;319:1701—7.
[90] Tisserand R, Robert T, Chèze L. Differences in elderly balance recovery response by stepping: effect of faller past and perturbation duration. Spain: ISPGR Wolrd Congr. Seville; 2015.
[91] Uemura K, Yamada M, Nagai K, Tanaka B, Mori S, Ichihashi N. Fear of falling is associated with prolonged anticipatory postural adjustment during gait initiation under dual-task conditions in older adults. Gait Posture 2012;35:282—6, http://dx.doi.org/10.1016/j.gaitpost.2011.09.100.
[92] Van den Bogert AJ, Pavol MJ, Grabiner MD. Response time is more important than walking speed for the ability of older adults to avoid a fall after a trip. J Biomech 2002;35:199—205.
[93] Van Dieën JH, Pijnappels M. Falls in older people. J Electromyogr Kinesiol 2008;18:169—71, http://dx.doi.org/10.1016/j.jelekin.2007.06.001.
[94] Visser JE, Carpenter MG, Van der Kooij H, Bloem BR. The clinical utility of posturography. Clin Neurophysiol 2008;119:2424—36, http://dx.doi.org/10.1016/j.clinph.2008.07.220.
[95] Weerdesteyn V, Laing AC, Robinovitch SN. The body configuration at step contact critically determines the successfulness of balance recovery in response to large backward perturbations. Gait Posture 2012;35:462—6, http://dx.doi.org/10.1016/j.gaitpost.2011.11.008.
[96] White KN, Gunter KB, Snow CM, Hayes WC. The quick step: a new test for measuring reaction time and lateral stepping velocity. J Appl Biomech 2002;18:271—7.
[97] Winter DA. Human balance and posture control during standing and walking. Gait Posture 1995;3:193—214.
[98] Wojcik LA, Thelen DG, Schultz AB, Ashton-Miller JA, Alexander NB, et al. Age and gender differences in peak lower extremity joint torques and ranges of motion used during single-step balance recovery from a forward fall. J Biomech 2001;34:67—73.
[99] Woollacott MH, Manchester DL. Anticipatory postural adjustments in older adults: are changes in response characteristics due to changes in strategy? J Gerontol 1993;48:M64—70.
[100] World Health Organisation. Global report on falls: prevention in older age. Ageing Life Course, Fam Community Heal; 2008.
[101] Zettel JL, McIlroy WE, Maki BE. Environmental constraints on foot trajectory reveal the capacity for modulation of anticipatory postural adjustments during rapid triggered stepping reactions. Exp Brain Res 2002;146:38—47, http://dx.doi.org/10.1007/765 s00221-002-1150-5.
[102] Zettel JL, Holbeche A, McIlroy WE, Maki BE. Redirection of gaze and switching of attention during rapid stepping reactions evoked by unpredictable postural perturbation. Exp Brain Res 2005;165:392—401, http://dx.doi.org/10.1007/s00221-005-2310-1.